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SEISMIC RISK ASSESSMENT OF MOTORWAY BRIDGE WARTH / AUSTRIA

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SUMMARY

The basic idea of the project is to apply sophisticated as well as simple methods to bridge Warth/ Austria, which was built 20 years ago, in order to assess its earthquake capacity. Comparing the results the simplest method should be defined which gives the structural behaviour in an adequate way. The goal is the development of simple methods for the assessment, which are based on measurements of structural parameters. In this project expensive testing is carried out (dynamic in-situ measurements for one week, pseudodynamic tests in ELSA lab) which cannot be the standard procedure for each bridge to be assessed. The benefit of the in-situ test is that we can start with an updated FE model which is close to the (linear) reality. The main benefit of the pseudodynamic tests will be the information on the ductile behaviour of large R/C bridge piers with hollow cross section. Hence, the first main goal of the project is to find the simplest procedure giving the necessary parameters in an adequate way. The second main goal is to elaborate information for the authorities and bridge owners about the most adequate retrofitting measures. It is emphasized that a lot of work has been done all over the world. But it is important to have in mind the bridge types mainly used in (Central) Europe and especially in the Alpine Regions. In the past the greater part of all research work on bridges in the field of Earthquake Engineering concentrated on small and medium bridges and some large special constructions like suspension bridges and cable-stayed-bridges. In our project, besides reliability also the intervention costs will be evaluated in order help the bridge owner to select the most adequate measure.

INTRODUCTION

Recent seismic events all over the world have shown that bridge structures are particularly sensitive to earthquake loading. There are several reasons for such sensitivity. First many existing bridges were designed without adequate consideration for seismic risk. This has resulted in inadequate detailing of confining steel and insufficient shear reinforcement in the bridge piers, insufficient seat length of bearings, and inadequate strength and stiffness of the superstructure-abutment connection. Furthermore, there are many open questions concerning the ductile behaviour of large bridge piers, in particular those with rectangular hollow cross-section. Also, the seismic zonation map of many European countries has been revised recently, prescribing now higher horizontal ground accelerations in several regions. Finally, local soil conditions and the possibility of asynchronous motion at the base of the piers of long bridges are factors which can cause additional difficulties in properly designing irregular bridges.

There is therefore a need for reliable methods for assessing the seismic vulnerability of existing bridges, in particular large and irregular motorway bridges having lifeline character.

In June 1998 the kick-off meeting of the European Environment & Climate Project *Advanced Methods for Assessing the Seismic Vulnerability of Existing Motorway Bridges (VAB)* took place. It is the aim of the project to give a significant contribution to the development of advanced methods for assessing the seismic vulnerability

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of bridges, for enabling to mitigate - through suitable structural upgrading interventions - the destructive effects of future earthquakes.

Towards this objective, an international team has been set up covering the following disciplinary tasks contributing to the seismic vulnerability issue:

1. Dynamic in-situ structural testing to identify the actual bridge properties including soil-structure interaction effects and to characterise the surrounding soil (arsenal).

2. Development and calibration (fitting to test results) of numerical models for predicting the linear bridge response (ISMES)

3. Numerical modelling for simulating the nonlinear behaviour of bridge piers under severe earthquake loading using damage mechanics concepts (UPORTO) .

4. Physical testing of realistically large bridge piers with rectangular hollow cross section to calibrate numerical models and assess the ductility demand and capacity. Tests will be performed using the pseudodynamic method with sub-structuring of the bridge deck which will be numerically simulated using a finite element computer code and the output of in-situ testing (JRC Ispra).

5. Analysis of the effects on the bridge seismic response of asynchroneous motion at the base of bridge piers. The objective is to define in a realistic way the seismic input of the specific sites of interest through the computation of realistic synthetic broad-band records, taking into consideration source, path and local effects. (ICTP)

6. Development of simplified analysis tools for assessing the vulnerability of complete bridges (CIMNE).

7. Development of retrofitting measures to improve bridge reliability, including an evaluation of intervention costs (SETRA).

The whole project is centered on an Austrian bridge, „Talübergang Warth“, which was built 20 years ago. The bridge was designed for a horizontal acceleration of 0,04 g using the quasi static method. Now, according to the new Austrian seismic code the bridge is situated in zone 4 with a horizontal design acceleration of about 0,1 g. Hence a detailed seismic vulnerability assessment is necessary.

DYNAMIC IN-SITU TESTING OF BRIDGE WARTH

Talübergang Warth is located on motorway A2, 63 km south of Vienna. One of the non coupled twin bridges (direction to Graz) was tested. The bridge has 7 spans and a total length of 459 m.

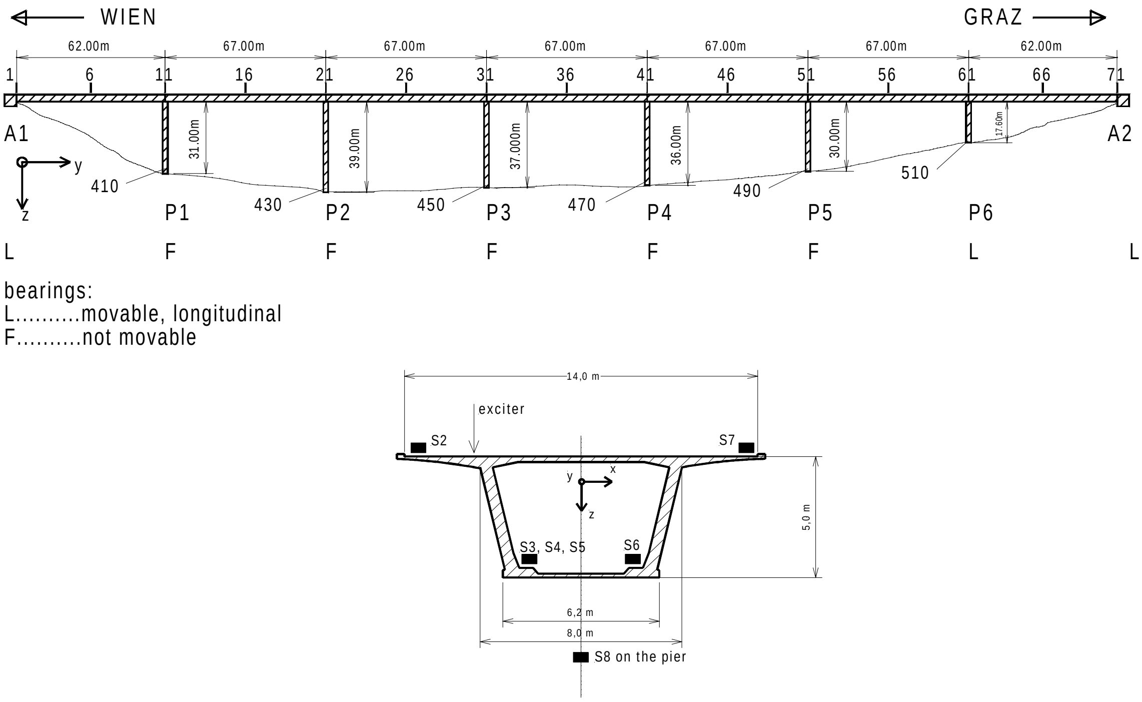

Figure 1: Bridge WARTH, axial and cross section

Talübergang WARTH was tested two times, The first dynamic in-situ tests took place in April 97 within the Brite Euram Project SIMCES. Frequencies, damping ratios and mode shapes of 6 vertical modes, 7 torsional modes and 6 horizontal modes were identified. Now, within the VAB project the second dynamic in-situ test was carried out in April 99. The program was repeated with some additional measurements, especially in order to to identify the soil springs.
The goal of the SIMCES project was the use of dynamic measurements for bridge inspection, hence a very detailed ABAQUS shell model was elaborated by the project team at TU Graz. The tendons in the webs are modelled in detail by bar elements. For the concentric tendons in the deck- and bottom slabs „rebar"-elements are used. The model consists of 7882 elements and has 23366 nodes. In addition, also a simpler equivalent beam model is necessary for the dynamic monitoring approach [Tu-Graz, 1999], [Flesch, 1999].
The analysis of the second measurements is not yet finished. Hence, the modal frequencies identified from the first measurements are given in Table 1. The calculated modal frequencies from the SIMCES project are presented in the same table.

Table 1: Measured and calculated modal frequencies

Type of mode	**Frequency**			**[Hz]**
	Measured	BEAM-Model Variant 2	BEAM-Model Variant 1	SHELL-Model
1. horizontal	0,8	0,707	0,665	0,723
2. horizontal	1,1	1,019	0,933	0,998
3. horizontal	1,62	1,521	1,349	1,420
4. horizontal	2,23	2,214	1,903	1,960
1. vertical	2,58	2,670	2,618	2,577
5. horizontal	2,98	3,089	2,620	2,615
2. vertical	2,97	2,995	2,824	2,782
3. vertical	3,22	3,420	3,142	3,108
6. horizontal	3,77	4,042	3,489	3,392
4. vertikal	3,65	3,841	3,521	3,509
5. vertikal	3,99	4,152	3,890	3,916

Further, two horizontal- and one vertical measured modeshape are given in Figures 2-4.

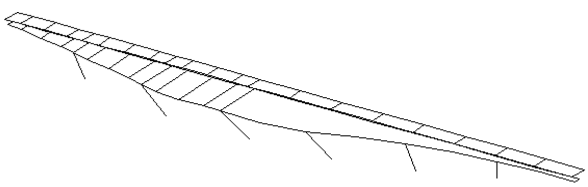

Figure 2: First horizontal modeshape 0,797 Hz (experimental)

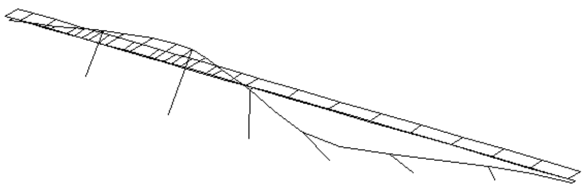

Figure 3: Second horizontal modeshape 1,102 Hz (experimental)

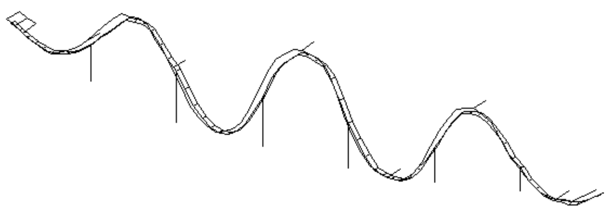

Figure 4: First vertical modeshape 2,58 Hz (experimental)

A refraction seismic survey has been done at the bridge site in order to obtain the characteristic wave velocities of the geotechnical units. The Central Institute for Meteorology and Geodynamics (CIMG) in Vienna, Seismological Service, has carried out the investigation. Four lines have been measured to explore the local rock properties. One spread was placed near to the northern and southern support of the bridge, respectively, and two profiles in the middle part of the bridge. The latter were perpendicular to each other to get information on rock anisotropy. P- and S-wave techniques have been applied to achieve realistic results on seismic velocities. The underground consists of mesozoic rock which is strongly weathered [Duma, 1998].

Within the second dynamic in-situ test, measurements in 71 profiles during horizontal and vertical excitation were done from 19.4.1999 to 23.4.1999. The investigations were carried out under traffic, only one lane was closed.

The bridge was excited by a reaction mass exciter placed in the closed lane above one web. The reaction mass is driven by a hydraulic actuator. The maximum excitation force is 25 kN, which can be kept constant from 3,4 Hz upwards. In the case of a maximum force 10 – 15 kN this is between 1,5 and 2 Hz. As the exciter could not be connected to the bridge by dowels, the maximum force of excitation was 10 kN in horizontal- and 15 kN in vertical direction. The frequency range 0,5 –11 Hz was swept within 10 minutes.
The frequency sweeps were repeated many times in order to measure the response of the deck in profiles at distances between 5 and 6,7 m. After each sweep the transducers were moved to the next profile. At the piers the response was measured at points close to the foundation. Due to the fact that the frequency sweep is repeated many times, the vibrations induced by traffic, which are (heavy) distortions of the response, can be eliminated quite well.
8 velocity transducers Hottinger SMU 30A were used to measure the response. For each measurement point transfer functions and tape recorded time histories are available.

In addition a team of ISMES carried out vertical measurements at the piers close to the foundation. The goal is the elaboration of realistic vertical soil springs. ISMES used 6 Teledyne GS13 high performance velocity transducers,
The response as well as the measured force of excitation are tape recorded using a PCM tape recorder TEAC RD-200T. Parallel to the tape recording, transfer functions are calculated on-line using a HP 3566/67A 16 - channel signal analyzer.

During the 2nd consortium meeting in Vienna, April 1999, there was much discussion on uncertainties concerning the bearings and the pier reinforcement. The bridge authorities were contacted several times in the past, but the drawings could not be found. After the meeting our problems were brought to attention again and this time the bridge authorities were successfull. The drawings could be distributed to the consortium partners in the meantime.

DEVELOPMENT AND CALIBRATION OF THE WARTH BRIDGE NUMERICAL MODEL

Two important influences were only inadequately modelled during the SIMCES project. First, the bearings, because no drawings were available at that time and their locations were not accessible. Further, only assumed soil stiffnesses were used, no updating of the soil springs was carried out. ISMES has started the new modelling campaign, where all influences will be considered finally [Palumbo, 1999].

An auxiliary numerical model, composed of beam elements and cantilever-type piers on rigid foundation, was first worked out: the finite elements mesh is made up of 171 elements with a total number of about 1000 dofs. At this first stage, a three-directional hinge connection was inserted at the bridge piers/box-girders interface and just longitudinal free displacement allowed for at the abutments. This more easily manageable auxiliary model was to serve for preliminary gross calibration purposes, in view of the more refined numerical model to be developed and calibrated later on.

The above-said auxiliary numerical model mesh data was introduced into the NASTRAN computer code and a first computation of the Warth highway bridge overall structural vibration modes made, with commonly accepted values for the (tentatively homogeneous) material characteristics **(E, ν, ρ).** Subsequently, a first attempt was made to fit the auxiliary Warth bridge numerical model to presently available experimental data. Using the modulus of elasticity as the basic fitting parameter, six vibration modes of the theoretical model were tuned as closely as possible to the corresponding experimentally determined values. The best fitting was achieved by minimising the sum of the squared differences between six measured characteristic frequencies and the corresponding calculated ones. The best fit was obtained for a uniform elasticity modulus of: E = 38.200 MPa. This value provided a practically perfect fit of the first vertical vibration frequency and a satisfactory one for other four structural vibrations frequencies. However, a relatively larger difference was obtained for the third transverse vibration frequency. Now with the information on the bearings and soil characteristics (identified from the measurements) the model will be further improved.

Subsequently to the above-outlined first computations, made by using the beam/cantilever numerical model, preparations were made for the development of the more sophisticated finite elements model of the Warth Bridge. Concurrently, a review of structural identification techniques and sensitivity analysis procedures was carried out.

DAMAGE MODEL FOR R/C SEISMIC ANALYSES

First subtask, *"Adaptation of a Damage Model for R/C Seismic Analyses"*, was devoted to the improvement of an already existing constitutive model, seeking for the modelling of the non-linear behaviour of reinforced concrete bridge piers (rectangular hollow sections included) [Delgado, 1999]. For the concrete itself, a constitutive law founded on the Continuum Damage Mechanics was proposed, combined with a 2D finite element discretization. For simulating the cyclic behaviour of the steel reinforcement the formulation proposed by Giuffré and Pinto was adopted.

The applicability of the developed constitutive model for the analyses of reinforced concrete structures under seismic actions was checked by reproducing the behaviour of a R/C wall tested on a shaking table. The numerical results provided by the proposed constitutive model agreed quite well with the experimental ones, pointing out its ability for the numerical simulation of this kind of structures.

For the sake of reducing the computational time required by the non-linear analyses inherent to the application of the proposed constitutive models, implementation of a constitutive tangent matrix was also initiated.

"Calibration of Model Parameters", which constitutes the second subtask, was performed by taking relevant information from a set of 'case study' bridge piers, experimentally tested in the ELSA Laboratory (Ispra, Italy) with pseudodynamic techniques. Two distinct and representative bridge piers were numerically analysed: a tall pier, where the bending effects are predominant, and a short pier, where non-linearity associated to shear is of relevance. Both piers were submitted to monotonically increasing shear loads until static collapse occurs, as well as to cyclic loadings in order to assess their dissipative behaviour. Comparison of the numerical results with the experimental ones pointed out that good agreement was obtained, evidencing the ability of the proposed constitutive models for the simulation of the seismic effects on this kind of bridge piers.

Preliminary analyses of the 36m high pier from the Warth bridge were performed, based on some idealised material properties and axial load conditions. A fibre constitutive model was used, either in monotonic or in cyclic loading conditions. Some relevant aspects of the behaviour exhibited by that bridge pier were outlined, namely its apparent low ductility and poor ability for energy dissipation, under the assumed idealised conditions.

PSEUDODYNAMIC TESTING OF PHYSICAL BRIDGE PIER MODELS

During the 1st year of the project, JRC concentrated on the definition of the test models (bridge pier models at a scale of 2~2.5) and on the development of the new pseudo-dynamic (PSD) test method with substructuring [Varun, 1999].

Concerning the development of PSD test method with substructuring, the JRC has made substantial progress. More precisely, this sub-task was almost completed (feasibility study and analytical developments) in the first year of the project time-life. Only the final experimental verifications on an equivalent model are currently running in the laboratory and analytical studies on the integration methods for the non-linear cases will continue during the second year, until the starting of the pseudo-dynamic tests. The JRC, Ispra, will issue a technical report on the subject.

Regarding the preliminary analysis of the bridge prototype and the design of the test models, the JRC undertook the following steeps:

- In the 1998 Vienna's meeting (kick-off meeting) JRC proposed to construct 3~4 test models obeying to the basic condition of being representative of the prototype and having low and high shear span ratios. Furthermore, it was agreed to test a pier model with displacement controlled cyclic quasi-static deformation history. This would allow to calibrate numerical models to be used in the non-linear simulation.
- The JRC started the non-linear analysis of the bridge piers in order to identify typical behaviours and to identify the most relevant input data required. A preliminary report on the non-linear analyses was distributed in the Vienna's 1999 meeting.
- At the Vienna's 1999 meeting the following additional data required for the progress of the work in task 4 was identified: **1)** Definition of the bridge material characterisitcs: Steel (smooth or ribbed bars) and concrete classes - strength and deformation characteristic values and average values for both steel and concrete *(already given)* 2) Shear/confinement reinforcement *(Drawings obtained in May 1999)*, 3)

Boundary conditions for the structures and corresponding model *(to be discussed)* 4) Definition of the input motions for different return periods (synchronous and non-synchronous motions) *(to be discussed).*

- Just after the last meeting, JRC started new analyses with the up-dated bridge model and recently with the data included in the drawings.

The non-linear analyses carried out at the JRC included: a) Modelling of the bridge and dynamic non-linear analysis to define the most vulnerable piers - fibre non-linear model was used for the piers and linear one for the deck; b) Dynamic non-linear analyses, which started in January 1999; c) Preliminary non-linear analyses carried out with an artificial accelerogram and with the Friuli record. The main objective was to define the most vulnerable piers in order to decide on the pier models to be constructed and tested.

On the basis of the preliminary analyses and also on the basis of the discussions during the last project meeting, the following testing programme, or better, set of test models and tests are suggested by the JRC (model scale 2.0 ~ 2.5):

- 1 cyclic test on one of the shortest piers (model calibration and capacity assessment)
- 1 cyclic test on one of the shortest piers retrofitted (retrofitting solutions/techniques and model calibration and capacity assessment). Final decision on this model should be made according to the available funds.
- pseudo-dynamic (PSD) tests on the bridge with two piers in the Laboratory (a bending dominated and another shear dominated) and with the deck substructured (linear) and the remaining piers substructured (non-linear). One PSD will be performed with non-synchronous input motion. Other partners in Task 5 will define the input motions.

GEOLOGICAL-, GEOPHYSICAL-, SEISMOTECTONIC DATA AND COMPUTATION OF SEISMIC INPUT

The deterministic approach is based on the computation of synthetic seismograms, using computer codes developed from a detailed knowledge of the seismic source process and of the propagation of seismic waves, that can simulate the ground motion associated with the given earthquake scenario. In such a way, synthetic signals, to be used as seismic input in a subsequent engineering analysis, e.g. for the design of earthquake-resistant structures or for the estimation of differential motion, can be produced at a very low cost/benefit ratio.
To define the possible seismic sources that could drive the seismic hazard of the Warth region, we adapted to the project needs a database of focal mechanisms developed at the Department of Earth Sciences at the University of Trieste (DST) for the EC project QSEZ-CIPAR. Taking into account the magnitudes, and the distances from the Warth region, we selected five sources to be considered in the remaining analysis. The regional structural model for the Vienna basin has been extracted from the I-dataset prepared at DST in the framework of the EC Project LP RISK. Starting from the available Warth bridge section plan, a digitised model of the geological cross-section underlying the bridge has been created. On the basis of the geological and geotechnical informations available, the elastic and the anelastic parameters have been assigned to the various polygons, corresponding to the different geotechnical units, contained in the section. All the materials are available on our ftp server.
At the base of each pier of the Warth bridge, the synthetic time signals (displacements, velocity and accelerations for the three components of motion) have been calculated with the modal summation technique for the structural model representative of the Vienna Basin region. In order to take into account the source, path and site effect, the hybrid method, combining the modal summation and the finite difference technique, has been applied to a highly realistic model that couples the regional and the local heterogeneous models. The synthetic time signals, with an upper frequency limit of 8 Hz, and the differential motion of each pier, has been computed for different source-sites configurations. The results show that the differential motion amplitude is comparable with the input motion amplitude when displacement, velocity and acceleration are considered.
All the synthetic seismograms and the differential motion time series are available on our ftp server.

SIMPLIFIED ANALYSIS TOOLS FOR ASSESSING THE VULNERABILITY OF COMPLETE BRIDGES

During the first year of the VAB project CIMNE performed: (1) an exhaustive state-of-the-art study [Soberón, 1999] of the vulnerability assessment of motorway bridges, (2) a carefully revision of the drawings and finite element models of the Warth bridge, and (3) the first steps in developing simplified models of the studied bridge.

The state-of-the-art includes the studies that estimate the fragility of bridges in different ways. Some studies use expert's opinion and statistical techniques to evaluate those structural parameters, which mostly influence on the bridge behaviour during earthquakes. In general, these researches use as parameters the structural material, the bearing type, the year of construction, the material and cross section of the piers, etc. The vulnerability of bridges is obtained starting from the subjective assignation of values for each parameter and the combination of this score in different forms. Other researches evaluate damage probability matrices and fragility curves for all structural types using ATC-25 report, expert's opinion and statistical techniques, to obtain as a result the probability of damage in each structural typology and for each damage state.

Among the vast number of analyses of bridges in the last years, only a few evaluate the vulnerability of bridges by using methods based on non-linear structural analysis. These studies use structural models ranging between the single-degree-of-freedom equivalent systems and the simplified finite element models. One of the most complete of these works is that of Ciampoli, which considers finite element bridge models to obtain, by means of Monte Carlo simulation, the fragility curves for the original bridge and the retrofitted one. Other researches evaluate the damage probability matrices and fragility curves for bridges that suffered the Tangshan (China, 1976), Loma Prieta (1989) and Northridge (1994) earthquakes by means of statistical analysis of the reported damage.

According to the performed revision, it can be observed that simplified analysis procedures and structural models are necessary to estimate the vulnerability of bridges, especially for regions with moderate seismicity, where damage databases are not available, in which case the use of Monte Carlo simulation would be necessary.

During the same period, a careful revision of the informations, drawings and finite element model, provided by arsenal has been performed. According to all this data the necessary input for developing simplified models, such as elements, dimensions, materials characteristics and connections between elements for the studied bridge, have been obtained.

Simplified models are developed for both the transversal and longitudinal directions. These models consider the box girder of the bridge as a concentrate mass element and the piers as structural elements with distributed mass. The effects of the girder rotation, of the soil-structure interaction and of the spatial variation of the earthquake input on each pier are also taken into account. The longitudinal and transversal deformation of the box girder is neglected. Damage models will be included in these simplified models to evaluate the local damage in each pier and the global damage in the complete bridge.

DEVELOPMENT OF RETROFIT MEASURES

During this first period, a bibliographical work has been carried out by SETRA and ISMES showing two ways of improving the reliability of existing bridges to seismic action : either by reducing the required forces on piers by use of isolation or damping devices or by strengthening the resisting elements.

The bibliography is organised in the form of technical data sheets established for each relevant retrofitting technique. These documents focus on potential applications, technical characteristics, design tools and elements of costs.

Identified retrofitting techniques that are to be examined are listed below :

Strengthening measures

- Casing and Jacket (Steel Casing, Concrete Jacketing, Fibre Reinforced Plastic Casing)
- Plate Bonding (Steel Plate Bonding, Fibre Reinforced Plastic Bonding)
- Strengthening by means of concrete jacket and bolsters (Bolsters Cast in Place, Shotcrete)

Isolation and dissipative devices

- Isolation devices (Laminated rubber bearings, Lead rubber bearings, Sliding bearings, Pendulum friction system
- Dissipative devices (Steel elasto-plastic dampers, Hydraulic dampers)

ISMES will organise, in concomitance with the plenary mid-term meeting of our project, a specific workshop to present and discuss both the state-of-the-art and latest developments using innovative antiseismic devices and techniques. Developers of such devices and bridge designers will discuss feasibility and potential applications.

However, no strengthening technique is presently used for hollow rectangular piers similar to that of the Warth bridge. It has been recognised during the first annual meeting that a retrofitting technique should be tested experimentally on a single pier at the ELSA laboratory, in the framework (and budget) of our VAB project. SETRA will perform the design.

CONCLUSIONS

This paper gives an overview over the work program of the European Environment & Climate Project *Advanced Methods for Assessing the Seismic Vulnerability of Existing Motorway Bridges (VAB)* and over the progress obtained during the first year. The work within the tasks dynamic insitu testing and calculation of synthetic accelerograms characteristic for the WARTH site is nearly finished. Considerable progress was obtained in all tasks. Further updated FE models can be expected soon. Then, the pseudodynamic testing at ELSA laboratory in Ispra will be the next project highlight. The main benefit from these tests will be the information on the ductile behaviour of large R/C bridge piers with hollow cross section. After the tests, with the final FE model, which includes also the non-linear pier behaviour, we will know if either the bridge WARTH is safe or retrofit measures have to be applied. Then, it will become more difficult, because we want to define the simplest assessment procedure giving the necessary parameters in an adequate way. This will be probably easy for the case of WARTH but our goal is to find more general conclusions allowing to deal with a large number of bridge types.
A retrofitting technique should be tested experimentally on a single pier at the ELSA laboratory, in the framework (and budget) of our VAB project.

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