

## USING THE NEW SAP2000 OPEN APPLICATION PROGRAMMING INTERFACE TO DEVELOP AN INTERACTIVE FRONT-END FOR THE MODAL PUSHOVER ANALYSIS OF BRIDGES

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***Abstract.** Seismic assessment of bridge structures often requires inelastic (static or dynamic) analysis methods to be used, in order to draw a realistic evaluation of the structural behaviour beyond the elastic range. While the widely-used non-linear static (pushover) analysis provides a low-computational-cost approach to this direction, it is inherently limited by the assumption that the structure's response is solely controlled by its fundamental mode. This limitation is raised by an extension of the "standard" pushover analysis (SPA) to take into consideration the effect of higher modes, a method known as Modal Pushover Analysis (MPA). This method however, can often prove to be time-consuming and strenuous both for pre- and post processing. The latter, provided the motivation for investigating the feasibility to take advantage of the recently released SAP2000 application programming interface (API) in order to develop a new computational tool that implements the MPA specifications for evaluating the seismic behavior of bridges in an organized and automatic fashion. The paper concludes with the application and demonstration of the software developed, for the case of an existing reinforced concrete bridge located along the Egnatia Highway in Greece.*

## 1 INTRODUCTION

Nonlinear static procedures have become a commonly used tool for assessing the seismic performance of buildings and bridges. Nevertheless, its main advantage of lower computational cost, compared to non-linear time-history analysis (NL-THA), is counter-balanced by its inherent restriction to those structures, wherein the fundamental mode dominates the response. To this end, Modal Pushover Analysis, as introduced by Chopra and Goel [1], [2] for buildings and extended by Paraskeva et al. [3], [4] for bridges, is deemed a useful alternative, as it can provide a reliable estimate of the non-linear structural response, based on the repeated application of a given nonlinear static analysis procedure for each of the significant vibration modes of the structure, followed by an adequate combination of the results. However, this procedure is time-consuming and the significant effort required for pre- and post-processing of the required and obtained data, respectively, quite often cancels the advantage of simplicity compared to the non-linear time-history analysis.

This limitation is raised herein by making use of the new SAP2000 [5] Application Programming Interface (API), for developing an interactive front-end for the modal pushover analysis of bridges. This API was recently introduced by CSI, the developer of the finite element code SAP2000, and grants access to the SAP2000 advanced numerical modules, thus permitting pre- and post-analysis computations to be efficiently programmed. An introduction to using this new computational tool is made herein and the capabilities that are opened for developing third-party earthquake engineering applications to be coupled with SAP2000 are also discussed. Subsequently, the architecture of the front-end is presented in detail, presenting the implementation approach that was followed and the way that the procedure's specifications were encapsulated into the software.

Finally, the front-end developed is also applied for the assessment of seismic response of an existing bridge structure in Greece, which is presented in this paper for testimonial purposes. It is shown that with the use of the new SAP2000 API and the aforementioned interactive front-end, the time and effort required for studying the inelastic response of bridges through a modal pushover analysis scheme is greatly reduced.

## 2 STANDARD AND MODAL NONLINEAR ANALYSIS

### 2.1 Nonlinear Static (Pushover) Analysis

When it comes to estimating the nonlinear behavior of structures that are subjected to seismic forces, pushover analysis is the most widely-used method, capable of providing a reliable estimate of the structural capacity. During this procedure, monotonically increased lateral loads are statically applied to the structure, in an invariant pattern that aims to resemble the distribution of the fundamental mode forces that the structure is subjected to when excited seismically along a given direction. Under the increasing load application, a series of plastic hinges develop at critical sections of the structure, leading force redistribution and gradually to a failure mechanism. As a result, it is possible to obtain the non-linear relationship between the lateral force applied and the deformation of the structure which is monitored at a specific location, usually expressed in the form of the pushover curve, that is, a "base reaction versus control node displacement".

By converting the base shears and roof displacements obtained to equivalent spectral accelerations and displacements ( $S_a(T)$  and  $S_d(T)$ ) and superimposing an earthquake demand curve (typically the prescribed seismic hazard spectrum for the site), the non-linear (pushover) analysis can then provide an estimation of the inelastic response of the structure at a given level of

target earthquake intensity. It is therefore a useful structural assessment tool as it offers a number of advantages, primarily being the fact that:

- it is a conceptually simple methods which is straightforward to apply low computational cost, in comparison to the nonlinear response history analysis (NL-RHA).
- the results obtained by SPA can be easily post-processed and interpreted, especially compared to NL-RHA. It is recalled that the latter method leads to time variant action effects (i.e., forces and displacements) and computing the statistics of response can be a demanding task. Moreover, the inelastic response results obtained by NL-RHA are very sensitive to both the characteristics (i.e, frequency content, amplitude, duration etc) of the suite of earthquake ground motions used and the assumptions made in modelling the cyclic response of RC members; thus the discrepancies associated with structural response are often large.

On the other hand, the applicability of nonlinear static analysis is limited by its:

- incapability of considering the contribution of higher than the fundamental modes and insensitivity to the dynamic characteristics of the structure.
- problematic application to three-dimensional, non-symmetrical or irregular systems.

As a result, in most realistic cases, “standard” nonlinear static (pushover) analysis (SPA) can only provide a rough estimate of the inelastic response, and more accurate procedures have to be followed.

## 2.2 Modal Pushover Analysis for the seismic assessment of bridges

Given the above limitations, as already mentioned, Chopra & Goel [1], [2] developed an improved Modal Pushover Analysis (MPA) procedure where the total seismic demand of inelastic systems is computed based on the combination of individual “modal” demands. With a series of adaptations and further assumptions, the method was extended for the assessment of the inelastic response of bridges ([3], [4]). The main steps of this method are summarized in the following [3]:

- *Step 1:* Calculation of the “elastic” natural periods  $T_n$  and the modes  $\varphi_n$  of the bridge. Due to the physical characteristics of bridges, the number of modes that need to be taken into account during the procedure may reach even a few hundred modes, until the total mass contribution sums up to a level of at least 90%, which is considered to be adequate.
- *Step 2:* Separate SPA are performed for each significant mode of the bridge, from which the base shear force – control node displacement relationship ( $V_{bn} - u_{rn}$ ) is extracted, in order to form the pushover curve that corresponds to each mode.
- *Step 3:* The pushover curve is transformed appropriately into an idealized bilinear equivalent, so that the yield point and the ductility factor can be obtained.
- *Step 4:* The earthquake displacement demand is defined. The idealized pushover curve of the multi-degree-of-freedom (MDOF) system is converted into a capacity diagram of the equivalent single-degree-of-freedom (SDOF) system, using the following relationships:

$$S_a = \frac{V_{bn}}{M_n^*} \quad (1)$$

$$S_d = \frac{u_{rn}}{\Gamma_n \cdot \varphi_{rn}} \quad (2)$$

wherein  $S_a$  and  $S_d$  are the spectral acceleration and displacements, correspondingly,  $\varphi_{rn}$  is the value of  $\varphi_n$  at the monitoring point,  $M_n^* = L_n \cdot \Gamma_n$  is the effective modal mass,  $L_n = \varphi_n^T \cdot m$ ,  $\Gamma_n = L_n / M_n$  and  $M_n = \varphi_n^T \cdot m \cdot \varphi_n$  is the generalized mass, for the  $n^{\text{th}}$  natural mode. In this way, by applying the capacity spectrum method ([6], [7]) it is possible to estimate the displacement demand corresponding to the applied earthquake intensity.

- *Step 5:* The displacement demand of the  $n^{\text{th}}$  mode inelastic SDOF system that was calculated in the previous step is converted back to the peak displacement of the monitoring point  $u_{rn}$  of the MDOF representing the actual bridge.
- *Step 6:* The values of the desired responses  $r_n$  are extracted from the analysis step at which the displacement at the monitoring point is equal to  $u_{rn}$  defined in Step 5.
- *Step 7:* Steps 3 to 6 are repeated for all the modes considered “important”.
- *Step 8:* An appropriate modal combination rule, such as SRSS or CQC, is applied to the peak modal responses  $r_{no}$  (i.e., for displacements and plastic hinge rotations) that correspond to each “important” mode, in order for the total value of the desired response to be estimated.

The procedure described briefly in the aforementioned steps is subjected to a number of important key-factors that should be taken into account while performing the analysis, such as the appropriate selection of the monitoring point (i.e., deck mass center, top of the nearest pier, location of maximum displacement etc) for each pushover analysis or the rule that is used during the idealization of the pushover curves. Further investigation of the details that describe MPA is beyond the scope of the present work. However, wherever applicable, additional reference to the specifications, which were followed along the development of the MPA software, will be made.

### 3 INTRODUCTION TO THE SAP2000 APPLICATION PROGRAMMING INTERFACE

Facing the challenge of developing new, more accurate and, inevitably, more sophisticated procedures for the needs of structural engineering does not come at no cost; the need for computational power and the subsequent requirement to embrace bleeding-edge technology tools and resources are demanding. Reversing the argument, it is this very availability of increasingly productive computational systems that motivates the researchers to investigate more advanced and optimized tools for the assessment of structures, leading in this way to a recursive pattern of development and adoption of new information technologies achievements. Furthermore, the need of simplifying the application of available procedures and making effective use of the computational methods already established is not to be neglected, as this can greatly improve the productivity and quality of performing every-day tasks. In this direction, the recently introduced computational tool SAP2000 API, which accompanies the structural analysis software SAP2000 as of version 11, has come to significantly expand the usage of its parent-application into wider research fields beyond the structural analysis framework currently established.

### 3.1 Description of the SAP2000 API

The SAP2000 Application Programming Interface (API) is a programming tool which aims to offer efficient access to the analysis and design technology of the SAP2000 structural analysis software, by allowing, during run-time, a direct bind to be established, between a third-party application and the analysis software itself [Fig. 1]. Additionally, through the use of this API, one has the option of developing plug-ins, which extend the program's usability and are totally embedded within the SAP2000 environment. In terms of computer programming, the API consists of a software library that offers access to a collection of objects and functions capable of “remotely” controlling the way that the SAP2000 behaves, thus, overriding the standard point-and-click procedure. A highlight of the main features that the API provides are summarized below:

- Direct, fast and robust coupling with the SAP2000 design and analysis methods.
- Two-way data flow as it can be used to facilitate both pre- and post-processing procedures.
- No need of using intermediate files, which reduces significantly the time needed for data exchange when working on large models.
- Compatibility with most major programming languages.
- Concurrent data transfer and control of a structural model by different third-party applications.
- Development of third-party applications that will remain compatible with future releases of SAP2000.
- Ability to develop a custom interface for SAP2000, calibrated to the user's needs, or to embed one in an application that allows for user programming.

### 3.2 Using the SAP2000 API

In order to make use of the above SAP2000 API features for developing new computing tools, usually a solid programming background is required, as the process may prove demanding, in terms of programming skills. However, this is not always the case, when it comes to simple computing tasks. In either case, the SAP2000 API offers a broad range of programming languages that it can be used which cover the vast majority of the modern software development options including Visual Basic.NET, Visual Basic for Applications (VBA), Visual C#, Visual C++, Visual Fortran and Matlab.

To get started with, accessing the API requires nothing more than a functional SAP2000 installation, as all the components that it consists of are automatically installed during the main program's setup. Using it, however, depends at large on the programming language that the developer is familiar with and the programming environment that is selected for this purpose. Different integrated development environments (IDEs) offer several options in order for the programming project to link successfully with the API and, additionally, in each case the syntax to be used and the potential planning of the application to be developed differ according to the language's standards. One should bear in mind, however, that in order to make effective use of the API it may be appropriate that the programming style, to which one is accustomed to, has to be adapted to the way the API is structured, due to its non-deviant attitude, regarding the SAP2000 approach to designing an assessing a structure; in any case though, the steps necessary to accomplish a task via the API resemble vastly the corresponding point-and-click procedure required by the standard usage of the parent-application.

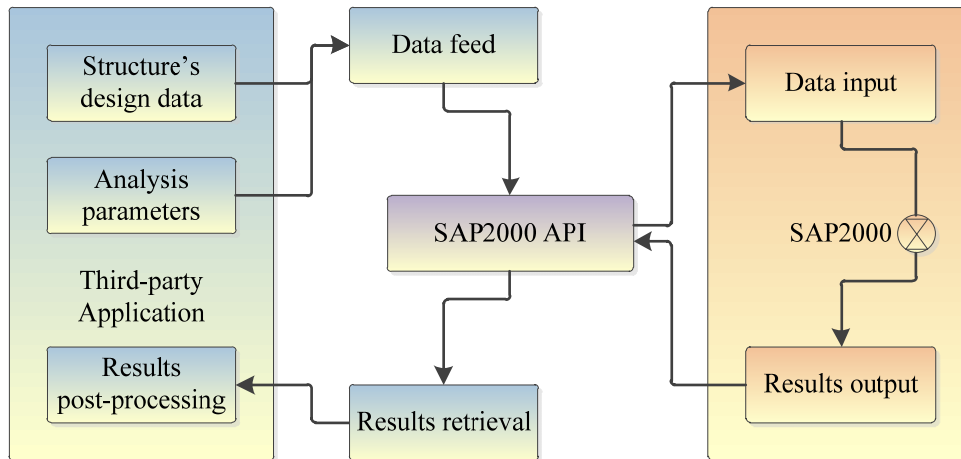


Figure 1: Application binding and typical data flow using the SAP2000 API.

As a general assistant in utilizing the SAP2000 API, a detailed documentation file is also provided along with the installation (SAP2000\_API\_Documentation.chm) including all the required information that will assist in getting accustomed to the API programming. This guide is to be used side-by-side when developing SAP2000 collaborated software, as it contains a full list of every single function provided, accompanied by its exact syntax, a detailed description of the arguments that it handles and a commented example of usage.

#### 4 MODAL PUSHOVER ANALYSIS IMPLEMENTATION

Implementing an innovative scientific method requires thorough planning and well-balanced decisions to be made, regarding the usability, flexibility and layout of the final product. Developing software capable of applying the MPA procedure to bridges involves taking into account a considerable amount of analysis parameters, storing and manipulating a large number of variables and ensuring that access is granted to important information at every stage of the analysis. Herein, an effort for simplicity and integrity to be respected has been made, while fulfilling the need for optimizing and supervising the applied procedure.

##### 4.1 Software architecture

The scheme chosen, so as to implement the MPA method, consists of an application arranged in modules, separated according to the tasks that are intended to perform. The analysis flow is controlled through an interactive graphical user interface (GUI), which consists of a main window that contains all the components necessary to define and review the analysis procedure. Linked to the interface is an external graphics component, which is used in order to visualize the bridge's deck deformation during the various analysis cases, while the pre- and post-processing is made entirely inside a separate dynamic link library (DLL) that binds the interface with the SAP2000 software. This is accomplished through the use of the SAP2000 API, which aims to regulate the flow of data within the bipartite scheme [Fig. 2].

The user is expected to interact entirely with the interface provided, while SAP2000 runs silently in the background of the operating system's desktop, throughout the analysis runtime. What is more, the required actions related to the manipulation of the SAP2000 model file are transferred, via the API, to the MPA software's interface. However, if needed, the user is allowed to bring the SAP2000 interface to the foreground, in order to make explicit definition of any advanced parameters that the MPA software does not provide, gaining, thus, complete control over the procedure.

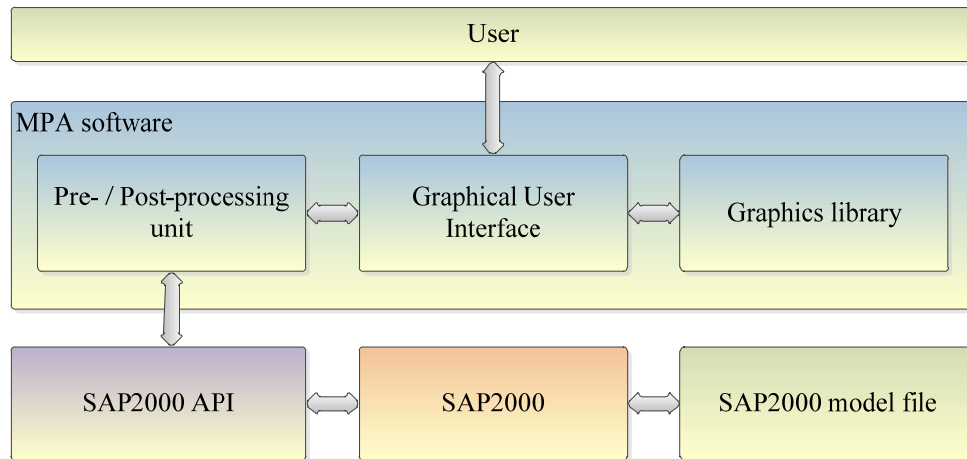


Figure 2: Modal Pushover Analysis software structure.

## 4.2 Description of the implementation

Researching and developing an innovative computational method is one thing, implementing one, however, into productive software requires combining a variety of different development tools in a way that sticks to the procedure. Furthermore, using the SAP2000 API, while expands greatly the computational power that lays before the engineer, raises the limitation of having to follow the SAP2000-way of arranging the analysis flow. In respect to the MPA procedure and taking the above into consideration, the approach that was selected in order to implement the analysis method concluded to an application providing the following features:

- Direct collaboration between the application and the SAP2000 suite, by making use of the dynamic data exchange capabilities that the API offers.
- SAP2000 model's loading and specification of the appropriate analysis parameters.
- Automated selection of the modes which are deemed as "important", allowing the user to interfere manually as needed.
- Automated creation of the necessary analysis cases, modal and non-linear, as well as using pre-run, user-specified cases.
- Visualization of intermediate steps' results, where applicable, in order to provide adequate information for the user's supervision of the procedure.
- Embedded calculation of the Design Spectrum required for the analysis, according to the EC8-Part 1 specifications [8], or making use of a spectrum data-file.
- Automated application of an appropriate combination rule, in order to calculate the analysis' final results – SRSS and CQC included.
- Visualization of the final deck deformed shape.
- Results' extraction to file, using plain text or comma-separated values format.

Finally, the implementation of the aforementioned was arranged as described by the following flowchart [Fig. 3]:

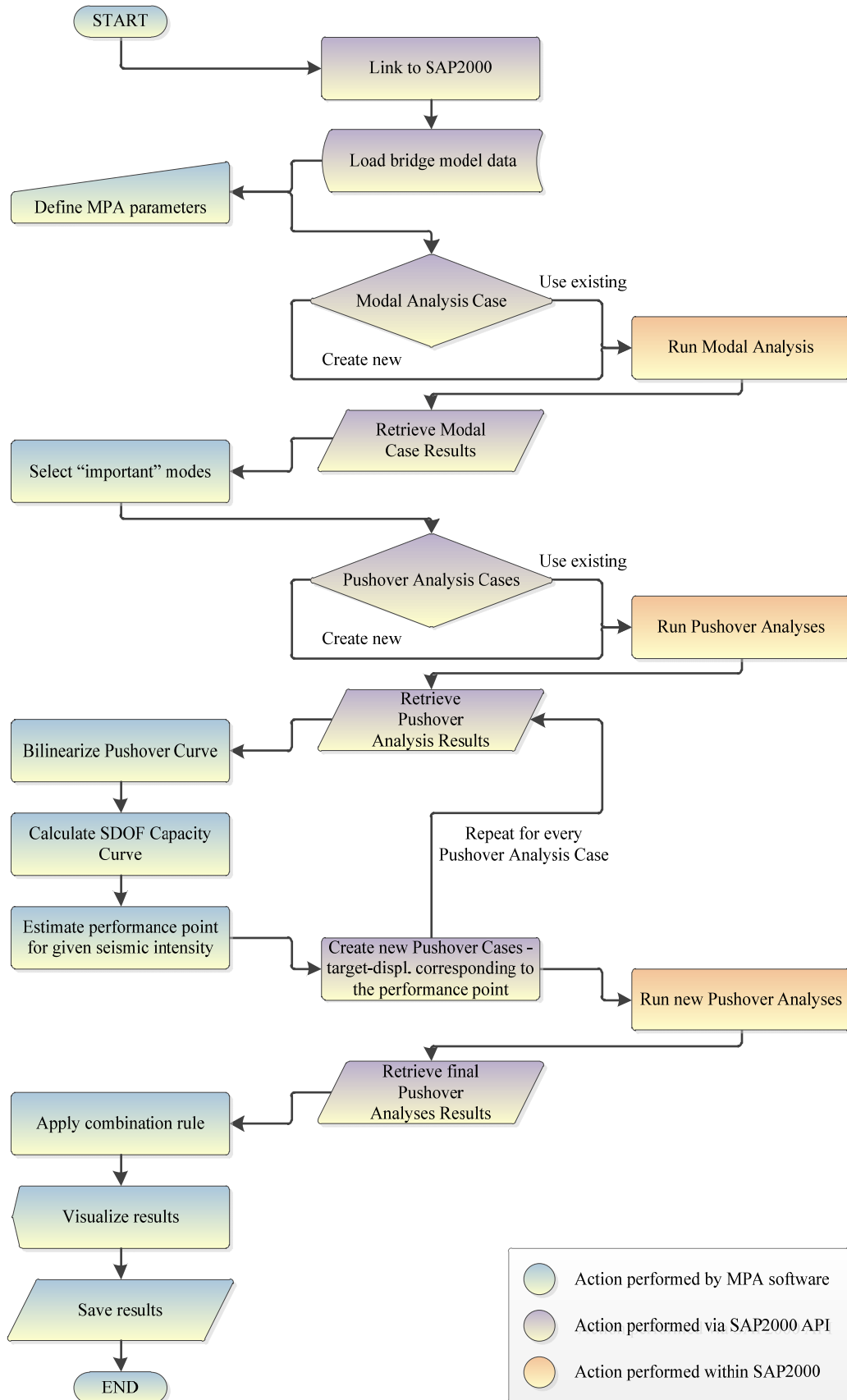


Figure 3: Modal Pushover Analysis software flowchart.



## 5 APPLICATION FOR THE CASE OF AN EXISTING BRIDGE

In order to investigate the accuracy and efficiency of the software developed around the MPA procedure, it was deemed appropriate to estimate the seismic assessment of an actual bridge structure, whose physical characteristics result to a reasonable contribution of higher modes. What follows is the description of the analysis procedure through the MPA software.

### 5.1 Description of studied bridge

The bridge selected for this task is a typical straight, three-span, symmetrical bridge, constructed of reinforcement concrete, that belongs to the highway network of EGNATIA ODOS A.E. (bridge T7). Its length sums up to 99.00m, divided into spans of 27.00 – 45.00 – 27.00 m, while the deck consists of a 10.00 m wide pre-stressed concrete box girder section. The deck has a slope of 7%, along the longitudinal direction, and it is supported by two solid piers of circular section, P1 and P2, of length 7.94 m and 9.34 m, accordingly, which are linked in a monolithic way, while each of the bridge's edges, A1 and A2, lay on two laminated elastomeric bearings [Fig. 4].

### 5.2 Preparation of the bridge model

Prior to performing any task within the application, it is necessary to have the structural model of the bridge properly prepared, in accordance to certain standards that will allow for its usage. This can be summarized into the following steps:

- Definition of the geometrical characteristics of the structure, within the SAP2000 application, including the applied sections, the required non-linear hinges etc.
- Creation of a new object group, named “DECK”, to which all the nodes, that the bridge's deck consists of, will be assigned.
- Definition of the gravity loads of the structure, in the form two Load Patterns named “G” and “Q”, referring to the constant and moving loads applied, accordingly.
- Subsequently, a new non-linear load case named “GRAV” is required in order for the gravity loads to be applied, which, however, can be created either manually or automatically via the MPA software's interface, at a later stage of the procedure.
- Saving the model into a new file, with the extension “.sdb” and terminating the execution of SAP2000.

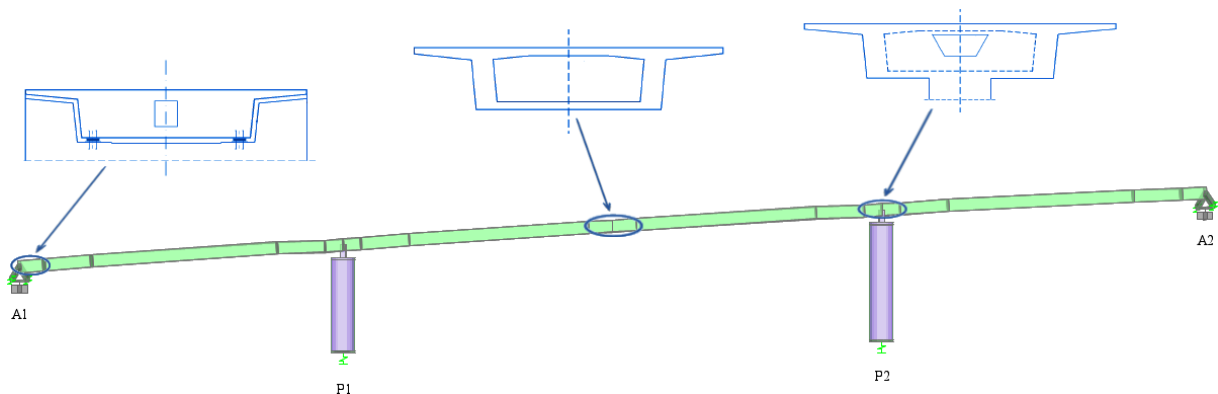


Figure 4: Three-span bridge model for the case of the T7 bridge along the Egnatia Highway in Greece.

After performing the steps described above, and in order to bring the model into a form able to be utilized, the file can be loaded into the MPA software. This is accomplished by running the application and using the menu “File → Open”, which will prompt for locating the file previously created. Following this, SAP2000 will be executed at the background of the operating system’s desktop and, via the API, the bridge model will be eventually loaded. When every parameter needed has been retrieved, the un-deformed shape of the bridge’s deck will be displayed at the center of the main window.

### 5.3 Definition of analysis parameters

Coming after the proper setup of the bridge model is the definition of the MPA parameters that is accomplished through the “Options” window, which emerges by selecting the sub-menu “Analysis → Options”. The parameters to be applied are grouped into tabs, in accordance with the intermediate stages of the MPA procedure. An effort has been made, in order to keep the analysis parameters required to a minimum, self-explanatory but adequate level.

For the bridge that was selected for testimonial reasons, the selected options defined in the “General” options tab will lead to a MPA along the “Y” directional “Degree Of Freedom” (DOF) of the bridge, as defined by SAP2000, using the “Advanced Solver” offered by the same analysis software and applying a “SRSS” combination rule at the end of the procedure, in order for the final displacement of the deck nodes to be estimated [Fig. 5a].

Subsequently, the parameters required for performing the modal analysis are defined as creating a new Modal Load Case, which will calculate the structure's natural modes up until the 99% of the participating mass ratio of the structure is reached, according to the pre-selected direction (Y). Among the modes that will be retrieved, those that sum up to a level of 97% will be selected as “important”, excluding those that participate less than 1%, in order to avoid computational instability during the remaining procedure [Fig. 5b].

Regarding the intermediate pushover analysis cases, for this particular bridge  $P - \Delta$  effects are excluded, while the monitoring point is defined, for each case, as the node that presents maximum modal displacement according to the corresponding mode. Additionally, the previously-defined Load Case “GRAV”, referring to the gravity loads, is selected as the starting point of each Pushover Analysis case [4][Fig. 6a].

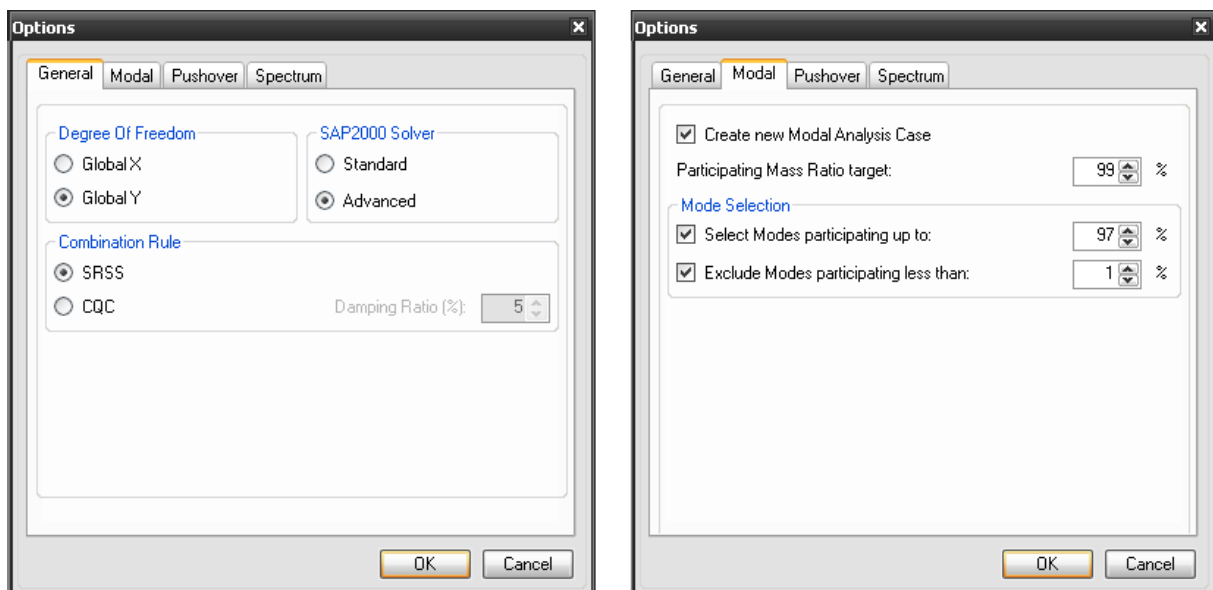


Figure 5: Definition of General and Modal Analysis parameters.

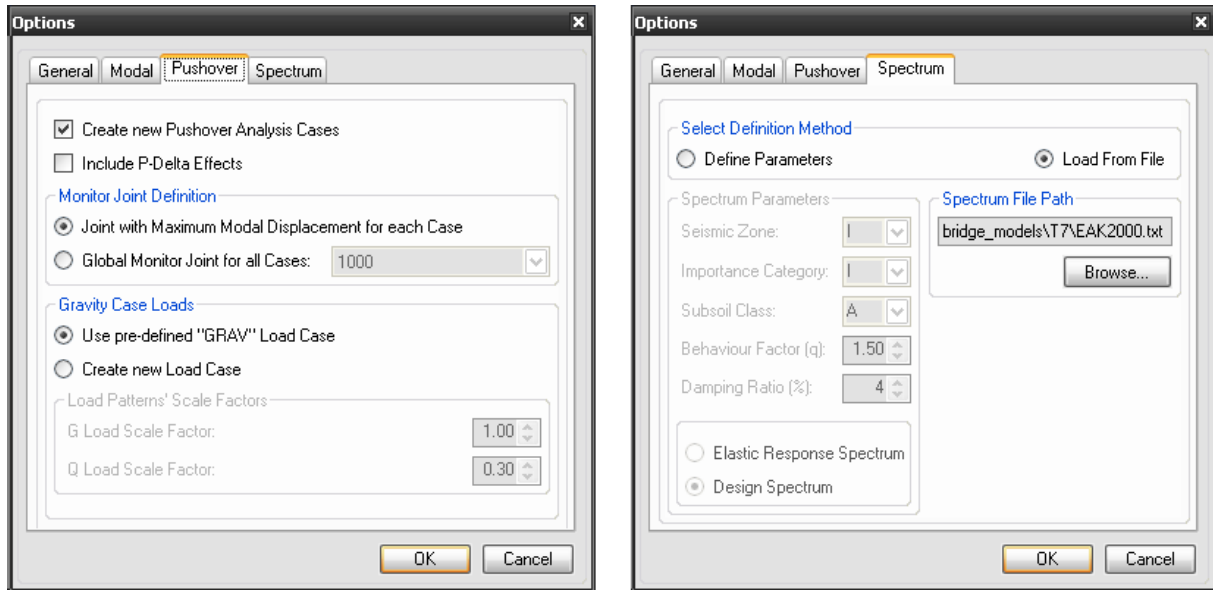


Figure 6: Definition of Pushover Analysis cases and Design Spectrum parameters.

Finally, using the “Spectrum” tab, an appropriate Design Spectrum data file is located on the system, which will be used in order to define the displacement demand for a given earthquake intensity. Alternatively, a spectrum following the EC8 specifications could be defined through the appropriate field that is provided [Fig. 6b].

#### 5.4 Performing the analysis

After the parameters’ definition is complete, selecting the menu “Analysis → Run → Modal Analysis” triggers the MPA procedure to begin, by firstly performing the Modal Analysis. With the completion of the analysis, the modal data of the bridge are retrieved and a list of the computed modes is displayed, allowing for the viewing of the mode-shapes through the main window’s graphics component. What comes next is the selection of the modes considered “important”, according to the user’s preference; this can be done in addition to the program’s prior automatic selection, which resulted, in this case, in pre-selecting the first three modes of the bridge, summing up to a percentage of 97.4% total mass contribution of the structure [Fig. 7].

When the desired modes have been selected, through the “Analysis → Run → Pushover Cases” sub-menu, the procedure continues to performing the separate Pushover Analysis Cases, one corresponding to each selected mode. This stage is the most time-consuming of the MPA procedure and it vastly depends on the bridge’s characteristics as well as on the “SAP2000 Solver” engine that was previously selected [Fig. 8].

By completing this step, the MPA software automatically proceeds to retrieving the pushover curves, for each case, their bi-linearization, according to the FEMA 356 [6] specifications, and the estimation of the peak displacement of the monitoring point. Subsequently, the desired node displacements are extracted and the analysis concludes by applying the combination rule that was selected, in this case a SRSS combination [Fig. 9].

The results of the MPA procedure, as well as the results of the intermediate non-linear static cases can be reviewed by the time the analysis is complete. By selecting the menu “View”, the user is capable of exploring the individual steps performed, which will provide useful data, adequate to indicate whether the analysis followed the desired or estimated route. Moreover, a graphical display of the deck’s final deformed shape, as assessed by the MPA software, is

available for visual evaluation of the analysis results. Finally, by selecting the sub-menu “File → Export Results”, the estimated displacement of the deck’s nodes can be saved in a file, using either a simple text format (.txt) or a “comma-separated values” format (.csv), which is suitable for inserting the extracted data in a spreadsheet application, should any further processing is considered necessary.

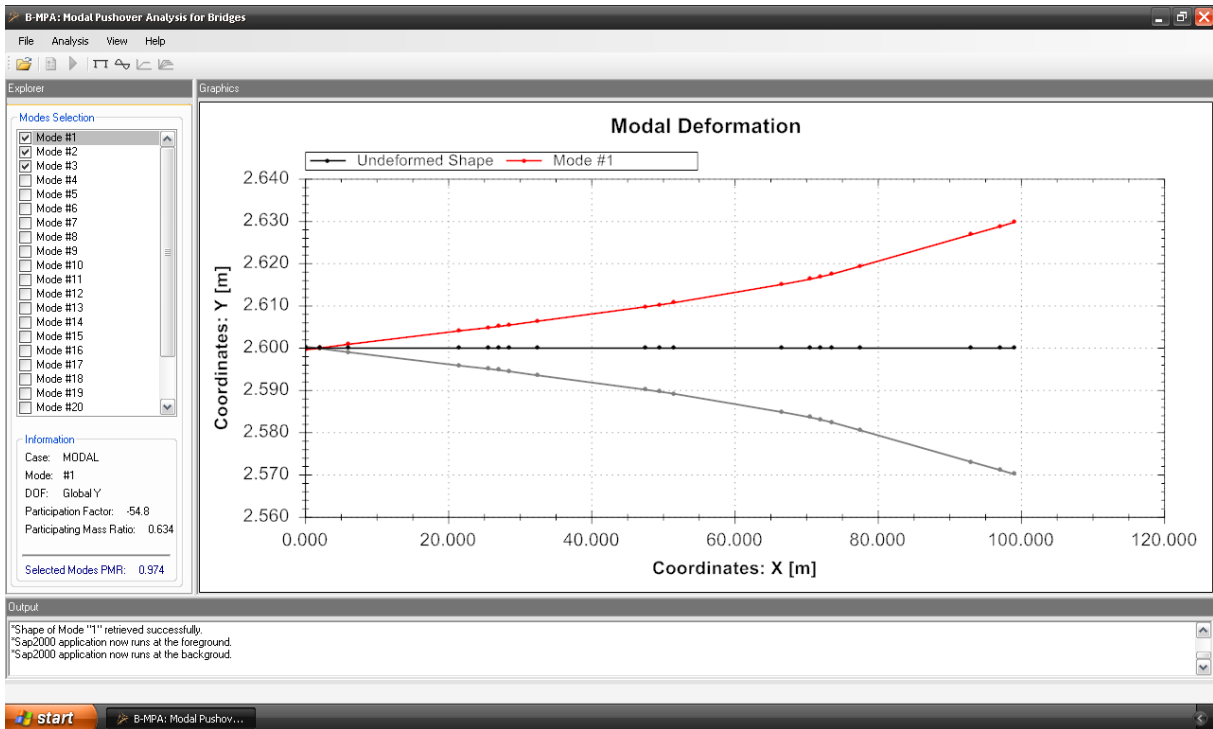


Figure 7: Selection of “important” modes, after the completion of Modal Analysis.

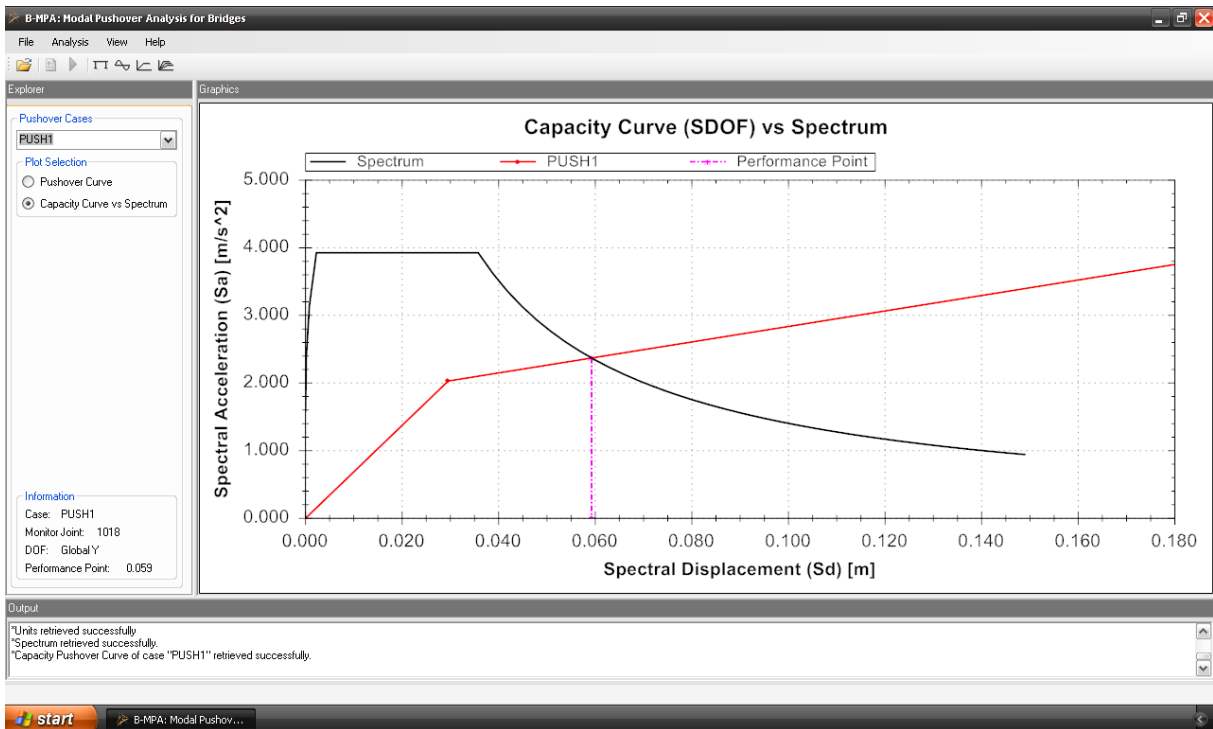


Figure 8: Estimation of the earthquake demand of the equivalent inelastic SDOF system.

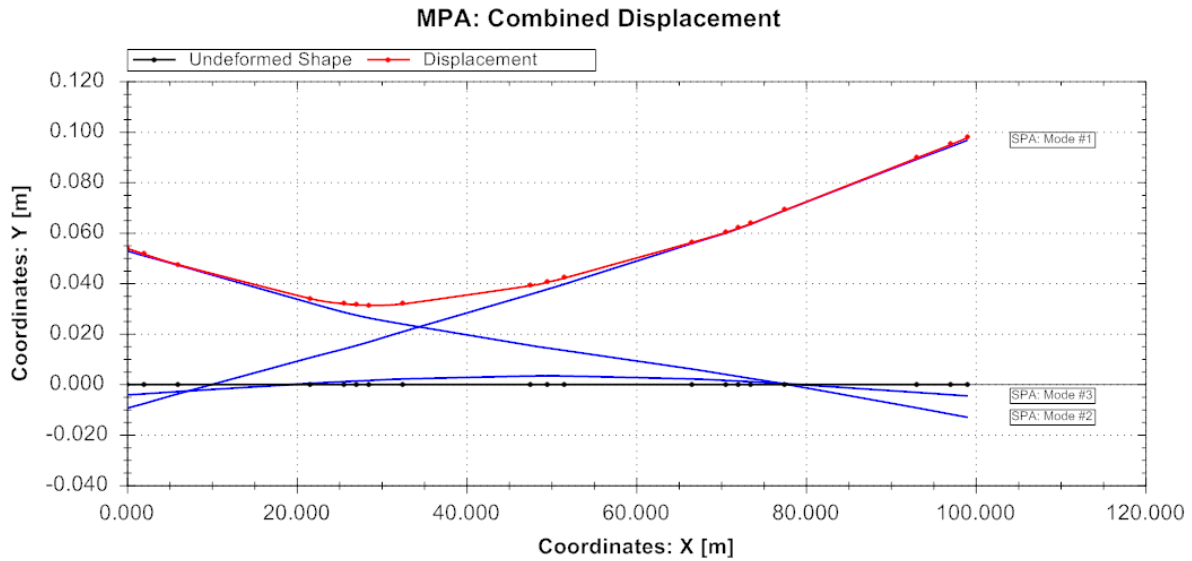


Figure 9: Modal Pushover Analysis software results visualization.

## 6 CONCLUSIONS

The aim herein was to introduce a new, effective approach to developing software for the seismic assessment of bridges, by implementing modal pushover analysis. The aforementioned was achieved by making use of some of the latest technology available in software development for engineers, such as the SAP2000 Application Programming Interface. In order to fulfil the targeted scope, a new application has been developed, capable of controlling the SAP2000 workflow through its API, while performs pre- and post-processing of the relative data. What is to be noted is that, as the use of generic programming tools has solely been made, the following conclusions are to be taken into account in virtually every case of modern procedures' implementation, through SAP2000 API, and are summarized as such:

- MPA proved a balanced example of a procedure strenuous enough, yet able to be divided to logical, repetitive subtasks, in order for being worthy of implementing via SAP2000 API. What is more, the benefits that occur by automating the procedure include the potential of improving faster and more efficiently its further, in-depth investigation.
- Developing software that is built around the SAP2000 platform, through its API, is considered feasible and, with most modern programming languages being supported, getting started with developing new earthquake engineering software should be a fast and effective task, at least for an engineer with reasonable programming skills.
- As the SAP2000 API is a generic programming tool able to control the internal structure of the analysis software that is bound to, programming style may need to be adapted to the API's guidelines, in order to allow for a productive development route. Moreover, prior experience to using the SAP2000 application is considered necessary, as the API's approach "mimics" the standard point-and-click procedure.
- Thorough consideration of every aspect, regarding the method's specifications, prior to commencing any engineering programming attempt, is crucial and can make the difference between easy-flowing and stalling development; setting clear and realistic goals during planning the software is essential, in order to achieve a well-balanced relationship

between time investment and productivity. Furthermore, forming collaborative development teams of experts, covering every scientific aspect encountered, is an effective the path to be taken, if possible, in order to maintain a flexible, and productive scheme.

- Finally, the importance of human supervision over the application of any scientific procedure, performed by computational tools, is not to be neglected, especially in cases that quantifying a problem's solution approach cannot be deemed adequate; the user's capability of parameterizing appropriately the MPA procedure, selecting applicable analysis variables, interfering with the software's pre-selected options and, above all, interpreting the analysis results to a meaningful perception are the most important factors of the analysis.

## 7 ACKNOWLEDGEMENTS

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