Advanced Method For Seismic Upgrading of Bridges Based on CET Bridge Diagnosis Concept–Initial Phase 1

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SUMMARY:
The new ongoing NATO Science for Peace Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)", involving five countries (Macedonia, Albania, Bosnia & Herzegovina, Serbia and Germany), is focused on fundamental development of an innovative technology for seismic protection of bridges. Presented in this paper is the specific project outcome of the initial Phase-1, devoted to development of an advanced diagnostic tool applicable for efficient and reliable seismic vulnerability assessment of existing bridges of various types. This initial phase actually resulted in development of two very important and urgently needed deliverables: D1 - Advanced Method for Structural State Diagnosis Applying Combined Experimental and Theoretical (CET) Approach and D2 - Advanced Method for Selection of Bridge Seismic Upgrading Technology. These two advanced developments represent a created possibility for application of a new, modern decision making tool for selection of an optimal bridge seismic upgrading technology.

Key words: *Seismic upgrading of bridges, state diagnosis, ambient-vibration tests, "Goce Delcev" bridge Skopje*

1. FOREWORD

The high seismic risk pertaining to transportation networks in Southeast Europe is a serious threat to public safety, sustainable economic and social development and security in the region. This risk has not been quantified to this date and sound seismic risk mitigation concepts are not available. Most of the existing bridges are constructed as non-aseismic and are older than 40 years, so that they are highly vulnerable to seismic loads and require immediate, reliable and cost-effective seismic upgrading.

Extensive experimental and analytical research in the frames of the new NATO Science for Peace Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)", focused on fundamental research and development of an innovative technology for seismic isolation and seismic protection of bridges, is presently being conducted at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje.

Discussed in this paper is the initial Phase-1, which is devoted to development of an advanced diagnostic tool applicable for efficient and reliable seismic vulnerability assessment of existing bridges of various types. According to the project plan, in the frames of this development phase, the main two very important and urgently needed deliverables have been developed: D1 - Advanced Method for Structural State Diagnosis Applying Combined Experimental and Theoretical (CET) Approach and D2 - Advanced Method for Selection of Bridge Seismic Upgrading Technology. These two advanced developments actually represent a created possibility for application of a new, modern decision making tool for selection of an optimal bridge seismic upgrading technology.

In the paper, the important elements of the proposed state diagnosis concept for bridges are discussed. Particular attention is paid to the conducted ambient vibration tests, since they are used for verification of the implemented analytical models to be used for the subsequent research purposes.

Several in-situ experimental ambient vibration tests have previously been carried out for the selected bridge prototype structures located in Macedonia. Based on the measured results from the successfully realized experimental tests, the real dynamic characteristics of the bridge structures have been obtained. In the frames of the actual NATO project, the well known twin "Goce Delcev" bridge with a very specific geometrical shape has been selected as the most representative structure from structural point of view, as well as, from the viewpoint of the real need for its operational and seismic safety re-evaluation by application of experimentally verified mathematical models. "Goce Delcev" bridge is located across Vardar River in the central part of the city of Skopje. The ambient-vibration tests that have recently been carried out for this bridge are based on application of new and advanced approach and newly integrated technology provided by NATO SFP project support in terms of measuring equipment, acquisition system and software support.

2. GENERAL CONCEPT FOR COMMON AND SEISMIC UPGRADING OF BRIDGES

It is evident that, with the aging of bridge structures, the applied construction materials, and consequently structural elements, change their mechanical properties and bearing capacity due to the existing unfavorable environmental conditions as well as due to other degrading effects including permanent and excessive earthquake or other damaging loads. Considering also the fact that, during their serviceability period, a large number of bridge structures are inadequately maintained, it is clear that the resulting structural deterioration may be very serious in some cases. Under such circumstances upgrading, retrofitting, repair and/or strengthening of critical structures may usually be needed. To optimize structural upgrading, repair and strengthening concept as well as to improve actual serviceability and seismic safety level of existing structures which have been in use for a longer period of time, structural state diagnosis should be initially completed in all the necessary details. The need for upgrading, repair and strengthening generally refers to all types of bridge structures. However, of particular interest are highly important bridge structures along the main highway lines (bridges, viaducts, overpasses, underpasses, etc.).

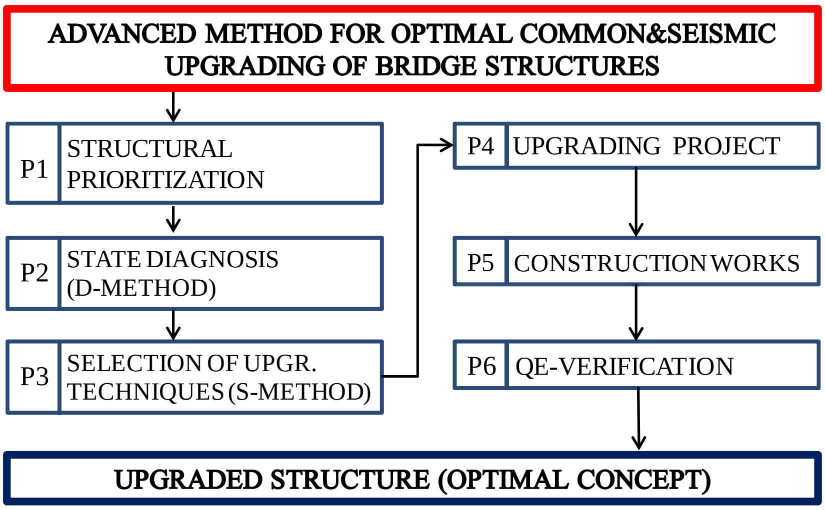

Figure 2.1. Advanced general concept for optimal common & seismic upgrading of bridge structures with six principal phases

These type of highway structures are constructed before 10, 20, 50, 100 and over 100 years, and during their long exploitation or serviceability period, they have usually been exposed to various changes such as:
(1) changes in live load; (2) changes in serviceability loads; (3) changes in design procedures and seismic design parameters, updated based on the latest observations and scientific knowledge; (4) modifications of service and seismic safety criteria; (5) aging and degradation of materials due to various destructive effects; (6) produced intolerable damages due to earthquake shaking or many other

disastrous effects, etc.
To optimize the structural upgrading and revitalization technology of commonly degraded or by earthquake damaged bridge structures, application of advanced practical and consistent method is essential. Regarding this evident need, developed and proposed is a practically verified advanced general concept based on six principal phases (P1 to P6) applicable for common (classical) and specific seismic upgrading of bridge structures and other transportation facilities along highway networks.

The optimal structural upgrading method consists of harmonized chain of six phases of activities, involving: (1) Prioritization of structures for upgrading; (2) Diagnosis of the existing state of structural system; (3) Selection of optimal upgrading technology; (4) Elaboration of upgrading project; (5) Realization of in situ construction works and (6) Quality and efficiency verification of the upgrading activities, (Fig. 2.1).

3. ADVANCED CET-METHOD FOR STRUCTURAL STATE DIAGNOSIS

The process of upgrading and revitalization of a particular structure starts with its state diagnosis. The diagnosis of structures is a specific technical discipline, which involves a number of activities aimed at identification of real effects of damages and poor behavior of structures under serviceability and/or accidental excitations. Presented herein are the main concepts, approaches and methods integrated in the proposed methodology for diagnosis of structures.

The real reasons for damages and generally, poor behavior of bridge structures can be divided into the following groups: I) damage in the phase of exploitation of the structures subjected to service loads due to: omissions and flaws in design; omissions and flaws in construction; deterioration of materials due to external natural (chemical) agents and II) damage due to occasional, intensive sudden dynamic effects such are earthquakes, explosions, etc. The activities that are carried out for the purpose of identification of causes and actual state diagnosis, can be divided into the following groups: I) field surveys, II) laboratory tests; III) diagnostic analyses. The first (I) and the second (II) are identified as Experimental Diagnosis Phase (EDP). The first group (I) consists of the following activities: 1) visual inspection, 2) non-destructive tests, 3) geodetic surveys, 4) dynamic tests, 5) acquisition of material samples and destructive tests. The second group (II) of laboratory activities consists of 1) material testing and 2) testing of the deterioration level of samples. The third group of theoretical activities (III) consists of linear static analyses and linear dynamic analyses, analyses of ultimate bearing capacity and non-linear static or dynamic analyses.

The activities of group III actually represent the Theoretical Diagnosis Phase (TDP), involving analyses necessary for final state diagnosis of bridge structures. In respect to the methods applied, these analytical activities have been implemented in two directions, i.e., approaches. The first approach is defined as a classical or traditional approach, whereas the second approach is defined as an energy (sophisticated) approach.

The classical or the traditional theoretical approach follows the principles of classical design, which means application of current regulations for design and analysis of structures. This approach does not take into account the actual behavior of the structure and the elements, which is generally nonlinear. However, it still yields results in compliance with a possible energy state of the system. The main characteristic of this approach is that the linear theory of elasticity is used in static and dynamic analysis and nonlinear constitutive relationships are only used for the materials in the analysis of the cross-sections. However, the interaction between the cross-sections (behaving nonlinearly) and the elements, i.e., the whole system is neglected. In other words, the redistribution of static quantities in the system as a result of non-linearity of materials is not taken into account. This represents, in fact, accepted inconsistency for the sake of simplicity and practical purposes. Still, this approach has been incorporated in the actual regulations of almost all countries of the world. This approach most frequently satisfies the criteria in the sense of achieving the necessary stability of new structures in the phase of their design and is largely applied in diagnosis of the state of the structures as a practical and relatively simple approach.

The energy approach is based on application of nonlinear models and it assumes use of more sophisticated analysis concepts and most frequently applies criteria which are not specified in the technical regulations. This approach permanently follows the new and advanced developments of scientific knowledge in the field of behavior of materials and structures under static and dynamic effects. The main advantage of this approach is that it takes into account the actual behavior of structures, which is always non-linear in the phase prior to failure. The static and dynamic analyses are performed taking into account the constitutive laws corresponding to the actual materials from which the structures are built. In this case, there is a permanent interaction between the cross-sections, the elements and the system. In compliance with the level of achieved deformations, i.e., stiffness, there takes place a permanent redistribution of load effects. In other words, this approach results in simulation of energy balance which is permanently changed in the system as a result of external energy input.

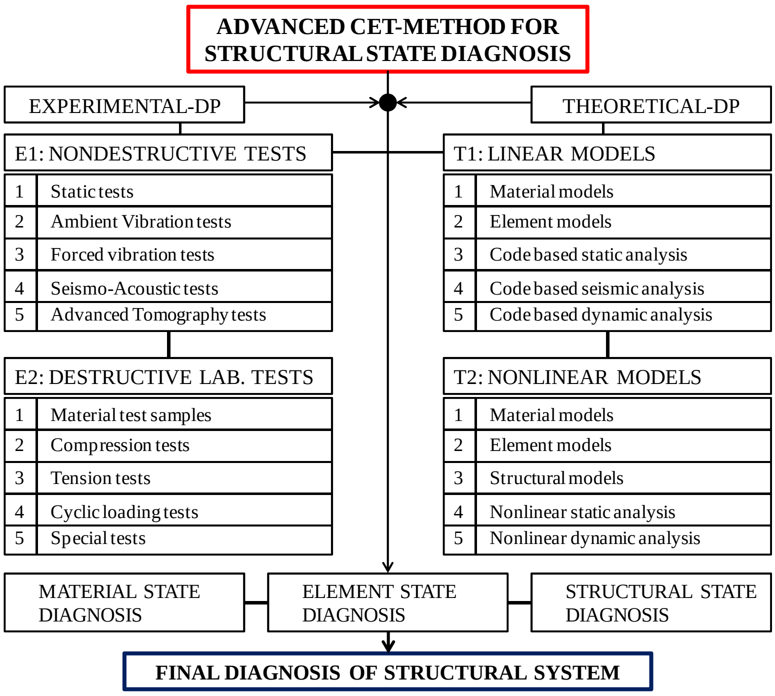

Figure 3.1. Advanced combined experimental and theoretical (CET) method for structural state diagnosis

The proposed advanced CET-method for actual state diagnosis of bridge structures (Fig. 3.1) is based on harmonized application of combined experimental and theoretical approaches which are permanently developed and refined. The efficiency and the practical applicability of the method is demonstrated by a very complex application example that is briefly described in item 5.

4. CONSISTENT METHOD FOR SELECTION OF OPTIMAL STRUCTURAL UPGRADING TECHNOLOGY

The selection of inadequate methods for structural upgrading in many cases in the past resulted in repeated severe flaws and enlarged problems in the practical structural and earthquake engineering field.

Structural upgrading, repair and strengthening represent one of the most complex structural engineering problems. For example, in the case of design of new structures, the design engineer can

implement a wide variety of creative options. In such a case, optimization of structural design is not basically difficult to achieve.
However, in the case of structural upgrading of existing structures, the expert will recognize many complex structural deficiencies and selection of optimal upgrading technology is very difficult to be achieved. Available techniques are considerably limited and, in many cases, their efficiency is not completely known. To overcome such real difficulties, implementation of advanced and verified method for selection of optimal structural upgrading technology is of essential need.

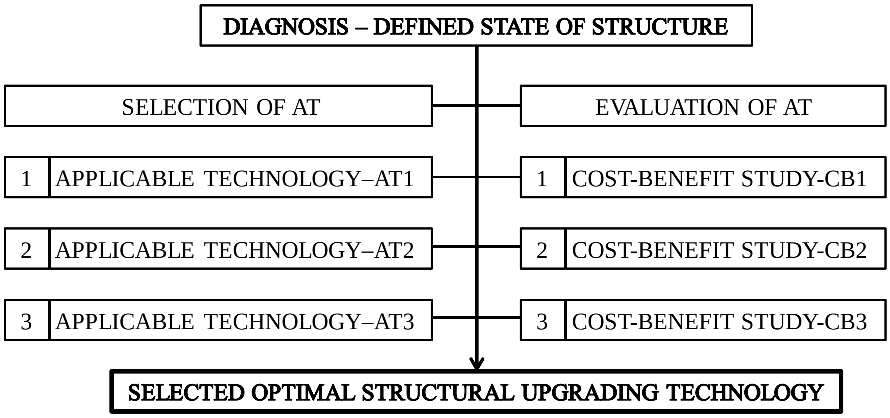

Figure 4.1. Advanced CB-Method for selection of optimal common and/or seismic upgrading technology

The proposed CB-Method (Fig. 4.1) practically represents a fully verified concept for selection of an optimal structural upgrading technology (item 5). It integrates the following four specific steps:

1. Identification of all critical structural problems based on successfully completed structural state diagnosis;
2. Formulation of several options of potentially applicable technologies for structural upgrading based on wide scientific, expert and practical experience of the design engineer;
3. Completion of cost-benefit (CB) studies for all the proposed structural upgrading options;
4. Ranking of the proposed structural upgrading technologies and selection of an optimal option.

Finally, considering the selected optimal structural upgrading technology, a full structural upgrading project should be elaborated in order to provide its successful practical realization.

5. PRACTICAL APPLICATION OF ADVANCED CET-METHOD FOR UPGRADING OF UNIQUE TWIN-CITY BRIDGE “GOCE DELCEV” IN SKOPJE

Practical application and practical verification of the proposed CET-Method has been achieved in the case of the successfully realized complex upgrading project related to the unique twin city bridge “Goce Delcev” in Skopje, Fig. 5.7. The twin bridges are constructed and put into operation in the year of 1971. During the initial period of one decade, recorded were large vertical deformations of both bridges in the middle of the middle span. These deformations with a permanent tendency of increasing and, in the year of 1994, the recorded maximum deformations were as follows:

1) For the upstream bridge: max D_U=31.8 cm, and
2) For the downstream bridge: max D_D=28.5 cm.

Following the obtained evidence from the conducted detailed in situ inspection of both bridges, a decision was made by the city representatives to conduct all the needed activities in order to realize an appropriate upgrading of the bridges, particularly to reduce and stop further progression of permanent vertical deformations in the middle span of both bridges, Fig. 5.8 and Fig. 5.9.

In the first phase, diagnosis activities have successfully been realized at IZIIS, Skopje. This complex project was led by the first author of the present paper who was the principal investigator of the project, together with the second author.

Figure 5.1. In situ measurement of actual prestressing force with steel-bar vibration frequency recording

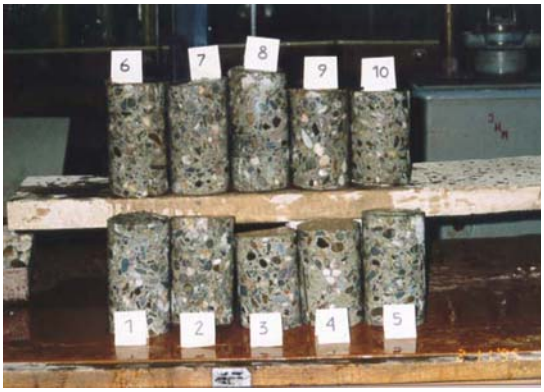

Figure 5.2. Determination of actual concrete strength based on compression tests on samples

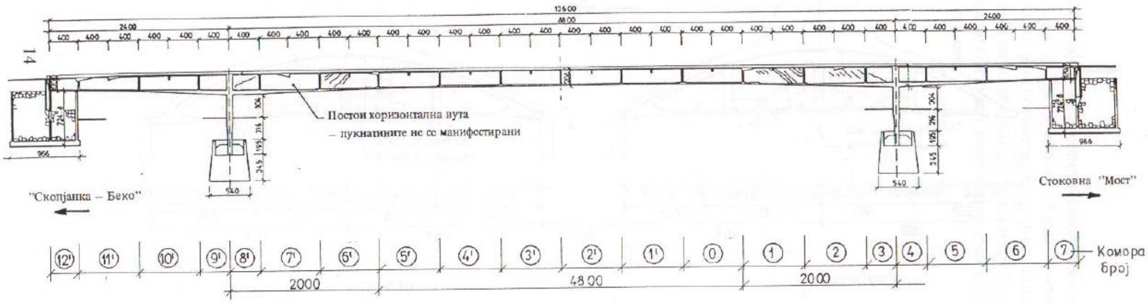

Figure 5.3. Upstream bridge: Distribution of inside recorded inclined open cracks along central RC longitudinal superstructure beam due to its unsatisfactory protection against concentration of large transversal forces

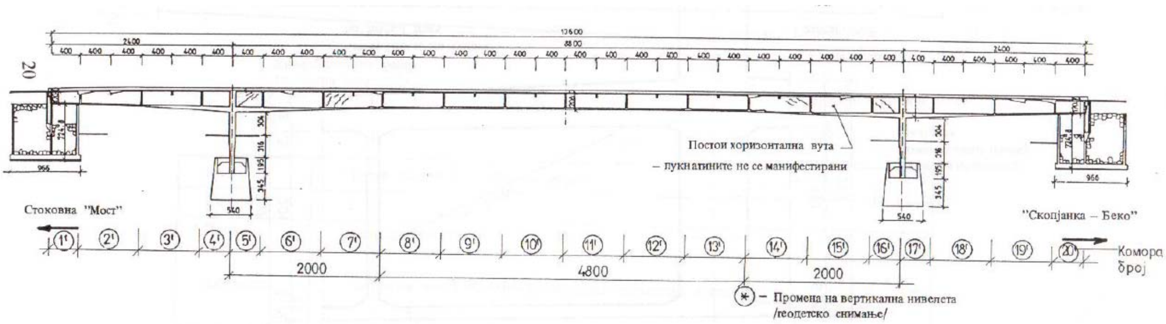

Figure 5.4. Downstream bridge: Distribution of identical inclined opened cracks along central RC longitudinal superstructure beam due to its unsatisfactory protection against concentration of large transversal forces

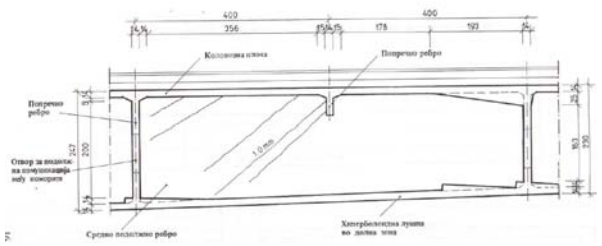

Figure 5.5. Upstream bridge: Detail of recorded inclined open cracks along RC longitudinal superstructure beam

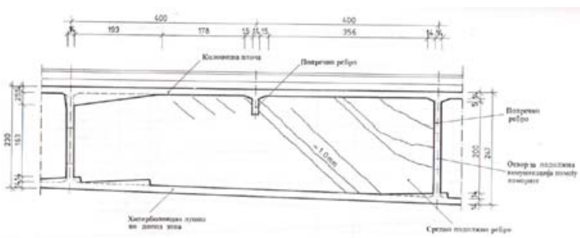

Figure 5.6. Downstream bridge: Detail of identical cracks along RC longitudinal superstructure beam

The established IZIIS' team of experts and researchers conducted an intensive structural diagnosis study which resulted in publishing of four extensive research reports (Ristic et al.1994), published as

IZIIS reports: Volume I, 94-10; Volume II, 94-31; Volume III, 94-32 and Volume IV, 94-33. During the successful realization of the integral and complex structural diagnosis study for both unique twin bridges in Skopje, there has been implemented the new integral concept of the proposed advanced method for structural state diagnosis presented in this paper (Fig. 3.1).

Generally, the following detailed investigation activities were conducted: (i) geodetic measurements of deformations of bridge structures; (ii) field inspection of the structures; (iii) dynamic testing of the structures by using the ambient vibration method; (iv) testing of the strength characteristics of concrete by taking samples (Fig. 2) and measurement of the pre-stressing forces in the cables at selected locations (Fig. 1); (v) static and dynamic analyses of the structures applying the classical analytical approach for diagnostic of their state; (vi) nonlinear static and dynamic analyses for prediction of the ultimate load.

From the performed diagnostic activities, it was generally concluded that the main reasons for the increase of deformations of the superstructure of the bridge are the following: (1) the effect of shear forces which produced diagonal cracks in the very beginning phase of the structural life (this is shown also by the diagnostic analysis of the shear stresses); (2) the effect of shrinkage and yielding of concrete and (3) the unfavorable ratio between the spans which contributes to occurrence of intensive tensile forces at the end supports. Also, the comparison between the results from the diagnostic analyses and the analyses performed within the original construction project on the bridge structure leads to the conclusion that, during the design, several omissions have been made from structural and computational aspects. So, for example, in addition to the inappropriate selection of the ratio between the spans, the selection of the cross-section is not the most optimum one since the middle rib (web) is the most loaded one which contributed to occurrence of diagonal cracks. The value of dead loads is also non-precisely computed as well as the effects of the rheological phenomena occurring in the concrete, particularly in computing the loss of pre-stressing forces. Thus, according to the diagnostic analyses done by the authors, it was proved that the number of cables was not sufficient to sustain the serviceability stresses within the allowable limits, which was also proved by the conducted nondestructive tests for testing the pre-stressing forces in the cables (Fig. 1). Namely, these tests showed that the stresses in the cables were extreme, not because of the low losses of pre-stressing forces, but because of the overloading of the cables, as was proved by all the diagnostic analyses and was evident from the deformations of the structure.

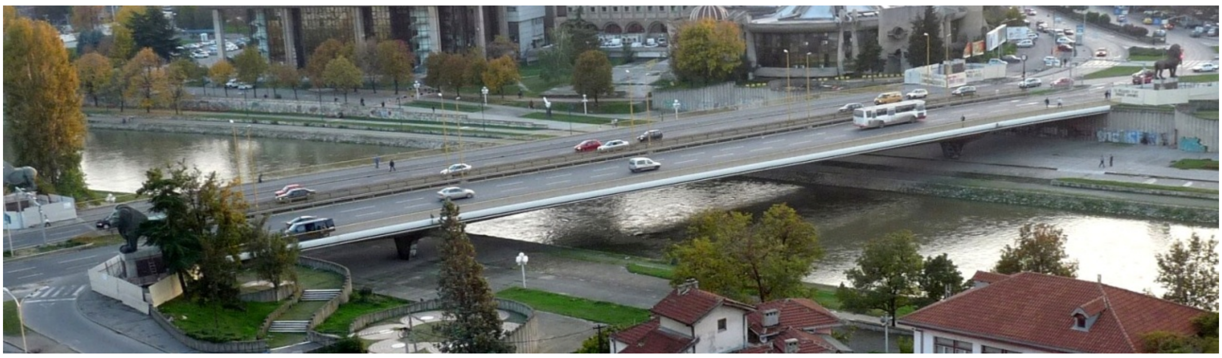

Figure 5.7. Preparation activities to stop traffic in order to conduct the second ambient vibration tests of the main and unique twin-city bridge “Goce Delcev” in Skopje (after the completed original and complex revitalization project)

In the second phase, expert and research activities have been continued with development of optimal structural revitalization, i.e. structural upgrading project. Applying the advanced CB-Method, Fig. 4.1, an optimal and very specific structural upgrading technology was successfully selected. The study of the second phase resulted in publishing of two reports (Ristic et al. 1995), denoted as IZIIS reports: Volume I, 95-74 and Volume II, 95-75. Defined with the developed upgrading project was an optimal concept for structural upgrading considering the existing conditions and the full complexity of the recorded structural problems, particularly the observed intensive cracks in the superstructure segments (Fig. 5.3, Fig. 5.4, Fig. 5.5 and Fig. 5.6).

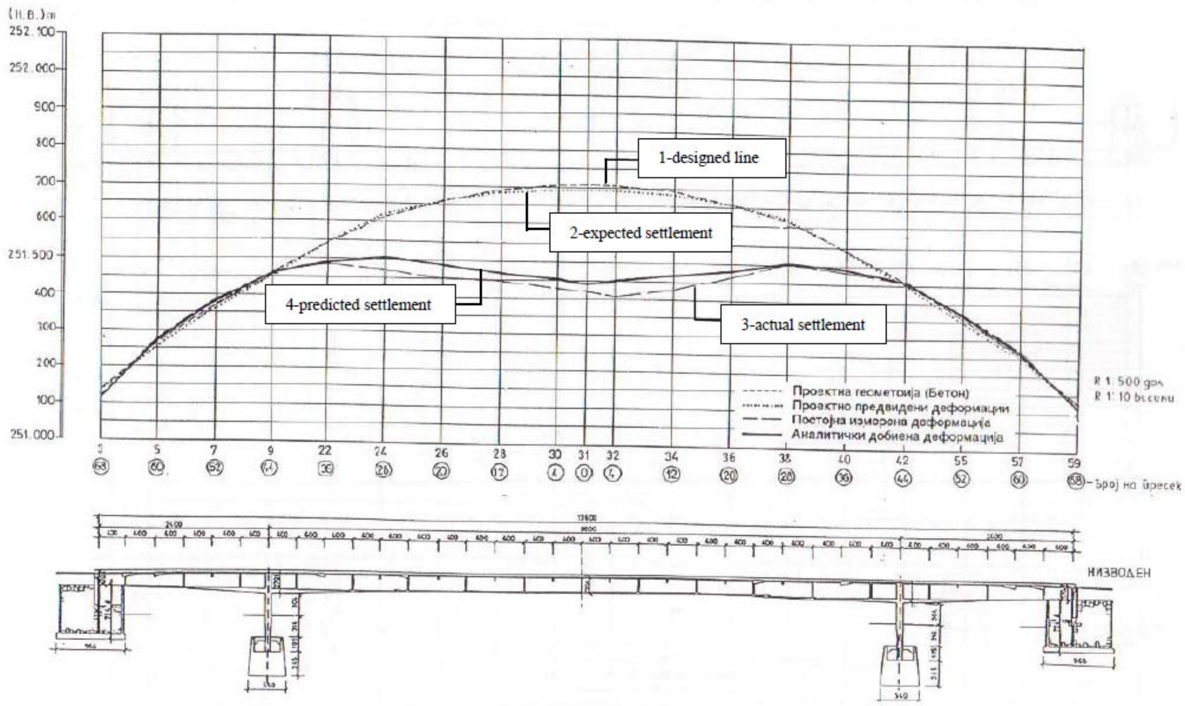

Figure 5.8. Upstream bridge: Longitudinal distribution of large settlements of the complete RC bridge superstructure defined by precise geodetical measurement (comparative plot: 1-designed line; 2-expected settlement; 3-actual settlement and 4-predicted settlement by the formulated experimentally verified nonlinear analytical model).

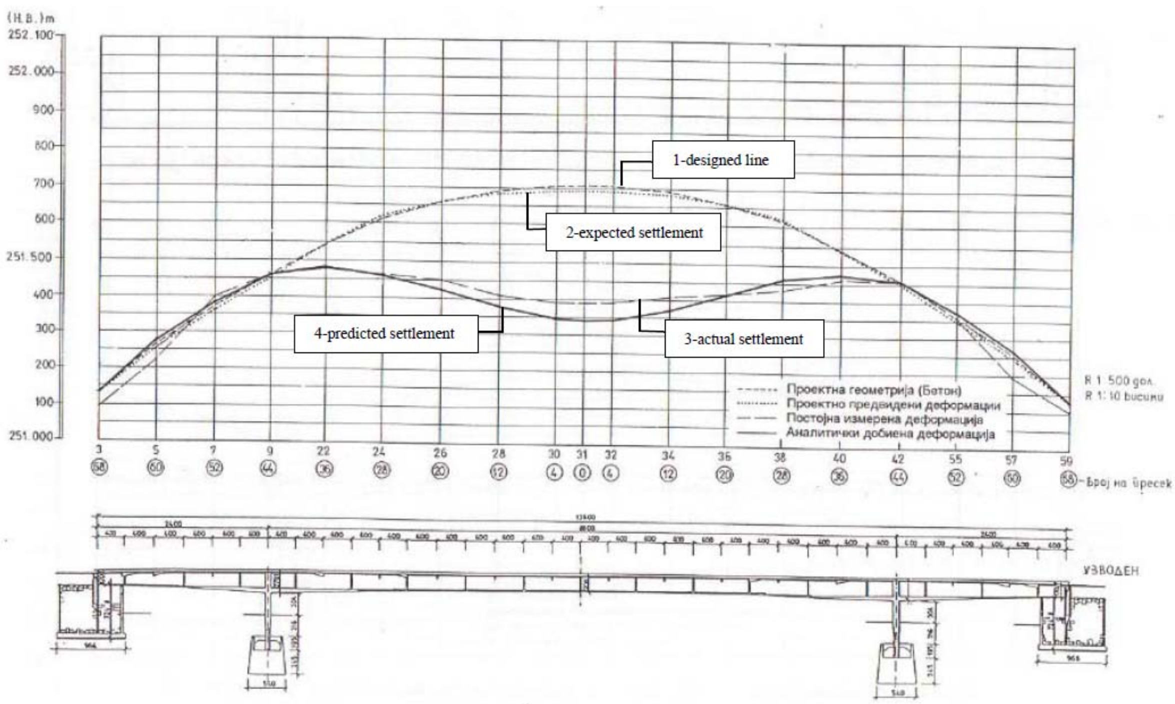

Figure 5.9. Downstream bridge: Defined identical longitudinal distribution of large settlements of the complete RC superstructure (comparative plot: 1-designed line; 2-expected settlement; 3-actual settlement and 4-predicted settlement by the experimentally verified nonlinear analytical model).

In the third phase, construction works have been completed and both twin bridges in Skopje have been upgraded, mainly by installation of additional prestressing cables and additional structural upgrading

elements as defined in the structural revitalization project.
Ambient vibration tests of both bridges were carried out before structural upgrading in 1994 and after structural upgrading in 2011 (Fig. 5.10). The comparative results from both ambient vibration tests are presented in Table 5.1. From both tests, the good agreement of the results is evident. This is a very important evidence. It clearly shows that, in some cases, the ambient vibration test measurements will not provide sufficient indicators for successful evaluation of structural upgrading.

This has particularly been confirmed in the case of very specific structural systems, as is the existing unique Skopje city bridge. To achieve reliable evaluation of the actual structural state, all the activities integrated in the proposed advanced diagnosis CET-method should be applied.

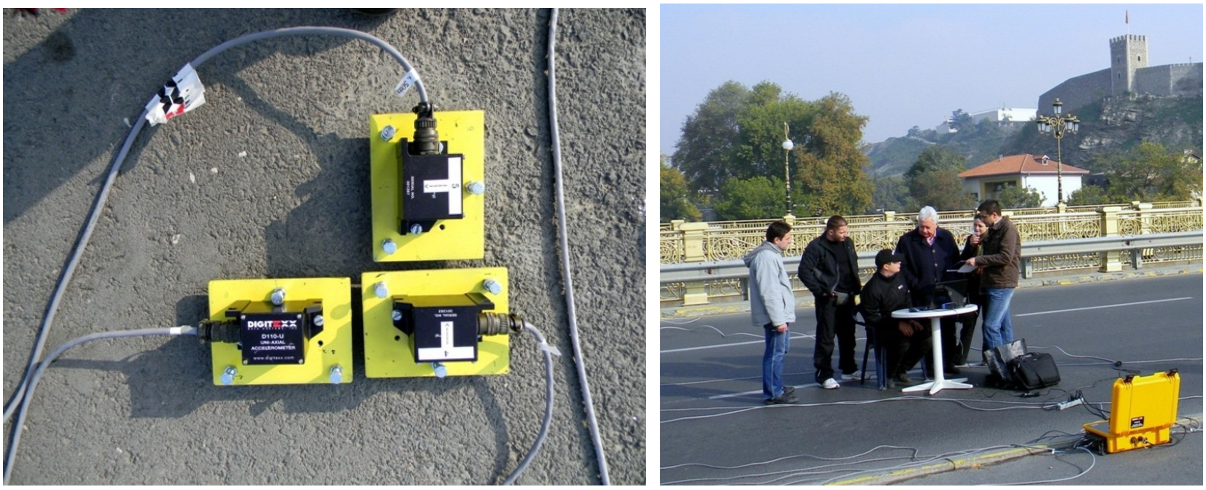

Figure 5.10. Realization of the second ambient vibration tests of the unique twin-city bridge "Goce Delcev" in Skopje after the completed revitalization project: (1) Installation of 3-componental DIGITEX sensors and (b) Part of project team preparing the testing procedure and permanent data acquisition unit)

Table 5.1. Comparative results from ambient vibration tests conducted in 1994 and in 2011.

Mode Shape No.	Comparative results from Ambient Vibration tests			
	1994: AV Test (UKIM-IZIIS)		2011: AV Test (DIGITEXX)	
	T (s)	f (Hz)	T (s)	f (Hz)
1	0.781	1.28	0.781	1.28
2	0.500	2.00	0.505	1.98
3	0.328	3.04	0.343	2.91
4	0.305	3.28	0.300	3.33
5	0.231	4.32	0.254	3.93

6. CONCLUSIONS

With the realization of the presented unique structural upgrading project as well as regarding the complexity and extended expert combined theoretical and experimental research activities, very useful conclusions can be derived as follows:
(1) The actual project with its complexity involving structural cracks and permanent deformations served to the authors as a unique full scale in situ experiment and as an excellent opportunity to conduct complex and detailed theoretical studies;
(2) The developed and proposed combined experimental and theoretical (CET) method for structural state diagnosis represents a powerful tool for successful and wide practical application;
(3) the suggested cost-benefit (CB) method for selection of an optimal structural upgrading technology can be very successfully applied in reducing many unclear problems and adopting the most advanced solutions;
(4) the proposed integral methodological concept for realization of the relevant common (classical)

and/or seismic upgrading of the existing bridge structures which is based on detailed structural state diagnosis represents a general and practical tool for successful wide practical application.

This is particularly important since there are several thousands of existing bridges in South-East Europe for which it is necessary to conduct optimal seismic upgrading activities urgently in order to satisfy the present high quality serviceability standards and the required respectively high seismic safety level.

ACKNOWLEDGEMENT

Presently, (at IZIIS, Skopje), extensive experimental and analytical research is being continued in the frame of the approved new three year NATO Science For Peace Project: *Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies* (SFP: 983828), focused on fundamental research and development of innovative technology for seismic isolation and seismic protection of bridges *(New large-scale scientific and research activity with participation of five countries).*

The extended NATO SfP support for realization of this innovative project is highly appreciated.

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