BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LXI (LXV), Fasc. 3, 2015
Secţia
CONSTRUCŢII. ARHITECTURĂ

PERFORMANCE EVALUATION OF BRIDGES IN IAŞI SEISMIC AREA

BY

LĂZĂRICĂ TEŞU*

"Gheorghe Asachi" Technical University of Iaşi
Faculty of Civil Engineering and Building Services

Received: July 15, 2015
Accepted for publication: July 30, 2015

Abstract. This paper presents the theoretical background for modal analysis necessary in performing the dynamic analysis for reinforced concrete bridge structures in seismic regions. In the first part of the paper a brief description of the most important aspects regarding the structural elements and the simplified ways of modeling a reinforced concrete bridge are presented. Modal analysis is used to analyze the responses of a structure under dynamic loadings and it is a widespread approach used in earthquake engineering. The main benefits from modal analysis is that one can determine the natural frequencies, the damping at natural frequencies and the mode shapes at natural frequencies for a given structure. It can also be used as a method of experimental procedure of vibration analysis, where given the response properties, one can predict the models properties and possible degradations in the bridge structure. A case study is presented, where a bridge from Iasi municipality has been investigated using FEM analysis software SAP2000/Bridge, in order to determine its dynamic characteristics. The results have been checked to see if they are in compliance with the requirements of EN 1998-1-2004. It was concluded that using FEM analysis software such as SAP2000/Bridge one can

*Corresponding author: *e-mail:* lazarica.t@gmail.com

calibrate the computational model of the bridge, using the dynamical characteristics obtained from experimental monitoring and with this knowledge one can establish the presence of a degradation process in the monitored bridge.

Key words: simulation; seismic analysis; modal analysis.

1. Introduction

Bridges are works of art that support traffic routes and that ensure their continuity, when obstacles are encountered in the path of the route. These obstacles can be watercourses, steep valleys or intersections with other routes of transportation (Negoescu & Fierbinteanu, 1985).

Depending on the design approach, the type of bridge (Railway Bridge, Highway Bridge, Pedestrian Walkway, etc.) and other parameters of the bridge, one can determine the dimension and characteristics for the abutments and bents, which best fit the desired requirements.

The bents can be manufactured out of steel or reinforced concrete (RC). If the height of the bents is very high then prestressed concrete is used, in order to avoid cracks.

The bearing blocks are devices that connect the bridge superstructure to the infrastructure. They are designed to transfer the vertical and horizontal forces from the superstructure to the infrastructure elements (abutments and bents). At the same time, the bearings must allow translation and rotation of the superstructure, according to the static computational model, otherwise far greater forces and stresses than those considered in the design phase, can be developed in the bridge structure. These are leading to lower bearing capacities for some of the structural elements of the bridge.

Depending on the degrees of freedom of the bearings there are three types of bearings: pinned bearing blocks, that rotate the superstructure in a vertical plane; roller bearing blocks, that provides the translation of the superstructure in that direction, taking over the horizontal and vertical forces; knuckled pinned bearing blocks, which provides translations in any direction and rotations in the vertical plane, taking over only the vertical forces.

The arrangement of the bearing blocks for a bridge structure depends on the static model adopted for the computation of the superstructure, on the number and the size of the spans and on the width of the superstructure. Depending on the type of bearing blocks used one can establish a computational model for road bridge structures made of concrete girders (Răcănel, 2007).

2. Modeling Aspects for Road Bridges

For this type of bridges the friction forces are exceeded only in the case of seismic forces, caused by earthquakes with high seismic intensity with a magnitude greater than 9 on Richter scale. For low intensity earthquakes, the infrastructure and the superstructure are oscillating together.

Bridges with sliding bearings usually have small spans, and the computational model is reduced to a single degree of freedom dynamic system. In order to determine the flexibility of the dynamic system, one can take in consideration the contribution of the foundation movement (rotation and lateral translation). The concentrated mass at the top of the bent is determined following the recommendation of Negoescu & Fierbin□eanu, 1985:

$$m = \frac{(R_s + R_d + G_s)}{g}, \tag{1}$$

where: R_s is the left-side beam reaction; R_d – the right-side beam reaction; G_s – the weight of the upper part of the bent; g – gravity acceleration.

To determine the reactions of the two beams one can also take into account the moving loads. The period of vibration for this type of structures, with normal foundation conditions, has small values, $T < 0.5$ s.

For bridges with rolling bearings the frictional forces have low values, and thus the superstructure will move independent from the infrastructure. The infrastructure can be modelled as a multi degree of freedom dynamic model, MDOFM, with concentrated masses distributed along its length, represented by a bar with variable cross-section.

When subjected to seismic ground shaking the bridge structure is modeled as having infinite stiffness, with the bent divided into levels, and the earthquake responses are applied to the masses of each level of the bent. The horizontal seismic response is determined with:

$$S_{kh} = c_h g m_k, \tag{2}$$

where: S_{kh} is the horizontal seismic response, at the k level of the bent; c_h – horizontal earthquake coefficient; g – gravity acceleration; m_k – the mass of the structure, at the k level of the bent.

The vertical seismic response is given:

$$S_{kv} = c_v g m_k, \tag{3}$$

where: S_{kv} is the vertical seismic response, at the k level of the bent; c_v – vertical earthquake coefficient.

3. Theoretical Basis of Modal Analysis

Modal analysis is used to analyze the responses of a structure under dynamic loadings, thus one can evaluate the dynamic response of a structure in a modal coordinate system. The modal analysis approach has a widespread use in earthquake engineering. The seismic design and analysis of structures with damping devices is based on the modal analysis concept, in which the motion within a plane and the assumption of classical damping are usually made [3].

The modal analysis is used to determine the natural frequencies, the damping at natural frequencies and the mode shapes at natural frequencies for a given structure.

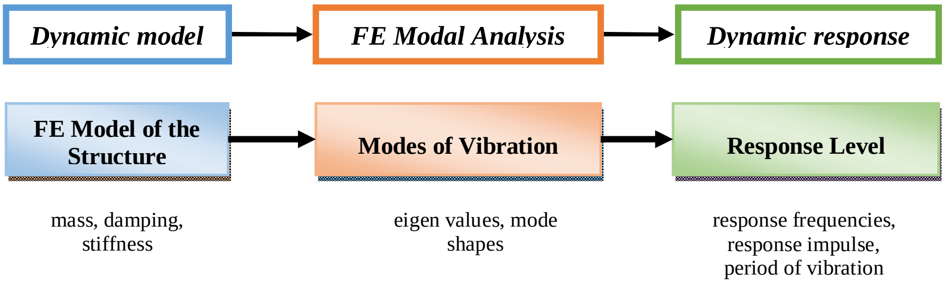

Fig. 1 – FE Procedure for vibration analysis of civil structures.

Fig. 1 displays the three phase procedure of the theoretical vibration analysis, starting with a description of the physical properties of the structures, usually the mass, stiffness and damping characteristics (Lengvarsky & Bocko, 2013).

The natural mode shapes of a structure during free vibration are determined by means of a modal model. This model is defined as a set of natural frequencies with damping factor and natural modes of vibration.

The response of model is described by a set of frequency response functions, which corresponds to the excitation and its amplitude.

It is possible to perform the analysis in the opposite direction, from the response properties, from which one can predict the modal model properties. This method is called the experimental procedure of vibration analysis and is shown in Fig. .

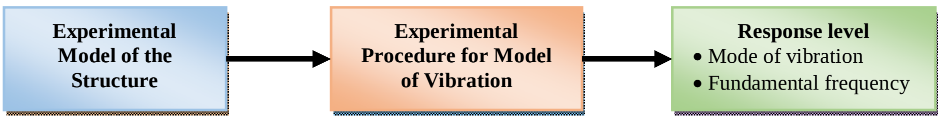

Fig. 2 – Experimental approach for modal analysis of bridges.

The models used in dynamic structure response analysis, can range from simple linear models, such as a single-degree-of-freedom SDOF system, to more sophisticated non-linear models, which are analyzed by means of the finite element method FEM. A structure can be roughly estimated by means of a linear model.

A SDOF or multi-degree-of-freedom MDOF system is often used in earthquake engineering for the dynamic response analysis of a structure. The analysis of a well-constructed MDOF system can reproduce the complicated responses of a structure. MDOF system analysis can have applications in structure health monitoring and diagnosis [5].

The theoretical approach for analyzing of a linear MDOF system, uses a time series function, $\mathbf{g_j(t)}$. The MDOF system has a response for each degree of freedom DOF, and they are represented as a function of time. The equation of motion for a MDOF model is represented by the following 2nd order differential equation, according to Chopra (2011), (Lengvarsky & Bocko, 2013):

$$\mathbf{M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t)}, \tag{4}$$

where: **M**, **C** and **K** are the mass, damping and stiffness matrices, respectively, all of dimensions $\mathbf{n} \times \mathbf{n}$; $\mathbf{\ddot{u}(t)}$ is the acceleration vector; $\mathbf{\dot{u}(t)}$ is the velocity vector; $\mathbf{u(t)}$ is the displacement vector, of dimensions $\mathbf{n} \times 1$; $\mathbf{F(t)}$ is the vector of time-dependent force vector.

The **M**, **C** and **K** matrices, describe the mechanical properties of the MDOF system. Using the modal analysis one can compute the modes of vibration given by the relationship:

$$\mathbf{u(t) = \Phi Y(t)}, \tag{5}$$

where: $\mathbf{\Phi}$ represents a matrix of size ($\mathbf{n} \times$ L) containing **L** spatial vectors and $\mathbf{Y(t)}$ is a vector that contains L functions of time.

By substituting **u** in the equation of motion, and **C** = 0 we obtain the equation of motion for free vibration:

$$\mathbf{(K - \omega^2 M)q = 0}, \tag{6}$$

where: $\boldsymbol{\omega}$ is the circular frequency of vibration and **q** is the vector of the displacement amplitudes.

The typical uncoupled modal equation for a linear structural system is given by eq. (7), according to Atanasiu & Roşca (2014):

$$\mathbf{\ddot{Y}(t)_n + 2\nu_n\omega_n\dot{Y}(t)_n + \omega_n^2 Y(t)_n = \sum_{j=1}^{J} p_{nj} g_j(t)}, \tag{7}$$

where: $\boldsymbol{\omega_n}$ is the circular frequency of vibration corresponding to the **n-**th mode; $\boldsymbol{\nu_n}$ is the damping ratio corresponding to the **n-**th mode; $\mathbf{Y(t)_n}$ is a vector of time functions corresponding to the **n**-th mode; $\mathbf{p_{nj}}$ – mass participation factors; $\mathbf{g_j(t)}$ – time functions.

The three directions of the mass participation factors are defined by:

$$\mathbf{p_{ni} = -\Phi_n^T M_i}, \quad (\mathbf{i = x, y, z}), \tag{8}$$

The modal response for a unit base acceleration can be written as follows:

$$\mathbf{\ddot{Y}_n = p_{ni}}. \tag{9}$$

The participating mass for the three directions can be defined as a ratio of the total mass in that direction, with the following relationships:

$$\mathbf{X_{mass}} = \frac{\sum_{n=1}^{L} \mathbf{p_{nx}^2}}{\sum \mathbf{m_x}}; \mathbf{Y_{mass}} = \frac{\sum_{n=1}^{L} \mathbf{p_{ny}^2}}{\sum \mathbf{m_y}}; \mathbf{Z_{mass}} = \frac{\sum_{n=1}^{L} \mathbf{p_{nz}^2}}{\sum \mathbf{m_z}}. \tag{10}$$

The natural frequencies can be determined by assuming a lumped mass with uniform spring MDOF system. The stiffness and mass matrices take the following form shape:

$$\mathbf{K} = \begin{bmatrix} \mathbf{k_1 + k_2} & \mathbf{-k_2} & \mathbf{0} & \cdots & & \mathbf{0} \\ \mathbf{-k_2} & \mathbf{k_2 + k_3} & \mathbf{-k_3} & \cdots & & \mathbf{0} \\ \mathbf{0} & \mathbf{-k_3} & \mathbf{k_3 + k_4} & \cdots & & \mathbf{0} \\ & \ddots & \ddots & \ddots & & \\ \mathbf{0} & & & & \mathbf{k_{n-1} + k_n} & \mathbf{-k_n} \\ \mathbf{0} & \mathbf{0} & & \cdots & \mathbf{-k_n} & \mathbf{k_n} \end{bmatrix}, \tag{11}$$

$$\mathbf{M} = \begin{bmatrix} \mathbf{m_1} & & \cdots & \mathbf{0} \\ & \mathbf{m_2} & \cdots & \mathbf{0} \\ & & \ddots & \\ \mathbf{0} & \mathbf{0} & & \mathbf{m_n} \end{bmatrix}, \tag{12}$$

The natural frequencies of a MDOF system are given by the roots of $\mathbf{det\left|\omega^2 \cdot M - K\right| = 0}$. The first root represents the natural frequency of the fundamental mode. For a given period of the fundamental mode $\mathbf{T}_1$ the natural frequency of the fundamental mode is given in eq. (13):

$$\boldsymbol{\omega}_1 = \sqrt{\frac{\boldsymbol{\Phi}_1^{\mathrm{T}}\mathbf{K}\boldsymbol{\Phi}_1}{\boldsymbol{\Phi}_1^{\mathrm{T}}\mathbf{M}\boldsymbol{\Phi}_1}}\,. \tag{13}$$

where: $\boldsymbol{\Phi}_1$ is the fundamental normalized mode vector; $\boldsymbol{\omega}_1$ – the fundamental natural frequency.

4. Evaluating the Modal Response of a RC Bridge Located in Iaşi Municipality

In order to illustrate the modal analysis using FEM analysis, a RC road bridge, situated in Iaşi municipality was chosen. The bridge is located in the Tudor Vladimirescu residential neighborhood, and it consists of a single span continuous superstructure, with a total length of 46 m. The superstructure is composed of two concrete box girder decks, each with 3 lanes of traffic, joined together. The total width of the superstructure is 26.4 m. The girders are interconnected by end-span diaphragms as well as intermediate diaphragms at a uniform spacing of 4.75 m. The deck weight is supported by two concrete wall-type bents of a height of 4 m.

Fig. 1 – RC Bridge location in Iaşi Tudor Vladimirescu residential neighborhood.

The analytical model considered in the modal analysis of the RC bridge is composed of a single span continuous superstructure simply supported by two FE shell type elements, which represent the wall-type bents of the bridge. Together they form a 3d frame with fixed supports. The meshed model for the bridge resulted with a total number of 2720 FE area elements and 10880 FE line elements. Each line element simulates the geometric and physical properties of the local material. The material used for the deck section and the shell type elements was concrete C 30/37, with the following material properties: density of 2,548.5 kg/m^3, modulus of elasticity E of 33,000 MPa, Poisson's ratio ν of 0.2, shear modulus G of 13,750 MPa, and the characteristic strength of concrete f_c of 30 MPa.

The entire bridge structure was analyzed using SAP2000/Bridge. SAP2000/Bridge is an analysis and design program for bridge structures which allows complex bridge structures to be modeled by engineers. The bridge models are defined parametrically and it allows the user to build simple or complex bridge models and to make changes during the design process [8].

The modal analysis performed in SAP2000/Bridge is a linear dynamic-response procedure which evaluates and superimposes free-vibration mode shapes to characterize displacement patterns. The program reduces the equations of motion, **n** simultaneous differential equations coupled by full mass and stiffness matrices respectively, to a much smaller set of uncoupled second order differential equations (Kalny, 2010).

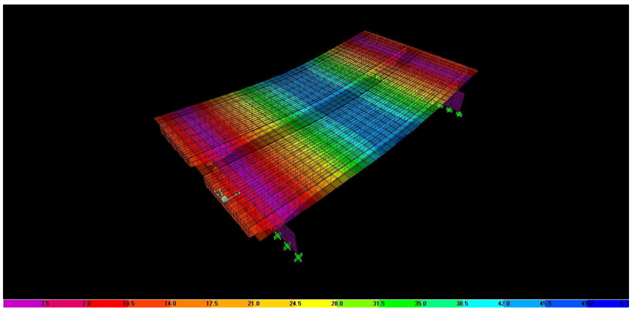

Fig. 4 – Deformed shape of the bridge for the 1st mode of vibration.

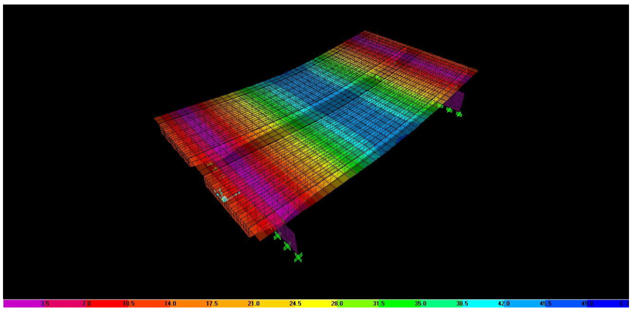

Fig. 5 – Deformed shaped of the bridge for the 3rd mode of vibration.

The number of modes used by SAP2000/Bridge is automated and depends on the number of bridge spans. For the bridge in this study, a total number of 12 modes of vibration was chosen. After the analysis the total mass participation was checked to ensure that an adequate number of modes was included in the modal analysis (CSi Computers & Structures, I. 2009). According to EN 1998-2-2006 section 4.2.1.2 the sum from all the modal masses should be at least 90% of the total mass of the bridge [11]. From the analysis of the R.C. bridge we easily obtain the deformed shapes of the bridge structure, as illustrated by Fig. and Fig. , and we also remark that a 93% modal mass participation of the structure resulted which indicates that the number of modes of vibration was chosen correct.

Table 1
Modal Participating Mass Ratios

Output case	Step type	Step num	Period	Sum UX	Sum UY	Sum UZ
		Unitless	Sec	Unitless	Unitless	Unitless
Modal	Mode	1	0.541192	6.798E-15	0	0.43468
Modal	Mode	2	0.449194	0.9313	0	0.43468

From the results shown in Table 1 one can see that the modeled bridge reaches a modal mass contribution of 93 % on the X direction of the orthogonal coordinate system, starting with the second mode of vibration. One can assume that the modal analysis using FEM, of the bridge is reliable.

From the FEM analysis it resulted a fundamental period of vibration T_1 = 0.541 s with a natural frequency f_1 = 11.61 Hz for the bridge structure. According to EN 1998-1-2004 section 4.3.3.2.1 the fundamental period of vibration should be $T_1 \leq \{4T_c; 2.0 \text{ s}\}$, where T_c is the upper limit of the period of the constant spectral acceleration branch of the response spectrum used in seismic analysis. For Iaşi municipality the value for T_c is 0.7 s. For the selected bridge in this case study, the dynamic analysis performed in SAP2000/Bridge is in accordance with the requirements of EN 1998-1-20004.

5. Conclusions

This paper offers a general theoretical presentation of the FE modal analysis and its application in the dynamic analysis of a RC bridge, as a study case for a bridge located in Iaşi, Tudor Vladimirescu residential neighborhood. The following remarks have been concluded:

1º The modal analysis can be viewed as a means of structural identification that can alert to the possible degradation of a bridge structure. By monitoring systems signals from dynamical tests one can identify the dynamical characteristics of the bridge through modal analysis (Comisu & Boaca, 2010).

2º Using FEM analysis software such as SAP2000/Bridge one can calibrate the computational model of the bridge, based on the dynamical characteristics obtained from monitoring. By comparing the values of these two one can establish the presence of a degradation process in the monitored bridge and correct the model of the bridge structure.

3º Modal analysis is an important tool in system the identification SI for structural heath monitoring SHM of bridges that are prone to degradation.

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EVALUAREA PERFORMANŢEI PODURILOR ÎN REGIUNI SEISMICE

(Rezumat)

Sunt prezentate concepte teoretice ale analizei modale utilizând metoda elementului finit MEF, necesară în efectuarea analizei dinamice pentru structuri de pod din beton armat situate în regiuni seismice. În prima parte a lucrării este prezentată o scurtă descriere a celor mai importante aspecte referitoare la elementele structurale şi modalităţile simplificate de modelare ale unui pod de beton armat. Analiza modală cu EF este folosită în identificarea răspunsurilor unei structuri supuse la încărcări dinamice, fiind o abordare larg răspândită în ingineria seismică. Principalele beneficii de analizei modale cu EF constă în determinarea frecvenţelor naturale, a amortizării corespunzătoare frecvenţei naturale şi a modurilor proprii de vibrare pentru o structură dată. Analiza modală este o metodă de analiză a vibraţiilor obţinute pe cale experimentală. Cu ajutorul softului de analiză dinamică SAP2000/Bridge, utilizând datele cu privire la răspunsul structurii, putem anticipa proprietăţile modelului şi posibile degradări în structura podului. Articolul prezintă un studiu de caz, în care s-a investigat un pod din beton armat din municipiul Iaşi folosind programul de analiză cu element finit SAP2000/Bridge, în scopul determinării caracteristicilor dinamice ale acestuia. Rezultatele au fost verificate pentru a vedea dacă acestea sunt în conformitate cu cerinţele din EN 1998-1-2004. S-a concluzionat că prin folosirea programelor de analiză prin EF, precum SAP2000/Bridge se poate calibra modelul de calcul al unui pod pe baza caracteristicilor dinamice obţinute din monitorizarea experimentală. Utilizând informaţiile obţinute se poate stabili prezenţa unui proces de degradare la podul monitorizat.