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BRIDGE-WIZARD: EXPERT SYSTEM FOR FINITE ELEMENT MODELING AND POST PROCESSING OF BRIDGE STRUCTURES

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Abstract. *Notwithstanding the abrupt increase in computational power and the subsequent advances in finite element analysis, many pre- and post-processing tasks still require a high level of engineering judgment while others remain significantly time consuming. Furthermore, commercial software, being inevitably of general purpose, does not always provide specific elements or constitutive laws tailored to the assessment of seismic response of structures. Powerful software for earthquake engineering has also been developed but, in most cases, it is equally lacking of a user-friendly interactive environment. Along these lines, the scope of this paper is to present the architecture and features of Bridge Wizard, an interactive front-end software for the seismic analysis and assessment of bridge structures, that takes advantage of a sophisticated, Open-Source software for Earthquake Engineering Simulation (OpenSees) to provide through its graphical user's interface: (a) conceptual assistance during the finite element analysis pre- and post-processing (b) finite element model development automations and (c) expert advice for modeling various bridge-specific issues that are key for the reliable prediction of structural response (such as boundary conditions, pier-deck connections, soil-structure interaction etc). It is deemed that the development of Bridge Wizard improves the efficiency and credibility of the finite element modeling developed, particularly for the case of complex bridge structures and gives the designer more control in critical modeling decisions affecting the overall system response.*

1. INTRODUCTION

Similarly to every other scientific area, the technological advancements of the last two decades have greatly affected structural engineering as well. The use of advanced finite element software and analysis methods has become a vital part of the structural engineer's every day work and it is even prescribed in modern seismic codes and design guidelines. Nonetheless, this major breakthrough has also triggered a number of second order sources of epistemic (modeling) uncertainty that tend to undermine to some extent the credibility of the structural design and assessment process as a whole. More precisely:

(a) General-purpose commercial finite element software is not tailored to the assessment of seismic response of structures. The inherent formulations are analytically articulate but inevitably generic, hence, requiring careful adaptation before simulating the salient features of structural response under earthquake loading. On the other hand, rigorous software has been developed during the last decades specifically for earthquake engineering purposes but still, in most cases, equally lacks of an illustrative and user-friendly interactive environment.

(b) Particularly for the case of long structures, such as bridges subject to seismic hazard, this problem is even more profound because, in contrast to ordinary buildings, the soil-structure system is significantly more extensive and coupled. Few software packages exist that could possibly combine, at equal rigor, all the features required for the advanced simulation of both the (non-linear) dynamic pier-foundation-subsoil [1], [2] and deck-abutment-embankment interaction [3–10], the shear deformation and flexural failure of reinforced concrete members (i.e. piers and piles) as well of any potential geometric non-linearity that commonly arises under large seismic forces (i.e. closure of gaps or joints at the deck level). The same applies to the selection of a realistic earthquake scenario and an appropriate set of representative ground motions [11–13] to be used for dynamic analysis, particularly considering that bridges are subject to multiple support excitation due to the spatially variable nature of seismic waves [14], [15].

(c) Modern seismic codes, acknowledge the progress made in numerical analysis and the present state-of-knowledge regarding the complex phenomena affecting the seismic response of bridges, but they only provide limited practical guidance on how to define the necessary level of modeling refinement, estimate the parameters involved and handling the corresponding uncertainty.

The side effect of the above three conditions is that the designer has a set of powerful numerical tools in hand and the necessary hardware to conduct extremely complex commutations in a limited amount of time, but at the same time, the epistemic uncertainty associated with his/her finite element modeling decisions remains disproportionally high. An additional issue is that, this uncertainty is also not easily quantified, an issue that is of paramount importance in the framework of Performance-Based Earthquake Engineering whose fundamental objective is to design structures to meet specific performance goals for specific probability levels.

To address the above limitations and link more efficiently state-of-the-art research with engineering practice, specialized software has been recently developed [16–18]. Along the same lines, a front-end software has also been developed and is presented herein that utilizes the widely used finite element program OpenSees (Open System for Earthquake Engineering Simulation; http://opensees.berkeley.edu) [19] as the core computational algorithm of a generalized expert system for the seismic analysis of bridges. The main features of the software are presented in the following sections.

2. SOFTWARE CONCEPT

Bridge Wizard is a windows-based application developed in Microsoft® Visual Studio as a stand-alone platform for facilitating the performance of static, modal and (linear/nonlinear) response history analysis of bridges. The main program is written in Visual Basic 2010 and is essentially translating in real time the user decisions into a Tool Command Language (tcl/tk) script. It also processes analysis results for visual illustration purposes. The software concept is based in five main principles, namely:

(a) A *wizard-like* process flow, restricting the user from navigating freely through the software. The user is requested to answer a uni-directional sequence of logical, qualitative and quantitative questions in order to describe the structural configuration of the bridge. Depending on the user response and decisions, the set of questions is modified accordingly.

(b) *Background automations* that minimize the time required for pre-processing by calling internal element generators and completing missing data without the aid of the user (described in detail in Section 4).

(c) *Expert suggestions* at every step of the simulation process for selecting the most appropriate modeling approach for each bridge sub-component (pier, abutment, deck, foundation) and accurately defining the material or analysis parameters involved.

(d) *State-of-the-art add-ons* that call and execute external Matlab scripts in the background.

(e) *An ad-hoc developed 3D visualization engine* for reviewing the structural system while generating the FE model or assessing the analysis results.

3. MODELING STRATEGY ADOPTED BY THE EXPERT SYSTEM

3.1. Pier and deck topology and constitutive behavior

The front-to-end analysis stages involve ten distinct steps, each one retrieving and storing into a large number of matrices, the information necessary to build the finite element model. The first three steps request information related to the general geometry of the Bridge, primarily the number and length of spans (Figure 2), the bridge curvature and elevation. In the following step, the user defines the (uniform or non-uniform along the length) deck properties by picking pre-defined, parameterized sections or drawing, point-by-point a more complex, hollow deck section. For cases that deck dimensions are varying with length, the user has the option to draw a finite number of separate sections at specific locations and the software will interpolate in between to define the section properties at all intermediate points (Figure 3). The coordinates of the deck center of gravity and subsequently of the 3D beam elements used are also computed based on the deck section and the bridge curvature and elevation. The deck is by default considered linear elastic under earthquake loading unless otherwise defined by the user. Regarding element discretization, the deck is initially divided into 20 elements within each span and a post-analysis check verifies that further mesh refinement by a factor of 2 does not modify the dominant natural frequencies (i.e., the ones that overall activate more than 80% of the modal mass) by more than 2%. In case that the prescribed accuracy threshold values are not satisfied, meshing refinement and successive analyses are repeated in the background until convergence is met.

Pier section properties are defined through a similar process. In the case that nonlinear response is sought, the user is navigated to define concrete and steel material properties. Both

Eurocode 8 compliant materials and user-defined constitutive laws are provided (Figure 4). Piers are then modeled with fiber finite elements and non-linear constitutive laws (Kent & Park model for unconfined concrete, Park et al. for confined concrete, bilinear stress-strain relationship for reinforcing steel).

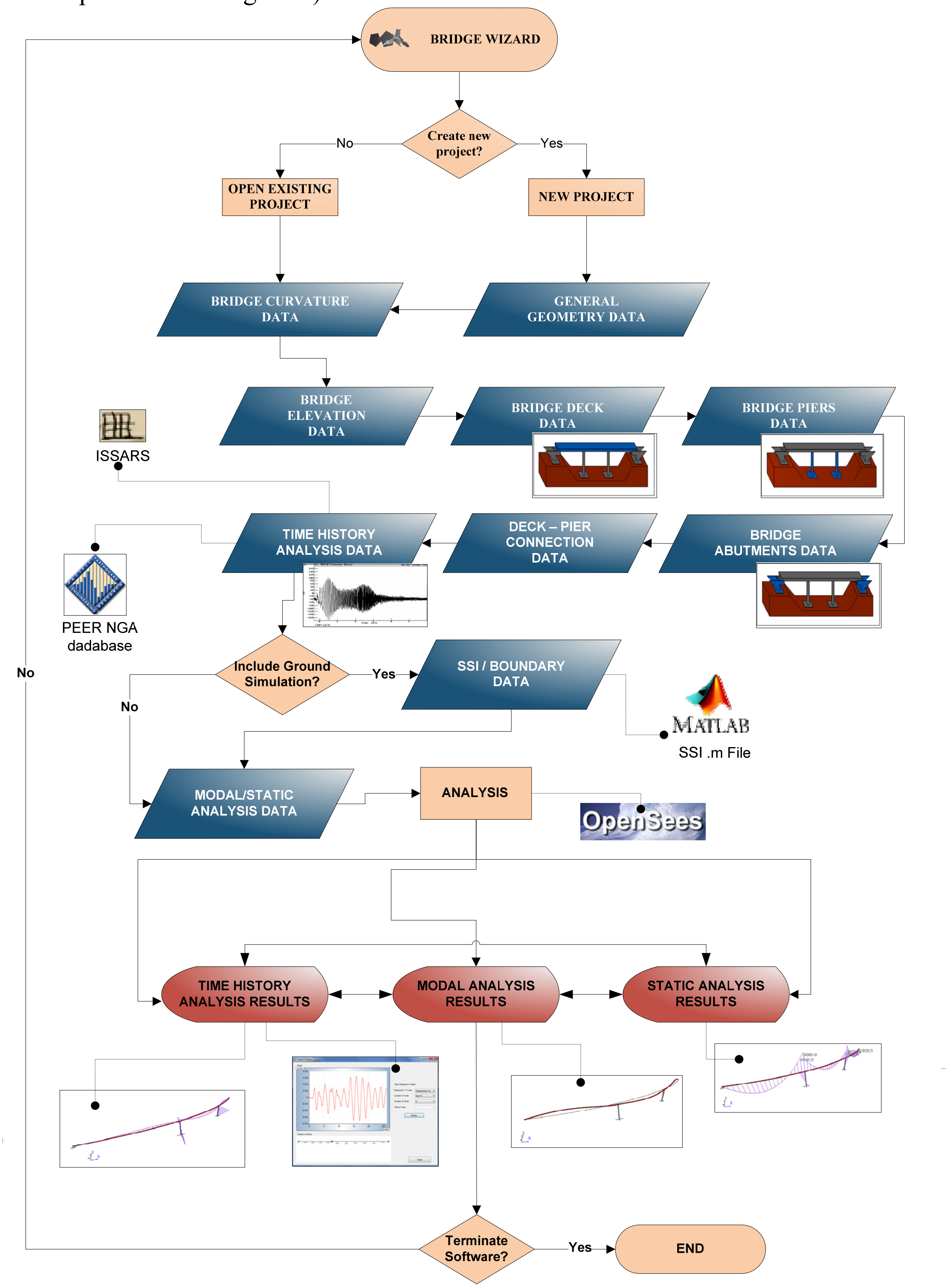

Figure 1: Program flow

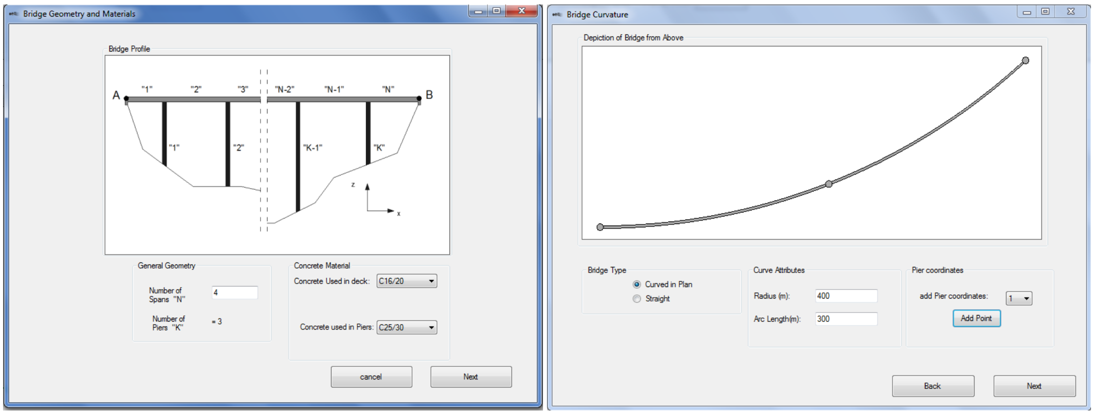

Figure 2. Bridge geometry input

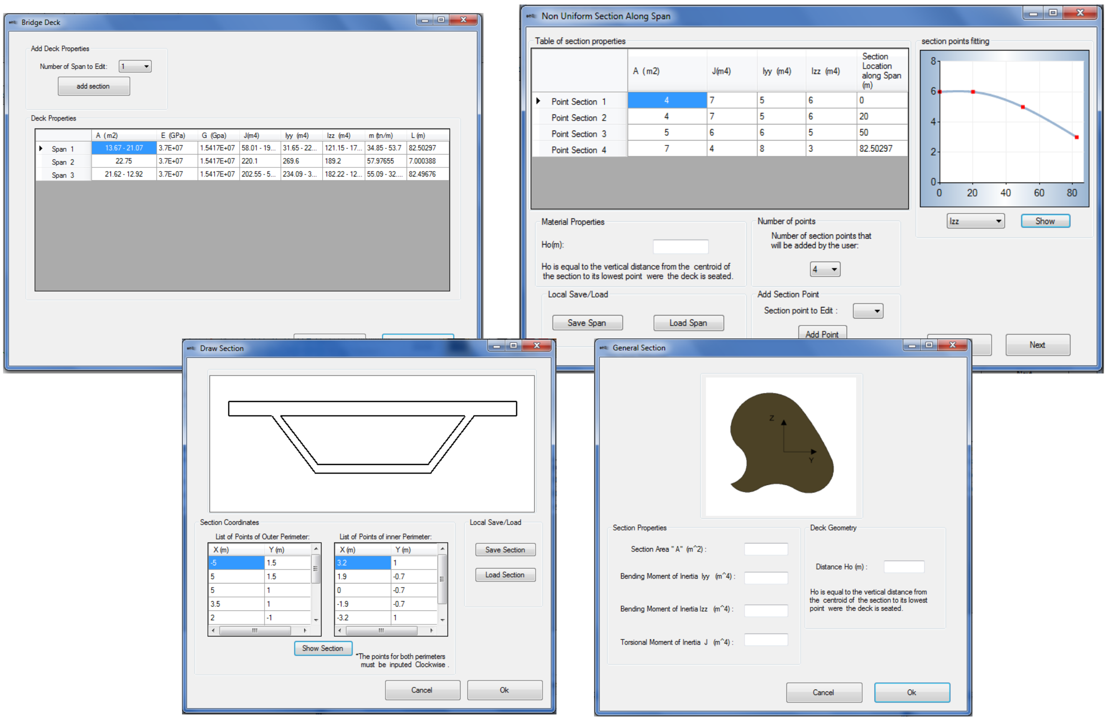

Figure 3. Definition and interpolation of deck section properties along the bridge length.

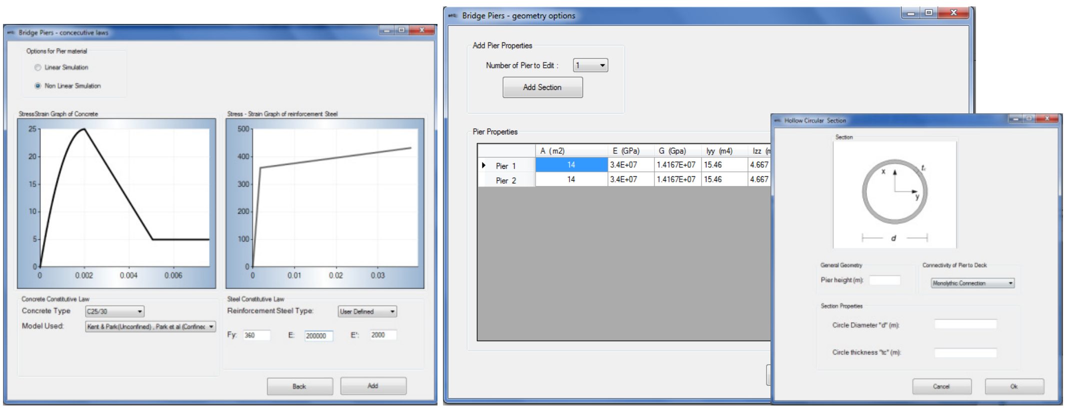

Figure 4. Definition of material properties

3.2 Pier-deck and abutment-deck connection

The deck can be supported on the piers either monolithically or through bearings utilizing the “elastomeric bearing element” of OpenSees and following a linear, bi-linear or tri-linear force-displacement relationship. The number of bearings, input by the user, defines the properties of the single, equivalent bearing element introduced in the finite element model by geometrically coupling the translational and rotational bearing stiffness along each degree of freedom. For the abutments in particular, the option is also given to release certain degrees of freedom or prescribe gaps along the two principal horizontal directions (Figure 5).

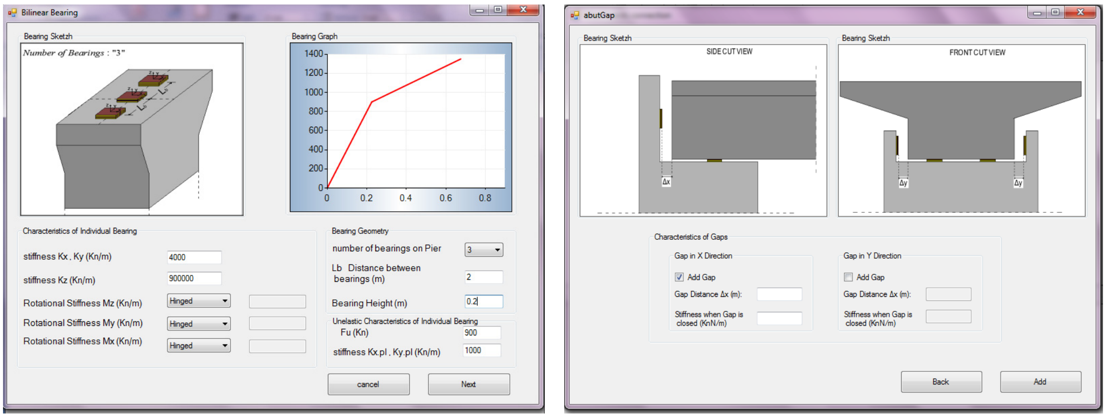

Figure 5: Bilinear force-displacement rule for elastomeric bearings (left) and consideration of deck-abutment gaps along the two principal directions.

3.3 Boundary conditions and soil-structure interaction

Unless the user specifies point fixity, the 6-DOF pier foundation dynamic impedance matrix is computed by calling an external Matlab script. Soil properties and geometry of foundation is required both for the case of shallow footings and *nxm* pile groups according to the literature [20–23]. In particular, the complex dynamic interaction factors α_{ij}^{dyn} are calculated for all modes of vibration (α_z for vertical, α_{uH} for horizontal and $\alpha_{\theta M}$, $\alpha_{\theta H}$ for rocking interaction). By assuming that interaction factors involving rocking vibration ($a_{\theta H}$, $a_{\theta M}$) are taken equal to zero, the static stiffness matrix of the pile group is expressed in the following form:

$$\begin{bmatrix} K_{HH}^{st} & K_{HM}^{st} \\ K_{MH}^{st} & K_{MM}^{st} \end{bmatrix}_{group} = \frac{1}{(f_{uH}^{st} \cdot f_{\theta M}^{st} - f_{MH}^{st\,2})} \begin{bmatrix} f_{\theta M}^{st} & -f_{uM}^{st} \\ -f_{\theta H}^{st} & f_{uH}^{st} \cdot \sum_{i=1}^{n}\sum_{j=1}^{m} a_{uH_{ij}} \end{bmatrix} \tag{2}$$

and the dynamic stiffness matrix of the pile group is then written similarly by introducing the damping coefficients $\zeta_{HH}, \zeta_{MH}, \zeta_{MM}$:

$$\begin{bmatrix} K_{HH}^{dyn} & K_{HM}^{dyn} \\ K_{MH}^{dyn} & K_{MM}^{dyn} \end{bmatrix}_{group} = \begin{bmatrix} f_{\theta M}^{st} \cdot (nxm) \cdot (1+2\zeta_{HH}(\omega)i)/\Delta & -f_{uM}^{st} \cdot (nxm) \cdot (1+2\zeta_{MH}(\omega)i)/\Delta \\ -f_{\theta H}^{st} \cdot (nxm) \cdot (1+2\zeta_{HM}(\omega)i)/\Delta & f_{MM}^{st} \cdot (nxm) \cdot (1+2\zeta_{MM}(\omega)i)/\Delta \end{bmatrix} \tag{3}$$

where $\Delta = (f_{uH}^{st} \cdot \sum_{i=1}^{n}\sum_{j=1}^{m} a_{uH_{ij}} \cdot f_{\theta M}^{st} - f_{uM}^{st\,2})$. The predominant frequency of the motion, required for the computations is defined implicitly by computing the mean period (T_m), a weighting the amplitudes over a specified range of the Fourier Amplitude Spectrum [24]:

$$T_m = \frac{1}{f_m} = \frac{\sum c_i^2 \cdot \frac{1}{f_i}}{\sum c_i^2} \qquad \text{for } 0.25\ Hz \leq f_i \leq 20\ Hz \text{ with } \Delta f \leq 0.05\ Hz \tag{4}$$

where c_i and f_i are the Fourier amplitudes and frequencies, respectively.

Abutment-embankment interaction can be optionally taken into consideration by introducing linear springs according to Caltrans [25], the most widely used expression currently provided in modern seismic codes. In particular, for fill materials that comply with the Caltrans Standard Specifications requirements, the initial longitudinal stiffness of the embankment can be taken equal to 28.7 kN/mm per meter of the width of the wall. In case of other fill materials, the value of 14.35kN/mm/m is to be used. The ultimate abutment load is then limited by a maximum passive resistance of 239kPa. Given the limitations that arise from the use of the particular expression, the user has also the option to utilize more refined force-displacement (P-y) relationships that consider the contribution of the abutment foundation prior to the backwall failure [26].

3.4 Analysis control and post-processing

Having described the structural configuration in maximum possible detail, the parameters for static, modal and (linear/ non-linear) response history analysis are then defined. Ground motions can be imported in the PEER-NGA [27] format for all three components. The software is also capable of importing records selected by an external Matlab-based software ISSARS [28] according to specific seismological, geotechnical and structural criteria. Having accomplished the problem description, a tcl/tk file is automatically generated to be used in OpenSees. The particular *.tcl input file consists of four distinct parts controlling the finite element model topology, the mechanical properties, the analysis method and the desirable post processing output data. OpenSees is automatically called and executed in the software background before the software switches to the post-processing visualization engine (Figure 6). Deformed shapes and eigenmodes are illustrated graphically while the user may easily generate plots of the variation of all the critical engineering demand parameters with time. Projects can also be saved for future reference and modification. Validation with alternative finite element software SAP2000 [29] for the case of real bridge structures [30] has shown satisfactory agreement in the predicted natural frequencies and time-variant action effects that did not exceed 5% (the average deviation found was of the order of 2%).

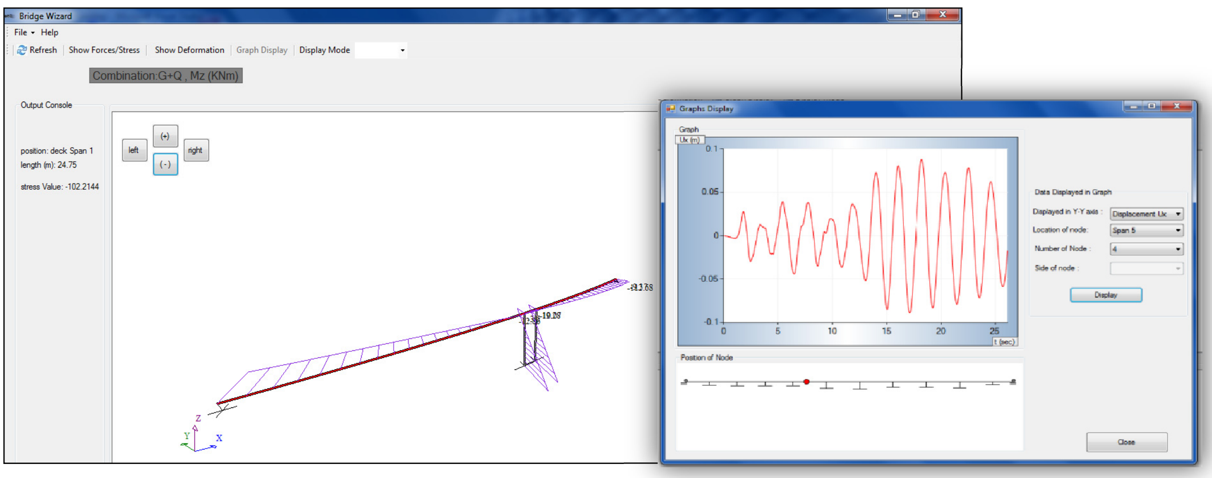

Figure 6: 3D visualization engine for post-processing the analysis results

4. CONCLUSIONS

This paper presents the development of an expert system aiming to (a) eliminate the time required for the numerical analysis of bridges using Opensees (b) improve the credibility of the FEM pre-processing by automatically generating critical model parts and (c) introduce, in an efficient and user-friendly manner, state-of-the art knowledge regarding the seismic response of bridges that the designers are often reluctant to consider during numerical analysis. The software is currently freely available at www.asextos.net/software and is currently under further development.

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