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NEW INTEGRATED CONCEPT FOR DIAGNOSIS OF THE STATE OF RC BRIDGES UNDER SERVICE AND EARTHQUAKE LOADS BASED ON PROGRESSIVE STRUCTURAL FAILURE PREDICTION

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ABSTRACT

During long serviceability period, the existing RC bridge structures in seismic regions may be exposed to serious deterioration. In many cases such a deterioration may become very critical under both, service loads and particularly under the effects of strong earthquakes. In such cases, to define an optimal system rehabilitation solution, an accurate diagnosis of the state of the integral structural system must be accomplished first.

The present paper describes a newly developed integral methodological concept for diagnosis of the state of RC and prestressed bridge structures under service and earthquake loads implementing linear and non-linear models of the integral structures. The developed diagnosis methodology basically includes realization of two separate phases: experimental and analytical phase.

KEYWORDS

Structural diagnosis; non-linear analysis; bridge structures; non-destructive in-situ tests; ambient vibration dynamic experiments; destructive tests.

INTRODUCTION

Lately, there has been an increased interest in our country and throughout the world regarding the problem of monitoring of the state and maintenance of bridge structures on transportation routes and in the towns. Considering the period in which these bridge structures have been designed and constructed (some even some 20-30 years ago), a question arises as to whether they are still properly functional and with a sufficient stability. In addition to the problem of proper treatment of service loads during their design, there is also the problem of inadequate treatment of seismic effects in seismically active regions. Hence, a conclusion is imposed that the seismic risk pertaining to these structures has been increased.

It is for several years that the authors have been working on different scientific and applicative projects associated with the problem of monitoring of the states and maintenance of bridge structures. For the purpose of systematic investigations into this problem, a procedure of activities necessary to be taken for monitoring and maintenance of such structures in Republic of Macedonia has been developed. The activities for the bridge structures along the transportation routes started on the Tabanovci-Titov Veles section, while those for the town bridges started with the bridges in Skopje.

Fig. 1 shows the block-diagram of the activities associated with monitoring of the states and maintenance of bridge structures. First of all, it is necessary to create a basic relational database on bridge structures per transportation sections of the road network as well as per transportation routes in towns. For this purpose, the MNT software has been developed (Ristic *at al.*, July 1994). This software enables storing and processing of data from performed inspection of bridge structures.

The processed data from this activity are needed for analysis and elaboration of priority lists for revitalization of bridge structures with manifested negative behaviour (under service and seismic loads). For this purpose, a model is proposed containing three indexes: (1) criticality index, (2)seismic vulnerability index, (3) usability index. The criticality index represents the importance of the bridge regarding the emergency need for transportation after an earthquake as well as the risk of loss of human lives in case of a collapse of the bridge. The seismic vulnerability index represents the vulnerability of the structure up to failure in case of a strong earthquake, whereas the usability index reflects the stress-strain state and the state of cracks under service loads. The second and the third index are obtained by means of nonlinear dynamic and static analyses. In this way a priority list is made for revitalization of the bridge structures.

The next phase for the bridge structures that are given priority is diagnosis of their state. Presented in the next chapter will be the methodology for diagnosis of bridge structures developed by the authors. This phase is necessary for determination of the reasons for negative behaviour of structures, no matter whether it is the result of service loads or seismic effects. After the identified diagnostic parameters, an optimal revitalization project is elaborated. Finally, after performance of revitalization, the structures are monitored for the purpose of verifying the measures taken.

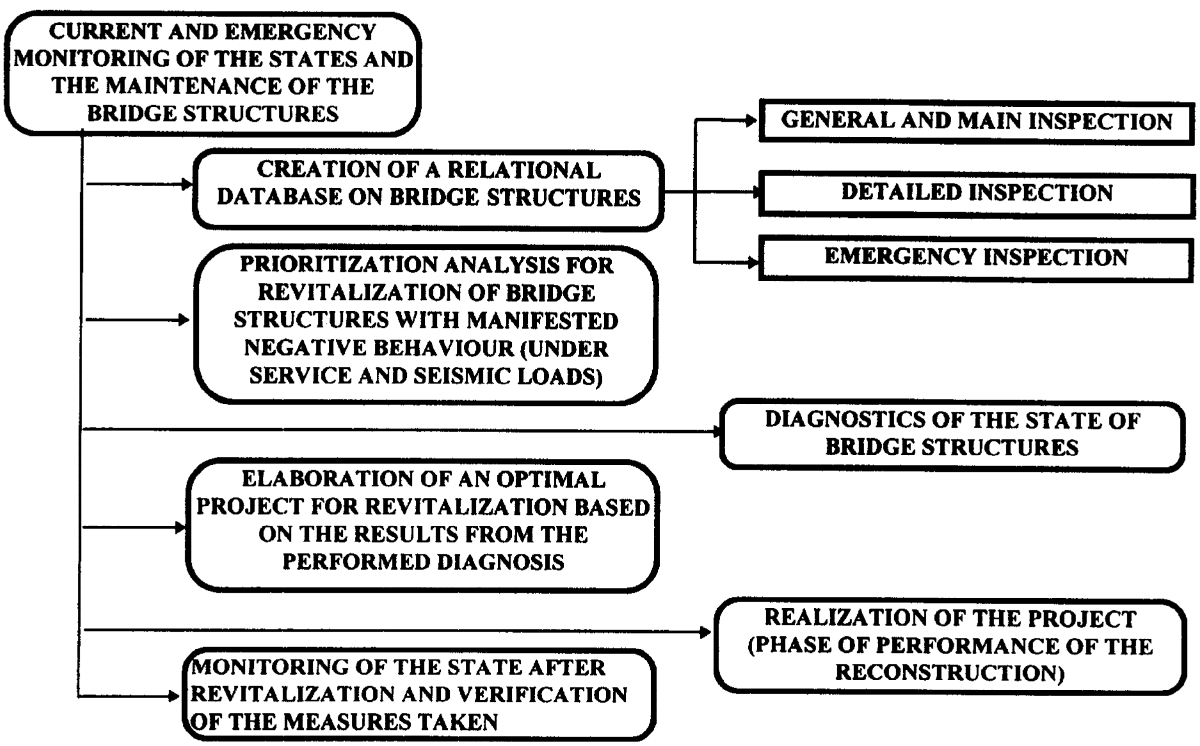

Fig. 1. Block-diagram of the activities related to permanent and emergency monitoring of the states and maintenance of the bridge structures.

General

Presented in this paper will be only the activities related to diagnosis of bridge structures, whereas the other activities mentioned in the introduction represent separate subjects of investigations that have parallely been carried out by the authors.

Analogous to the diagnosis in medical sciences, here one can talk about "pathological" behaviour of structures during their "life time" under service conditions, as well as behaviour of structures after heavy damages due to abrupt dynamic effects of different nature (earthquake, explosions, etc.). In both cases, it is necessary that their state is diagnosed for the purpose of finding out corresponding measures for their "curing" (see the block-diagram in Fig. 2).

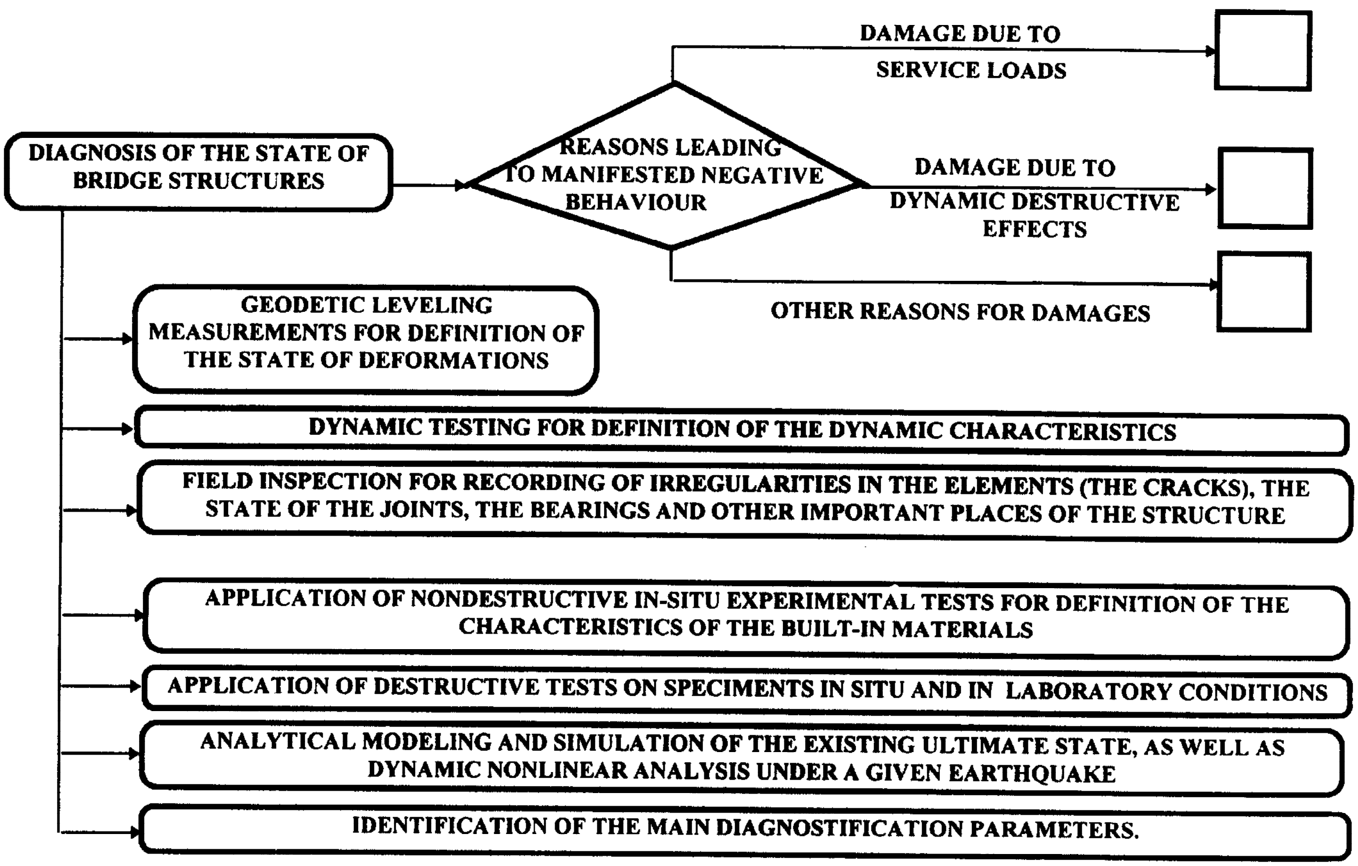

Fig. 2. Block-diagram of activities for diagnosis of the state of bridge structures.

The main objective of diagnostic analysis is identification of the parameters that characterize the state of the structure at a certain time moment or interval. Diagnostic parameters are: elastic-mechanic, strength and rheological characteristics of the materials that are incorporated in the substructure and the superstructure of the bridges, as well as the characteristics of the materials constituting the soil in which the structure is founded, the dynamic characteristics, the extent and the distribution of cracks, the homogeneity of the built-in material, the stress-strains state under exploitation conditions, the state of the joints, the bearings, the expansion joints, the footings and other important elements of the structure, the geometry of the cross-sections, the number, the diameter and the position of the reinforcement, the actual static system of the structure, etc. The identification of all the necessary diagnostic parameters is a complex process, taking into account the fact that some of these are modified in the course of time. Hence, despite the existence of technical documentation on some structures of an older date, that give an insight into many structural characteristics, the question arises as to whether these have changed from the time of construction until the moment of diagnostification.

The increment values of the diagnostic parameters in the course of time can be either positive or negative regarding the stability and functioning of the structures. If any of the variable parameters is indicated by Sci, its increment value in the course of time interval $\Delta t=t-to$ will be $\Delta Sci=Sci_t-Sci._{to}$. Apart from defining the actual modification of the concrete parameter Sci, it is of interest to introduce a new notion that could be referred to as "increment gradient" or "average gradient of deterioration" for the time interval Δt, i.e., $GD(Sci)=\Delta Sci/\Delta t$. However, the gradient (the rate) of increment values can often be different for different time intervals. If there is a permanent following of the increment values of the parameter in question in the course of time, it is possible to define a discrete function Sci = Sci(t). This discrete function could be approximated using the least square method with a continuous function of the n-th order and then starting with its derivation, the deterioration gradient is defined for any time moment $t:GD(t) = dSci/dt$. It can be concluded that permanent monitoring of states is necessary for correct determination of these two functions.

Brief Description of the Procedure

Figure 2 shows the block diagram along with the scheme of the necessary activities for performing the diagnostification process. Basically, all the activities could be divided into experimental and analytical.

Geodetic leveling measurements. These measurements represent basic diagnostification activities since they enable exact determination of the state of deformations of the structure. This, in fact, identifies an important diagnostic parameter which is further used (deformations), through iteration analysis, for obtaining several other parameters as are the stress state, the rheological characteristics of concrete and steel (which is of a particular importance for the prestressed bridge structures) etc.

Dynamic tests. The dynamic tests are carried out for the purpose of obtaining the dynamic characteristics of the structure like: the natural periods and shapes of vibration, damping under different excitation levels, the soil-structure parameters under dynamic effects, etc. The most commonly performed tests at our Institute are the dynamic ones carried out by using the ambient vibration technique. The dynamic characteristics of the structure obtained from these experimental tests are used for proper definition of the static system, i.e., creation and verification of the mathematical model for analysis. Also, these characteristics can be used for analytical evaluation of the values of some parameters as is the elasticity modulus, the Poisson's coefficient, the concrete strength, the specific gravity and the density of concrete, etc.

Field inspection. Simultaneously with the above mentioned two field activities, field inspection is obligatory for the purpose of recording all the irregularities within the elements, the state of the joints, the bearings, the expansion joints and other important places of the structure. Unlike the global data recorded in the relational data basis, the detailed data on these irregularities are to be considered with this field inspection. For example, for structures with a pronounced number of cracks, a scheme should be elaborated in which will be indicated the propagation zones of these cracks, their orientation, the distance between them and their width. For structures damaged by dynamic destructive effects (earthquake, explosion, etc.), places of failure and plastic hinges should be particularly investigated.

Application of non-destructive in-situ experimental tests. The Institute of Earthquake Engineering and Engineering Seismology in Skopje has a certain equipment for performance of nondestructive in-situ experimental tests that is primarily used for investigation of geotechnical profiles, but also testing of structural elements of bridges. For performance of geotechnical studies, used is the standard refraction method with application of geophones of 14 Hz, with no filtering limitations of the signals. For testing of structural elements of bridges, the method of seismic illumination is applied using geophones of 28 Hz and selective filtration of signals with frequencies lower than 50 and 100 Hz. This equipment enables definition of the elasticity modulus and the Poisson's coefficient of the materials, as well as the shear modulus for soil deposits. Non-destructive methods are quite developed throughout the world (Japan, Italy, Sweden, USA, etc.), particularly in respect to the problem of inspection of reinforcement : number, position and diameter of bars (Kasai, *et al.*, 1993). Future plans of the Institute are therefore related to this field and directed toward procurement of additional and latest equipment.

Application of destructive tests in-situ and in laboratory conditions. Usually, the application of these destructive tests make the investigations much more costly, however, in shortage of equipment for nondestructive tests, they are still in use, particularly for definition of the strength characteristics of concrete, definition of the prestressing forces in the cables of prestressed bridge structures etc. Due to their destructive nature, these methods are not recommendable for permanent monitoring of the state of certain strength parameters, wherefore they should gradually be replaced by nondestructive methods.

Analytical modeling and simulating of existing and ultimate state. In this phase, the afore mentioned activities are compiled. The known parameters obtained from the field and experimental studies are used for definition of mathematical models for analyses, and then iteratively, analytically, the remaining parameters are obtained. The following analyses are necessary to be performed: (1) linear analyses for simulation of the stress-strain state under service conditions, (2) nonlinear analyses for definition of ultimate states under ultimate service static conditions, (3) nonlinear analyses for determination of the behaviour of the structure under earthquakes and definition of its vulnerability.

ANALYZED SAMPLE OF A BRIDGE STRUCTURE

Applying the above described methodology, diagnosis of the state of the Goce Delcev bridge structure (in Skopje) was made and a project for its revitalization was elaborated. This bridge acquired a high priority index for revitalization, considering the fact that it connects vital transportation routes in the town. As to the seismic risk, the Skopje central area where the bridge is situated, belongs to a zone with seismic intensity of IX and half according to the MCS scale, and the nonlinear dynamic analyses of the bridge pointed to a high vulnerability of the bridge for this high level of seismicity. This bridge proved also critical in respect to the usability index. Namely, large deflections were observed in the middle of the central span. The structure consists, in fact, of two parallel independent bridges (twins), connected with a foundation plate. Their static system represents a cable prestressed symmetric frame with three spans (24 m + 88 m + 24 m) and two piers in the middle. At the ends, the superstructure rests on movable bearings (Fig. 4). The cross-section of the superstructure is of a box-type shape (Fig. 3), with three longitudinal main ribs, upper flat deck and a lower shell. The bridge was designed and constructed in the period 1970 - 1972.

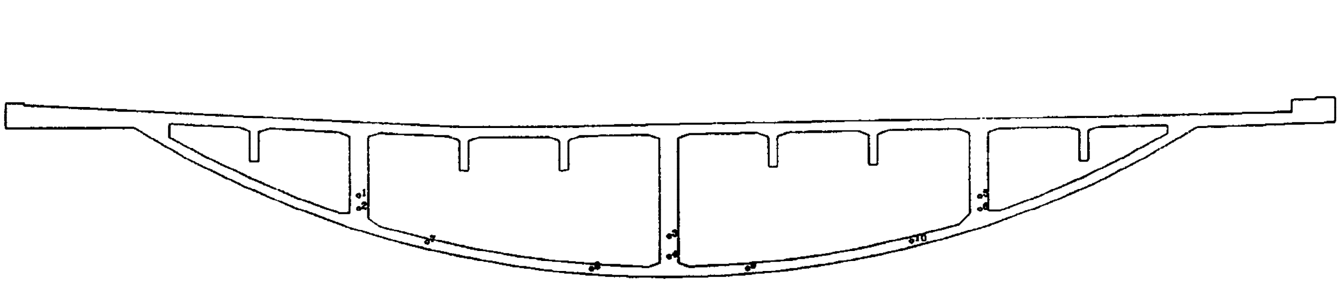

Fig. 3 Typical cross-section of the superstructure

Identified with the geodetic leveling measurements were deflections of 28.5 cm on one of the bridges and 31 cm on the other. The field inspection pointed to existence of two large zones of propagation of cracks over the piers of both bridges. These were most probably due to the effect of principal stresses (Fig. 4). Dynamic tests of the bridge by using the ambient vibration method were done at the same time. These dynamic tests confirmed and verified the mathematical model for further analysis, since the natural periods and modes of vibration correlated well (with some slight differences) with those defined analytically. For definition of the concrete strength and stresses in the prestressing cables, in-situ experimental methods were used. These pointed to a high compressive strength of concrete (over 70 MPa), while the obtained increased stresses in the prestressing cables confirmed their analytically proved overloading, i.e., the improper design of their number (probably due to the improper treatment of losses due to prestressing in the original project of 1970).

Finally, the phases of performing the analytical studies involving nonlinear and linear static and dynamic analyses were carried out. Simulated with the static linear and nonlinear analyses was the state of deformations under service loads and ultimate state of the bridge. By an iterative procedure, assuming the input prestressing forces before each iteration, the line of deformations of the structure under service conditions was obtained. Identified in this way were the input prestressing forces and hence was defined the actual stress state for each analyzed cross-section under service conditions. The performed nonlinear dynamic analyses proved insufficient strength and ductility of the piers, at the cross-sections at the connections with the superstructure under strong earthquakes.

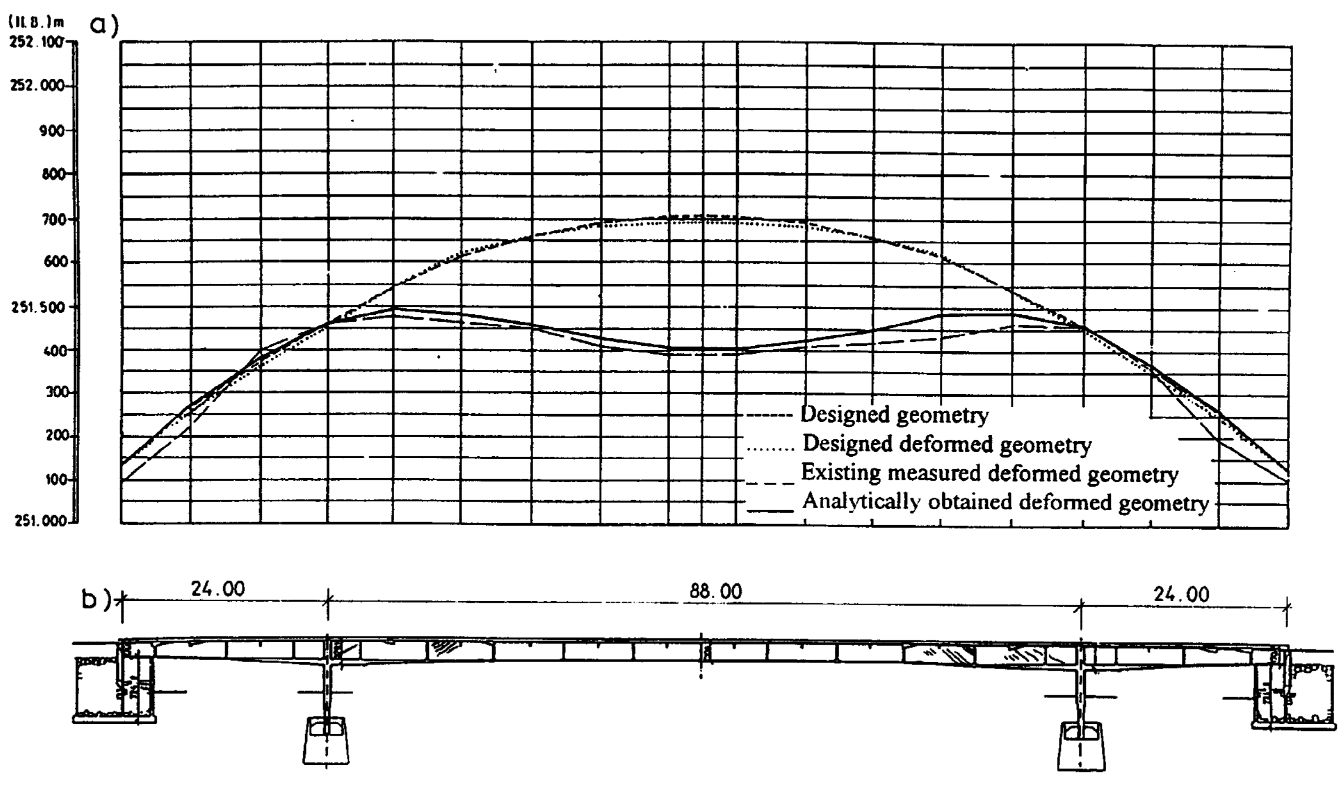

Fig. 4 a) Comparison of the analytically simulated deformation state of the bridge with the results from geodetic leveling measurements

b) Inspected zones of crack propagation

CONCLUSIONS DRAWN FROM THE PERFORMED INVESTIGATIONS

Within the frameworks of several projects on monitoring of the states and revitalization of the bridge structures in Republic of Macedonia, the authors are presently elaborating a general methodology for diagnosis of the states of these structures. In developing the methodology, the authors have so far achieved remarkable results in the domains of application of both experimental and analytical methods for diagnostification of the states of the structures. Noteworthy is the development of the software package NORA95 (Nonlinear Response Analysis Program, 1995) based on the NORA program (Ristic, D., June 1988) which is used for performance of all static and dynamic as well as nonlinear analyses necessary for the diagnostification of the bridge structures.

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