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# SOFTWARE FOR THE PRELIMINARY DESIGN OF SEISMICALLY ISOLATED R/C HIGHWAY OVERPASS BRIDGES

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## ABSTRACT

The features of an expert system, developed for the pre-design of highway overpass R/C bridges, are presented and discussed. This system is implemented into a software and is aimed to facilitate the seismic upgrading of an overpass by isolating its deck with the inclusion of elastomeric bearings. The preliminary design of such an upgrade scheme is the target of this software based on the current design provisions of Eurocode 8 (Part 2) as well as on engineering decisions included in the expert system; it can also be extended easily to comply with alternative design provisions. The developed software is connected with a database of typically used steel laminated rubber bearings and relevant laboratory test results and it performs a series of checks according to Eurocode 8, in order to ensure the satisfactory seismic performance of the selected upgrade scheme. The parameters that are addressed within this software as independent variables are: the geometry of the overpass, the number of bearings at each deck support, the level of seismic action and the characteristics of the bearings (i.e. their geometry and shear modulus). The final selection of the bearing scheme (in terms of number of bearings and bearing dimensions at each support) is based on a cost-benefit criterion aiming at optimizing structural performance at minimum cost. The methodology proposed for the preliminary design of seismically isolated overpasses and the software developed were validated through more rigorous dynamic analyses employing multi-degree of freedom numerical simulations of realistic bridge overpasses.

## Introduction

The objective of this paper is to present the tools developed to facilitate the preliminary design of base-isolated highway overpasses. The upgrade of seismic performance of both new and existing highway bridges has been extensively studied (Calvi and Pavese, 1998, Dolce and Marnetto, 1998, Priestley et al.,1996, Naeim and Kelly 1999 among many others) and is also of particular interest for the case of a large road network that has been constructed in Northern Greece with more than 646 bridges built of a total of 40km length (Panetsos and Konstantidis 2003) most of them being of relatively small dimensions (L<100m). This particular research framework

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presented herein focuses on both existing and new R/C bridge overpasses, which represent the majority of the bridge stock, and aims at a) the design and pilot production of elastomeric (steel-laminated) bearings, specifically by a local Hellenic industry, which then can be used in practice, b) the investigation of the mechanical properties of these pilot bearings at the Laboratory of Strength of Materials and Structures of Aristotle University under static and cyclic dynamic loading and c) the development of a an expert system which can link the produced steel-laminated elastomeric bearings as well as same type bearings that are usually employed with the current design practice in the selection of an appropriate elastomeric bearing scheme for typical R/C bridge overpasses in Greece.

In this framework, a series of tests were performed on unit slice specimens of properties and dimensions representative of the pilot bearings. Summary results are presented in this paper of the aforementioned ongoing experimental investigation along with the measured mechanical characteristics under standard loading sequences. The parameters investigated are the extent of shear strain, the frequency of loading, as well as the intensity of loading acting perpendicular to the bearing layers. Moreover, a methodology and an expert system for the design of seismically isolated bridges was developed primarily based on the Greek and the Eurocode 8- Part 2 guidelines and engineering judgment where appropriate. By considering the overpass as a single degree of freedom system in the longitudinal direction (response in the transverse direction is deemed to be restrained by stoppers), the seismic performance of the bridge is assessed for all possible bearing sections, which are included in the relevant database linked to the software; moreover, the given level of earthquake loading and the corresponding code-based criteria are checked. Through this process, a limited number of 'suitable' bearings are selected for the preliminary design of the structure on the basis of a cost-performance index defined herein for this purpose.

The methodology proposed and the predictions made towards the selection of such an 'optimal' laminated-steel rubber bearing scheme for a particular structure is also validated through response spectrum and transient dynamic analyses of the multi-degree of freedom simulations of the bridges under study. In the following, the experimental and computational framework of the particular research effort is presented.

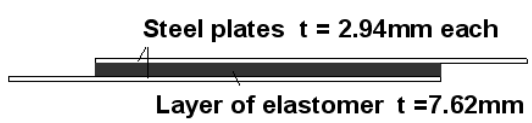


Figure 1a. Slice bearing unit

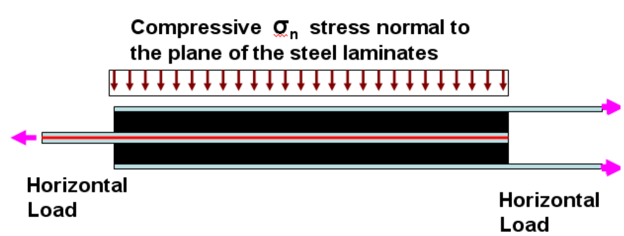


Figure 1b. Slice bearing specimen

## Laboratory Testing

The target of the experimental campaign was twofold: At first, the mechanical properties of the bearings were investigated based on qualification tests conducted according to the ISO 22762-1 standard. Next, in an effort to study the influence of certain parameters in the mechanical characteristics of these elastomeric bearings, the vulcanization process was studied especially in terms of the influence of its duration on the mechanical characteristics of the final product. To this end, specimens were produced composed of two slice bearing units (figure 1a); these slice bearing specimens were subjected to horizontal (shear) loading under various compressive stress levels (figure 1b). Two characteristic splice-bearing specimens were chosen: (a) two unit slices of elastomer (200mm x 200mm and 7.62mm thickness each) bonded to their steel plating (four steel plates) as seen in Figure 2 (left), and (b) two cylindrical bearing specimens formed by two slices of elastomer and four steel plates of 250mm diameter and 7.62 mm thickness each (Figure 2, right).

Throughout all the tests the applied load producing the shear strains was monitored together with the corresponding displacements of the specimen that were utilized to deduce the applied shear stress and shear strain levels to the specimen. At the same time the applied vertical load, normal to the slices of neoprene, was recorded and checked for any significant variations; the objective in this case being to keep the vertical load almost constant at the range of 2.0 to 2.5 Mpa throughout all tests. The loading arrangement of a unit slice and the cyclic shear strain imposed on the bearing specimens are illustrated in Figure 3. Initially, the vertical load was monitored in-order to assess the level of variation throughout the loading sequence (figure 3 left). As a refinement of this process, the loading setup was changed to include dynamic actuators with the capability to control the horizontal (shearing displacement) as well as the applied vertical load, thus controlling the applied compressive stress normal to the plane of the laminates (figure 3 right). The tests performed are summarized as follows:

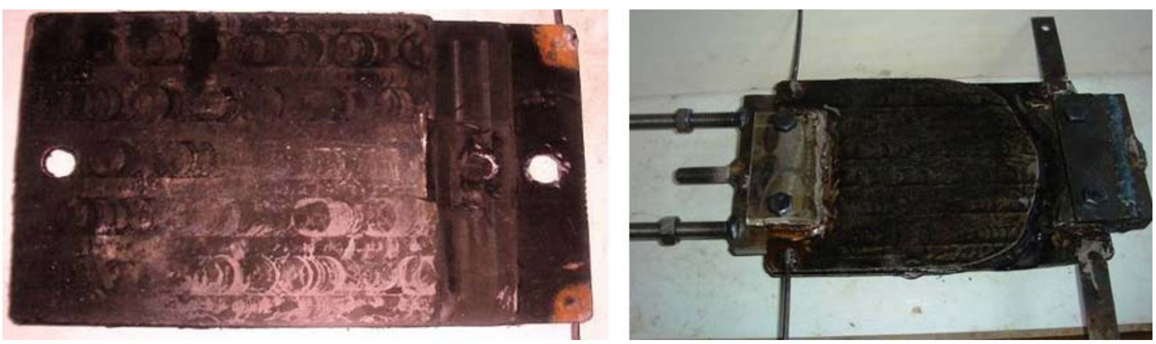

Figure 2. Rectangular specimens 200x200mm (left) and cylindrical specimens of 250mm (right)

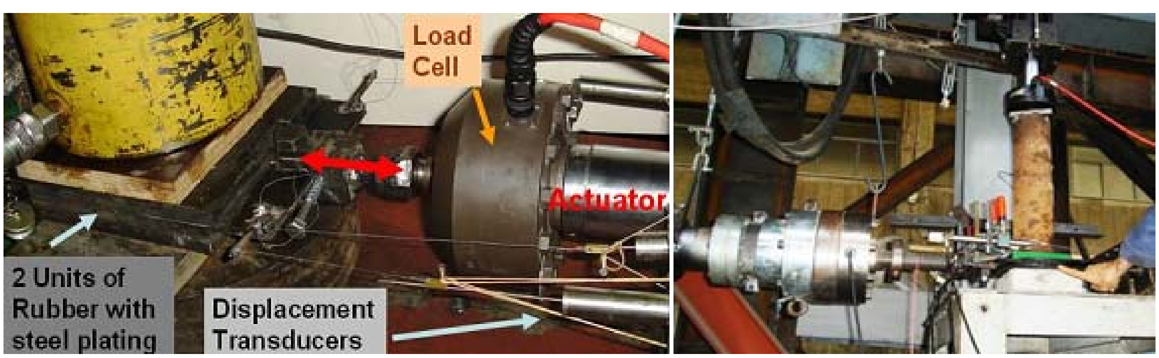


Figure 3. Loading arrangement of a unit slice (left) and cyclic shear strain imposed simultaneously with the application of the desired constant compressive force perpendicular to the bearing layers (right).

a1. The applied shear strain was varied in the nominal range of 5%, 10%, 25%, 50%, 75% and 100%. The particular levels of strain were imposed in a cyclic manner while retaining the frequency of the loading constant while the amplitude of loading was gradually increased. The excitation frequency was set equal to 0.2Hz (Figure 4).

a2. The frequency content of the applied shear strain was varied for a given amplitude that was kept constant (at the level of 75% to 110%). Sinusoidal pulsed were applied of frequency equal to 0.09Hz, 0.2Hz and 1.0Hz, 1.5Hz (Figure 5).

a3. Moderate to large levels of shear strain were applied (i.e. 100%, 150%, 250% and 300%) either cyclically as previously (cases a1 and a2) or through monotonic loading.

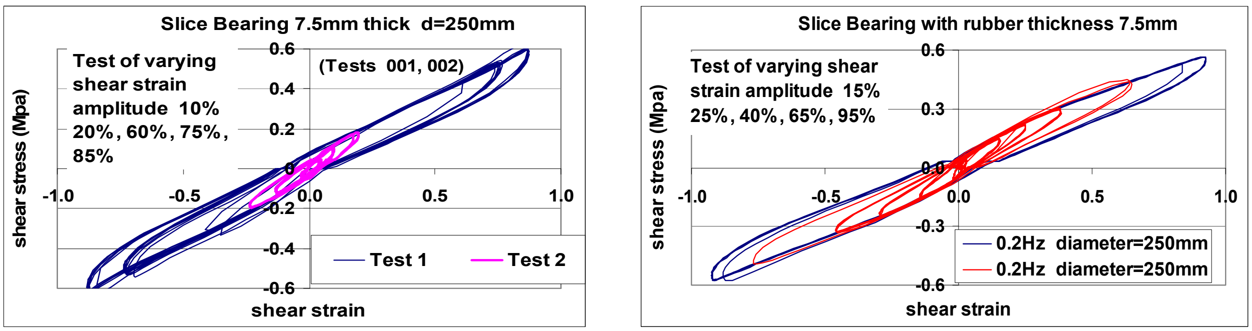


Figure 4. Response of the circular specimen with diameter of 250mm .Variation of the shear strain amplitude (10% to 95%) for constant frequency content 0.2Hz.

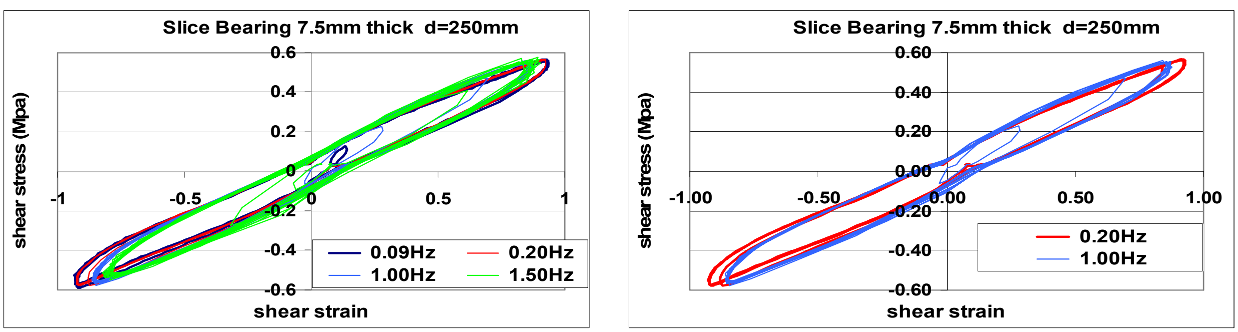


Figure 5. Response of the circular specimen with diameter of 250mm .Variation of the frequency content of the imposed shear strain (0.1Hz, 0.2Hz and 1.0Hz, 1.5Hz) for constant shear strain amplitude (95%).

## Experimental Results

The response of the circular specimen with diameter of 250mm, subjected to different shear strain amplitude (nominal values from 5% to 100%) or different frequency content of the imposed shear strain (0.1Hz, 0.2Hz and 1.0Hz, 1.5Hz) is presented in Figures 4 and 5, respectively. Figure 6 depicts a comparison between the cyclic response for applied level of shear strain equal to 200% with equivalent test under monotonic loading that reaches and exceeds this shear strain level. It is observed that the shear stiffness of the sliced-bearing specimens under cyclic loading of moderate amplitude is higher than the one derived from the large strain monotonic experiment. Moreover, during the last cycle of the monotonic test and for large levels of shear strain, the cylindrical specimen exhibited an abrupt drop of shear stiffness (for shear strain higher than 200%). Such controlled tests that were performed for splice-bearing specimens was next extended to subject the whole elastomeric bearing to combined shearing and compressive critical stress levels. The complete set of experimental results which can be found elsewhere (i.e. Manos et al., 2008) was used for the optimization of the pilot bearings production and the enrichment of the bearings database developed to support the preliminary bearings design expert system presented in the following.

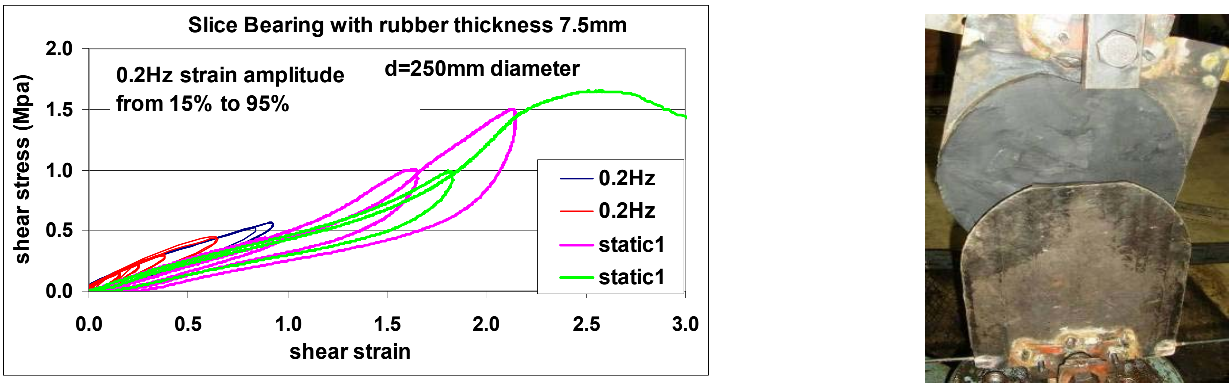


Figure 6. Comparison of the cyclic response for applied level of shear strain equal to 160% with equivalent test under monotonic loading for the cylindrical specimen of 250mm diameter (left). Failure of the 250mm cylindrical specimen (right).

## Software for the preliminary design of bearings

It is well known that highway overpasses, although relative simple structures, may be designed in multiple configurations depending on a set of performance, economic, safety, serviceability or even aesthetic criteria. This gives the designer the flexibility to choose among various structural configurations; this choice is further enhanced when the concept of base-isolation is adopted, which in a way "relieves" the structure from relatively high levels of earthquake-produced stress levels. The process to select the desired dimensions and number of bearing for each support is often a repetitive effort as it commonly leads to iterative analyses, design and checks against code-based criteria concerning the maximum level of bearing strain.

Along these lines and in order to facilitate the designer in selecting between a smaller sample of bearing types and sections, the current research initiative was formed in order to develop a sequential design-process that was expressed as a set of decision criteria (i.e. expert system) and finally developed in the form of a software. With the aid of this preliminary design tool, an appropriate and cost-effective scheme of elastomeric bearings can be selected for new or existing overpass bridges with typical structural configurations based on requirements posed by the Greek and Euro code 8 guidelines for the design of bridges with seismic isolation.

Within the framework described in the introduction and depending on (a) the period of construction and the corresponding seismic code used, (b) the pier type and cross-section, (c) the deck type and (d) the pier-deck connection, a series of bridge overpasses was first classified appropriately (Kappos & Moschonas, 2006, Manos et al., 2007). Then, an electronic database was developed specifically for overpasses containing commercially available bearings that can be used in design and construction. Numerous geometrical (rubber and steel plate thickness, height, width and type) and material (shear modulus, maximum strain) data, were archived for each (circular or rectangular) bearing and were accessed by the expert system developed for the selection process.

Having decided the type of overpass (in terms of number of spans, span and total length and locations of bearing-type pier-deck connections), the bridge class (in terms of number of lanes per direction), the number of bearings at each support, the preferred bearing shape and the parameters that define seismic loading (soil classification, seismic zone, importance category), the system automatically evaluates the performance of a given bridge for all bearings available in the database through a sequence of checks in order to filter out those that do not comply with the design criteria set. This staged filtering process is illustrated in Figure 7.

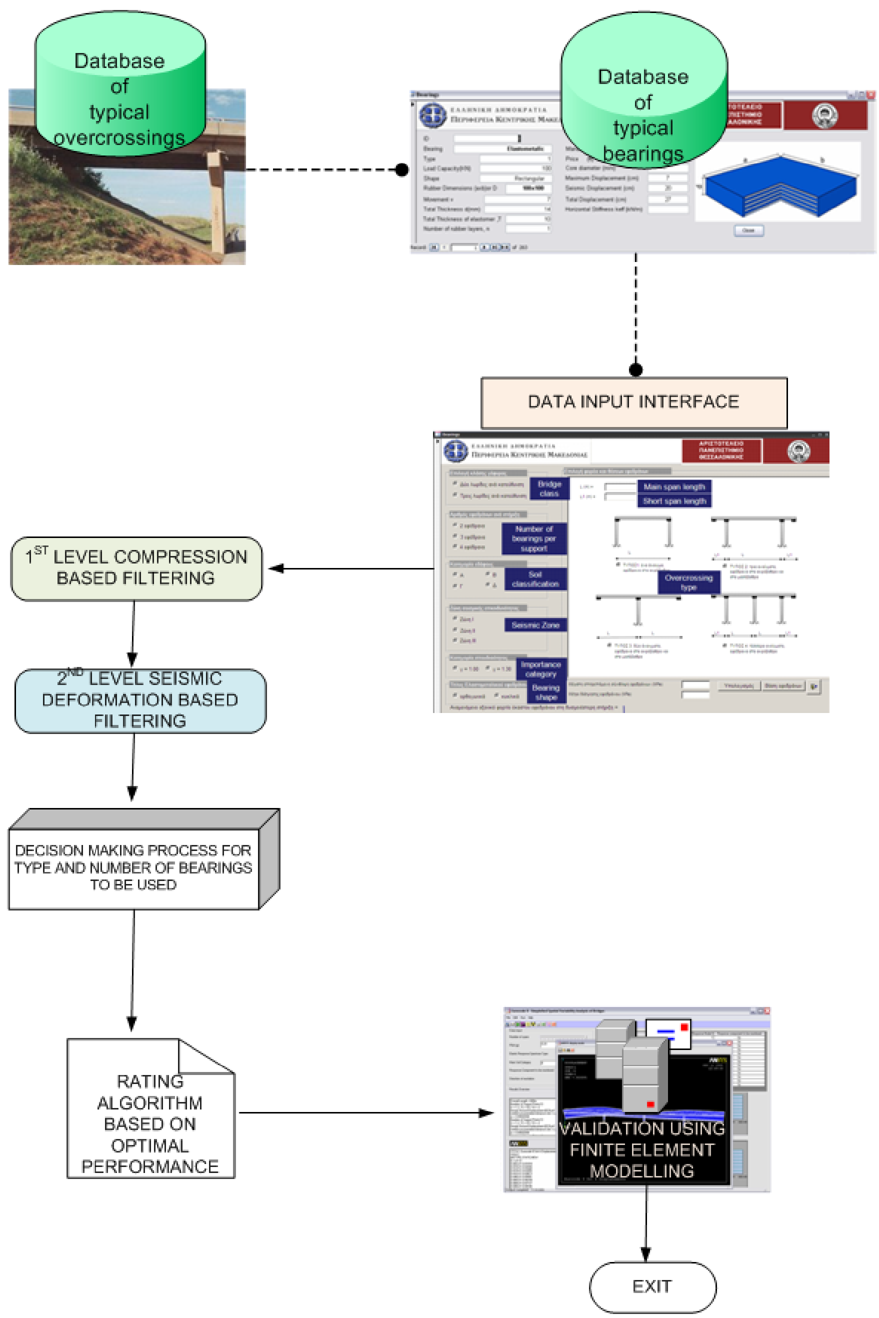


Figure 7. Overview of the software structure

### *Preliminary selection of bearings*

The first criterion adopted for the preliminary selection of bearings was the maximum anticipated compression which corresponds to a given level of acceptable shear strain of the bearing due to the interaction between the neoprene and the steel plates. This check is performed automatically by the program for all available steel-laminated elastomeric bearings (approximately 250 different circular and rectangular sections) while the allowable compression range is set between 3.0MPa to 5.0MPa based on the available literature (Abe et al., 2004). It is noted that the limit imposed for axial compressive stress $\sigma_e$ by the Greek Code for seismic isolated bridges is significantly higher, being equal to:

$$\sigma_e \leq \frac{2b_{min}}{3\sum t_i} G_b S \tag{1}$$

where $\Sigma t_i$ is the total thickness of the elastomeric, $G_b$ the shear stiffness of the bearing and S a shape coefficient. For the estimation of the (preliminary design) axial load at each bearing a static analysis is performed for the combination of gravity (G) and moving (Q) loads (G + 0.2 Q) and the vertical component of seismic motion as derived by the vertical elastic spectrum prescribed in Euro code 8.

### *Strain-based criteria for the equivalent Single Degree of Freedom System*

All the bearings that passed from the above initial filter are then checked against a set of code-prescribed criteria, involving the normalized shear strain of the bearing due to (a) seismic loading, (b) vertical load and (c) rotation the latter being clearly the less critical.

The shear strain due to the vertical loading combination $\varepsilon_{c,d}$ can be derived prior to lateral loading analysis and should remain in all cases below $\varepsilon_{c,d} < 50\%$ in order to comply with the criterion set in equation (1). A second criterion that has to be satisfied is also prescribed in the Greek Guidelines for Seismically Isolated Bridges, according to which the maximum total shear strain of the equivalent system ($\varepsilon_{b,d}$) should not exceed:

$$\varepsilon_{b,d} \leq \varepsilon_{u,k} / \gamma_m \tag{2}$$

where: $$\varepsilon_{b,d} = \varepsilon_{s,d} + \varepsilon_{c,d} + \varepsilon_{a,d} \tag{3}$$

$\varepsilon_{s,d}$ = the shear strain attributed to the seismic loading
$\varepsilon_{c,d}$ = the shear strain attributed to the vertical loading
$\varepsilon_{a,d}$ = the shear strain attributed to the rotation
$\varepsilon_{u,k}$ = the characteristic ultimate shear strain prescribed equal to 7.0
$\gamma_m$ = the partial safety factor equal to 1.15.

Another criterion set by the aforementioned guidelines is that the seismically induced shear strain should be limited to $\varepsilon_{s,d}$ <200% and as such it is also checked by the software for all eligible bearings that passed the first (compression-based) filter. The above strain is computed for the equivalent single degree of freedom system after deriving a reliable estimate of the:

- total mass of the superstructure
- total number of bearings needed at each support

- total stiffness and fundamental period of the equivalent SDOF system

Given the above data, the displacement $d_{Ed}$ of the system under study is derived and in turn, the criterion $\varepsilon_{s,d}$<200% is checked in all cases since:

$$\varepsilon_{s,d} = d_{Ed} / \Sigma t_i \tag{4}$$

where $\Sigma t_i$ is the total thickness of the elastomeric and $d_{Ed} = \sqrt{d_{Ed,x}^2 + d_{Ed,y}^2}$ the two horizontal components of seismic displacement.

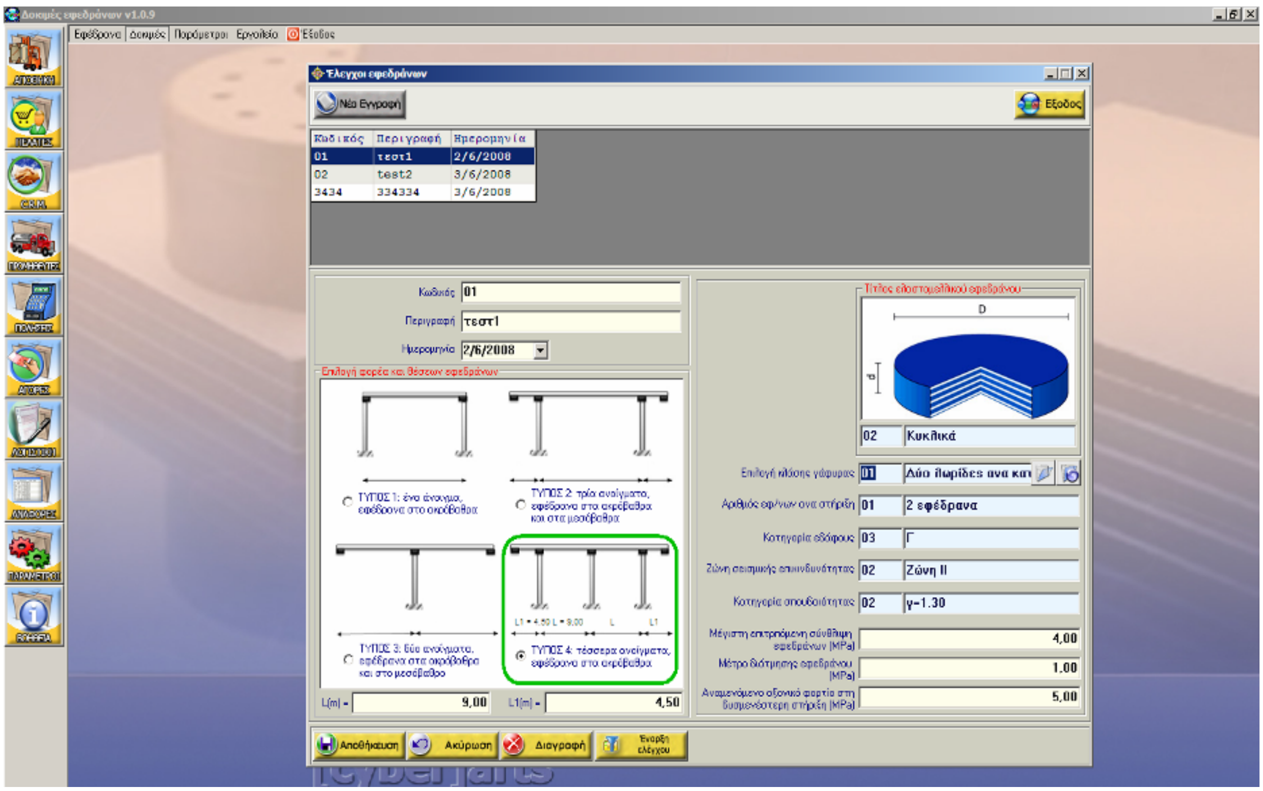


Figure 8. Overview of the software developed for the preliminary selection of the overpass bearings.

### *Optimal Performance Criteria*

For the final selection of the 'optimal' bearings among the ones that passed both the above criteria, a combined criterion is developed accounting for both the performance and the cost of each particular solution. In this framework, the preferred bearing section is the one that presents the highest OP (optimal performance) ratio, that is, corresponds to the higher safety factor for the minimum possible cost:

$$OP(i) = SF(i) \;/\; CC(i) \tag{5}$$

where $SF(i)$ is the safety factor derived for each eligible bearing $i$ as:

$$SF(i) = \varepsilon_s^{\text{limit}} \ / \ \varepsilon_s\,(i) \qquad (6)$$

and $CC(i)$ is the cost ratio defined as:

$$CC(i) = FC(i) \ / \ minFC(i) \qquad (7)$$

It is noted that the cost $FC(i)$ for each bearing $i$ is expressed in €, and is approximated as:

$$FC(i) = 200 + V_b(i)\ c_v \ \ (\text{in €}) \qquad (8)$$

where $V_b$ is the volume of bearing $i$ and $c_v$ is its corresponding cost per unit volume. On the other hand, min FC(i) is the minimum cost of all eligible bearings (i.e. the ones that passed the strain-based checks).

## Validation of the software developed – Conclussive remarks

- The aforementioned preliminary design process and software developed to facilitate the seismic isolation of highway overpasses was also validated through more rigorous response spectrum and transient dynamic analyses of the multi-degree of freedom simulations of the same overpass bridges leading to satisfactory agreement.
- The permissible compressive stress of the bearings criterion, adopted initially, represents an important parameter of the proposed preliminary selection process and, as already stated, is more restrictive than the corresponding provisions of the Greek and Euro code 8 guidelines. Along these lines, in the final version of the software this criterion was somewhat altered to have as an acceptable compressive stress level range for the steel-laminated elastomeric bearings equal to 2.0Mpa – 6.0Mpa. Moreover, the software is providing the option to the designer-user to specify an alternative range for this acceptable compressive stress level according to the bridge configuration under study.
- The tests that were performed at the Laboratory of Strength of Materials and Structures of Aristotle University were extended to subject elastomeric bearing to combined shearing and compressive critical stress levels. Such results can be used for the optimization of the pilot bearings production as well as for the enrichment of the bearings database developed to support the preliminary bearings design expert system presented before.

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