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A computer interface for the asynchronous seismic excitation of bridges simulated in ANSYS

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Summary

During earthquakes, it is expected that bridge structures are subjected to excitation that is non-uniform along their longitudinal axis in terms of amplitude, frequency content and arrival time, a fact primarily attributed to the wave arrival delay, their loss of coherency and the effect of local site conditions. Although considerable research has been carried out over the last twenty years in all the aforementioned directions, the knowledge gained has only partially been reflected on modern seismic code provisions and design procedures due to the significant complexity in predicting the spatially variable earthquake wavefield. As a result, and due the major advances in numerical analysis tools, the FE models developed are often disproportionally refined compared to the earthquake loading assumptions made. The scope of this paper, is to present a modular scheme for integrating state-of-the-art knowledge in earthquake, structural and geotechnical engineering into the dynamic analysis of bridges, by coupling through the APDL scripting language, a comprehensive algorithm for the generation of multiple support excitation scenarios, a module complying with the (simplified) latest Eurocode 8 provisions and the finite element development environment of ANSYS. It is concluded that not only the aforementioned link is feasible and effective, but also the use of more realistic earthquake ground motion patterns can potentially reveal significant aspects of the dynamic response of a bridge structure while the assumption of synchronous excitation can strongly underestimate the imposed seismic demand.

Keywords

Seismic analysis, bridges, ANSYS, APDL, software development

1. Introduction

From all the parameters that define the non-linear dynamic response of complex structures such as bridges, the earthquake ground motion has by far the highest level of uncertainty. The last three decades, different approaches, methodologies and tools have been utilized to deal with this uncertainty and put it in a framework that can be predicted and quantified, thus uniformly interpreted by the practicing engineers and the scientific community. Along these lines, the extensive use of actual, refined or code-defined response spectra and the utilization of natural or artifficial accelerograms that correspond to different soil and seismotechtonic conditions is a precious source of information regarding the potential excitation of bridges, which when combined with the increasingly enhanced capabilities of specialised inelastic dynamic analysis software, provides a very good estimate of the expected seismic excitation and response of bridge structures. Nevertheless, the uniform application of a unique response spectrum or a single accelerogram along the whole structure is not necessarily valid for extended structures since, as recent research has shown, seismic motion can be not only significantly different at each pier support point, but also induce forces and deformations that could not be predicted with the assumption of synchronous excitation. The sources of spatial and temporal variations of seismic motion are well known [1] and can be summarized as the effect of a) waves travelling at a finite velocity, so that their arrival at each support point is out of phase b) loss of coherency in terms of statistical dependence, that is, loss of signals 'similarity' due to multiple reflections, refractions and superpositioning of the incident seismic waves that occur during propagation and c) local soil conditions especially for cases that the soil media through which seismic waves propagate vary significantly. All these parameters may substantially affect the actual peak ground acceleration and frequency content of the motion that arrives at the foundation of the successive piers. Additionally, although it is often neglected, the potential filtering at the foundation level that results from the relative flexibility of the foundation-soil system components is another parameter that contributes to the extent of variability of the motions which are actually imposed at each separate pier.

Despite the major practical interest for generating such motions, the considerable research carried out over the last years, has not yet been implemented into detailed guidelines in modern seismic codes, a fact that can be primarily attributed to the significant complexity and the multi-parametric nature of the particular problem. As a result, the potential effect of asynchronous excitation is only partially considered and most modern codes deal with the problem solely and rather indirectly, on the basis of seating length provisions, such as the US Standard Specifications for Highways and Transportation Bridges (AASHTO) [2], ATC-32 [3], and the 2002 Japanese Design Specifications for Highway Bridges [4]. Eurocode 8-Part 2 for Bridges Design [5] in its latest revision on the other hand, has acknowledge the importance of the phenomenon and is the only seismic code worldwide that provides a clear and detailed framework for considering the effect of spatial variability of ground motion in bridge design, through both a simplified and an analytical approach, the latter being introduced as an 'informative' annex. However, recent research has indicated that under certain circumstances (for instance bridges with significant curvature in plan or supported on soils considerably varying with length) the EC8 simplified apporach can underestimate the anticipated dynamic response of the structure [6].

Moreover, it has been shown [7], [8], [9], [10] that when the structure is multiply excited, it can be stated that it is essentially 'obstructed' from vibrating at its fundamental mode, while higher modes are excited, a fact that leads to a rather unpredictable modification of the dynamic (elastic or inelastic) response of the superstructure. It has been shown that these oscilation characteristics cannot be easily assessed in advance, nor be captured with the use of a single, 'average' response spectrum or a single accelerogram in the frequency and time domain respectively. As a result the problem is strongly case-dependent and the necessity of further investigation is widely recognized by expert committees [11], [12] while its practical interest is highlighted by the fact that asynchronous excitation has been investigated during the design of major technical projects such as the Metsovitikos [13] and the Rion-Antirion bridge [14] in Greece, a highly active seismic region.

Still though, the gap between Finite Element modelling complexity and earthquake loading refinement is wide and in case of long bridges constructed on a complex geotechnical and geotechtonic environment the advanced capabilities of the FE software is often unbalanced with the accuracy of the assumptions made with respect to the ground motion excitation scenarios. Along these lines, the scope of this paper is to present a computer interace developed with the aim to integrate the widely used commercial FE code ANSYS [15] with:

- the new version of the computer code ASING (Asynchronous Support Input Generator) [16] for the synthesis of spatially varying ground motions that account for wave arrival delay, incoherency and (site-induced) amplifiaction as well as for soil-structure interaction and
- the computer program EC8-SSVAB (Eurocode 8-based Simplified Spatial Variability Analysis of Bridges) [9] that calculates the imposed displacement sets according to the new EC8 provisions.

With the use of visual object-oriented programming and the powerful APDL (ANSYS Parametric Design Language) scripting language [17], existing experience and state-of-the-art knowledge in earthquake engineering and asynchronous excitation analysis can be reflected into the FE models developed in ANSYS, thus significantly enhance analysis and design reliability.

2. An object-oriented apprach for coupling the asynchronous motion analysis modules

Based on an Object-Oriented Programming approach (OOP) [18], [19] the problem is discretised into separate modules which are hierarchically deployed and communicate internally. As explained above, a comprehensive software for accounting for spatial variability is used as the primary (core) module to generate spatially variable accelerograms at each support point, a second module computes the EC8-prescribed imposed displacement sets and a third module acts as an interface to transmit the excitation data to the FE model developed with ANSYS using the APDL language. The interface also executes the analyses required and returns selective analysis results for processing, evaluation and design optimization. With the use of this simple in principle, yet effective scheme, the computer interface integrates thousands of lines of source code aiming at the generation of realistic seismic input into the FE model at minimum computational cost and without the requirement of extensive scientific background regarding wave propagation theory.

The software structure is illustrated in Fig. 1, where the blue frames represent Application Program Interfaces (API) developed using Visual Basic and communicating with the ANSYS code, VB being one of the last generation programming languages that offers object-oriented programming and integrated computing and visualization capabilities. Clearly, a number of alternative programming frameworks (.NET, C++ or Matlab among others) could be equally effective, provided that the algorithm of the physical problem had been structured and clarified.

2.1. Desription of the core spatial variability algorithm

The core algorithm for the synthesis of artificial spatially variable earthquake ground motions at the supports of a bridge is shown in Fig. 2. The scope of the comprehensive approach presented, is the development of a user-friendly parametric analysis scheme, as a means to identify potential bridge sensitivity to multiple-support excitation. This is achieved by incorporating and uncoupling all important issues (asynchronous motion, site effects, soil-structure-interaction) within the context of a general concept for the inelastic analysis of bridges in the time domain. The methodology adopted and the analytical tool developed for its implementation are presented in detail elsewhere [16]. The main idea, is to first generate synthetic time histories, distinct at each support point (piers and abutments), through a refined spatial variability model which accounts for wave passage effect (arrival delay of non-vertical seismic waves), loss of coherency (coherency being a frequency dependent measure of the statistical dependence between seismic waves that decays with distance as waves are refracted, reflected and superimposed) and the effect of local soil conditions in terms of amplitude and frequency content of earthquake ground motion.

Next, further modification of motion in the frequency domain allows for the consideration of kinematic interaction between soil and the foundation piles, that is, filtering of seismic motion due to the inherent difficulty of the foundation to vibrate according to the imposed displacement field. The derived motion can then be used as the asynchronous input to the bridge structure which is assumed to be supported on (different at each support point) Beam-on-Dynamic-Winkler-Spring (BDWS) systems [20] - also internally calculated by the program. The corresponding dynamic impedance matrices for the foundation-soil system at each pier support location are derived for all horizontal, rocking and coupled modes of vibration. In addition, for the rotational stiffness, a non-linear moment-rotation relationship is proposed in order to combine the rotational compliance of the foundation with a lumped plasticity model for the RC section that accounts for the plastic rotations caused by yielding at the pier base. The aforementioned comprehensive approach has been implemented into the fully parameterised computer code ASING (Asynchronous Support Input Generator) [16] that results to different time histories and linear/non-linear spring-dashpot systems at all support points of a given bridge.

In the general case, the program allows the performance of inelastic dynamic analysis of the superstructure with the use of any commercial finite element code, without the requirement to use Finite Elements also for the simulation of the complex (and often prone to errors) coupling of wave propagation, site response and soil-structure interaction. Consequently, the study of the bridge sensitivity to the above phenomena can be investigated using the artificial records generated and, if necessary, a Monte Carlo or directional simulation scheme. In the latest version of the code presented herein (Fig. 3) apart from the enhanced visualization tools, the spatially varying motions can be exported to ANSYS as imposed displacement time histories along the bridge supports.

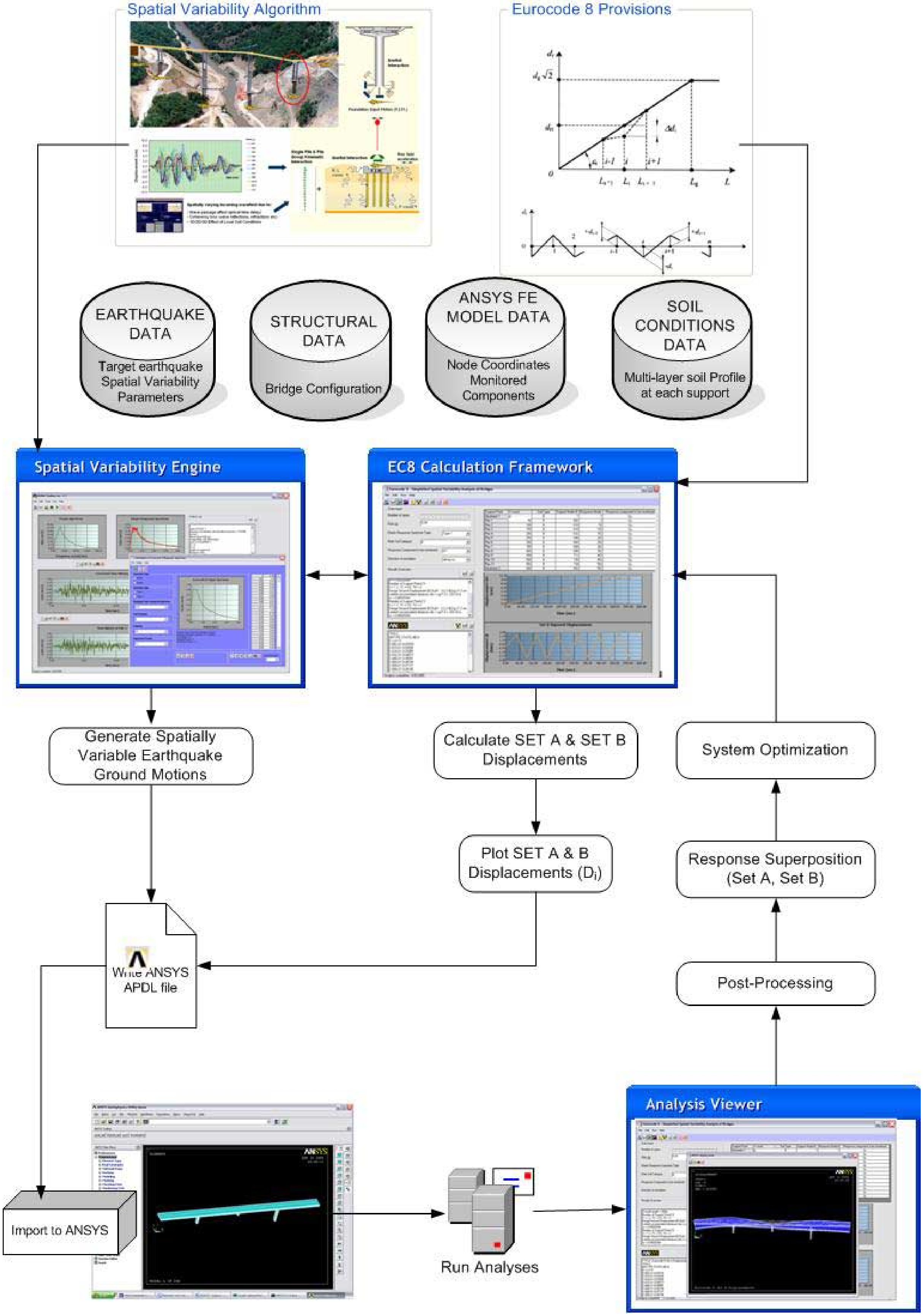


Figure 1: Overview of the software structure

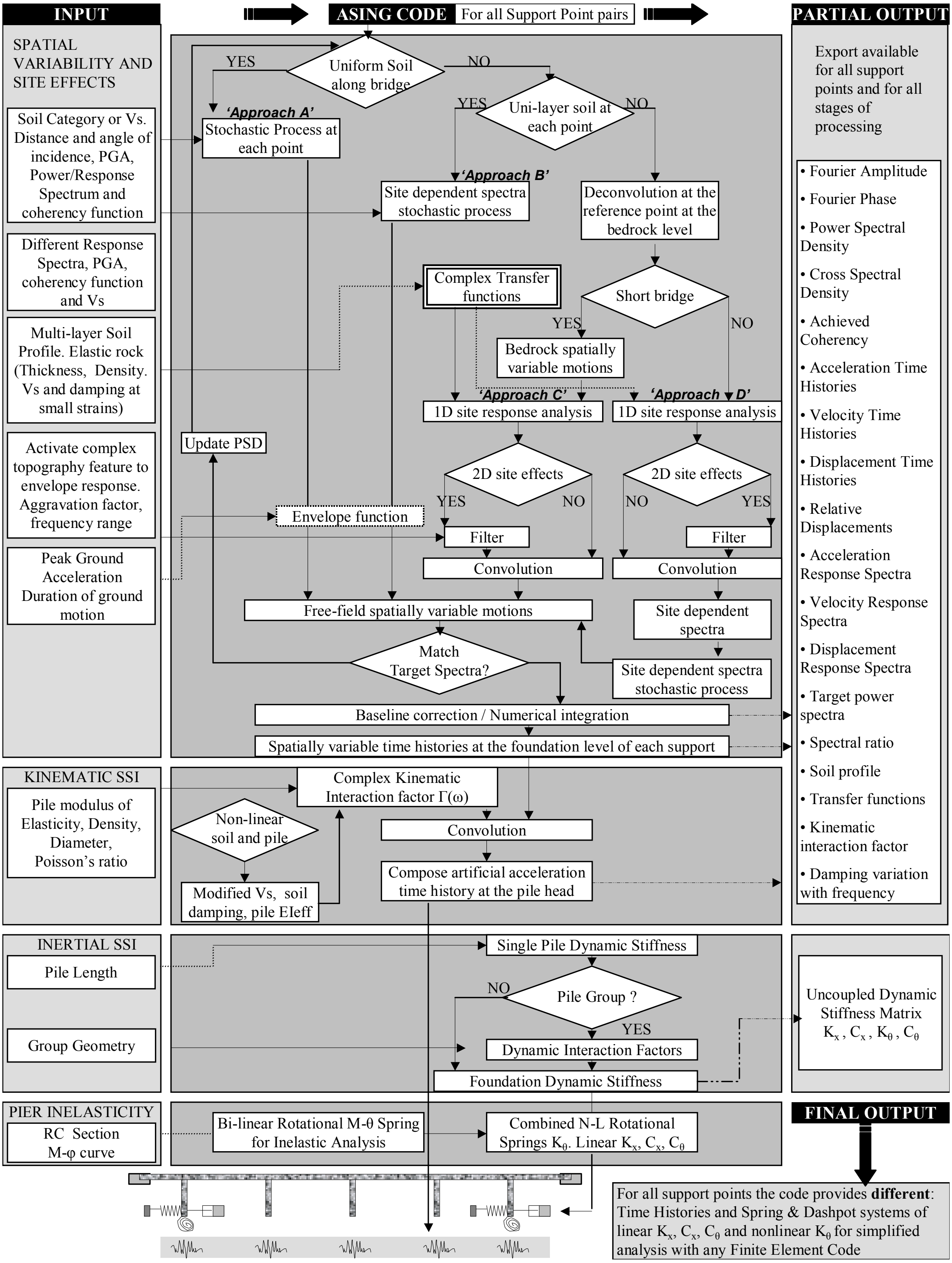


Figure 2: Overview of the Asynchronous Support Input Generator structure (ASING, [9], [11])

Moreover, the generated APDL file automatically controls all the multiple support excitation analysis parameters, thus linking the ASING engine to the FE model. This is achieved through the computer interface where the FE model–related data are declared (i.e. model geometry, response components sought and coordinates of the nodes to be monitored). The asynchronous excitation results can then be assessed with the use of the viewer module.

2.2 Programming the EC8-Part 2 provisions

Additionally to the core spatial variability algorithm presented above, it was deemed useful to develop a complementary (although simpler) program that incorporates all the new Eurocode 8 provisions in order to facilitate the application of the method for long bridges where the code-prescribed hand calculation becomes time consuming, as well as the execution of parametric analyses. In particular, Part 2 of Eurocode 8, in its latest (prENV) version, prescribes that during design, an adequate (albeit simplified) model should be implemented in order to account for the propagatory character of the seismic waves, as well as for the progressive loss of correlation between motions at different locations that arises from both propagation and potential differences in the mechanical properties of the (non-uniform) soil media. In order to address the previous requirements, a simplified approach is proposed for the estimation of the pseudo-static effects, involving sets of appropriate displacements that are imposed statically at the supports of the bridge deck. From the numerous combinations of relative support vibration, two cases are identified as the most critical: a) all piers are subjected to ground displacements of the same sign (but not the same magnitude) and b) the two piers in each pair of two successive piers are displaced in opposite directions. According to these two deformation cases (called Set A and Set B), the structure is subjected to pseudo-static forces, whose effects are then combined with those that result from a typical uniform excitation analysis using the SRSS (square root of the sum of squares) rule. The basic steps of the procedure are summarized in [6].

To tackle the above calculation, the computer program EC8-SSVAB (Eurocode 8-based Simplified Spatial Variability Analysis of Bridges) was developed that allows the quick and accurate analysis of the structure due to the derived Set A and Set B support displacements as they are calculated according to EC8 and are described in [6]. A snapshot of the code is illustrated in Fig. 4. As previously, an export file is generated with the use of APDL and the calculated displacements are imposed at all the corresponding bridge supports of the original finite element developed in ANSYS. Again, this import facility is easily performed, independently of the complexity of the FE model created, while the analysis is also automatically performed through the generated APDL commands. As a result, the (user defined) monitored response components resulting from the Set A and Set B analysis (typically transverse or longitudinal pier top displacements, or bending moments along the specified axis) are derived. The deformed shape of the FE model is then loaded (Fig. 5) and the monitored action effects obtained by ANSYS can then be superimposed with the effects of the uniform excitation analysis according to the Eurocode 8 provisions.

3. Design Procedures and Implications

Depending on the specific structure, the foundation and soil properties and the design requirements, the analysis framework described above can be summarised into the following steps:

1. Development of the Finite Element model of the bridge structure under study using ANSYS.
2. Use of the EC8-SSVAB module to compute the (simplified) code-prescribed displacement sets, execution of the analysis and assessment of the potential (pseudo-static) effect of spatial variability of ground motion on the bridge response.
3. For cases of complex structural configurations (i.e. bridge curvature in plan), significantly varying soil conditions, overall length that exceeds 300m [10] and/or evidence of higher mode excitation due to spatial variability, use of the ASING module for the generation of the artificial wavefield. Automatic execution of the analysis and assessment of the modifications on the dynamic response.
4. Evaluation of the overall bridge performance through a parametric scheme using the asynchronous motion scenarios for a set of well selected target earthquake characteristics in terms of frequency content, amplitude, duration and angle of incidence.

5. In case that the structure is found sensitive to multiple support excitation, performance of design optimization.

By applying the above methodology for the case of 20 different bridge configurations as well as for two real, already built bridges, i.e. the Talübergang Warth Bridge in Vienna [21] and the (curved in plan) Krystallopigi bridge in northern Greece [22] (Fig. 6), it is observed that under certain circumstances, the imposed demand can be increased by a factor of 2 in the extreme case [22], but most importantly, its distribution among piers cannot be represented by any 'standard' unique accelerogram dynamic excitation. The latter is a strong indication that for important bridges, a well designed, case-dependent implementation of the software structure and analysis scheme presented herein could significantly contribute towards a more realistic representation of the dynamic response of bridges under earthquake loading.

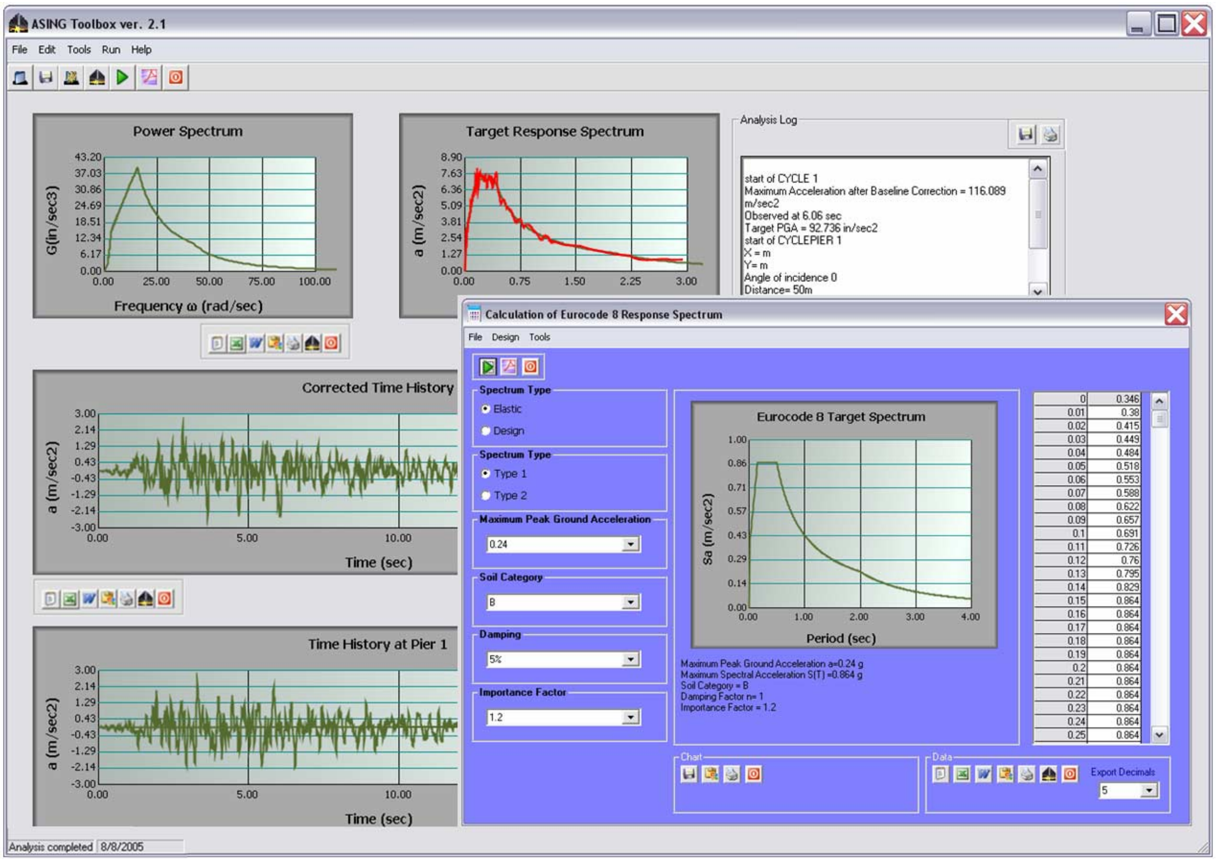
4. Advantages of integrating asynchronous seismic excitation algorithms with ANSYS

In addition to the above argurment on the importance of considering asynchronous excitation in the design and assessment of particular bridges, the proposed software framework itself, that couples the (otherwise stand–alone) procedures is considered to exhibit a certain number of advantages regarding the reliability of the overall analysis process. In particular, it can be stated that with the implementation of the above scheme and the utilization of the developed modules:

- a specialised and detailed algorithm for the generation of spatially variable motions is integrated into ANSYS and the bridge model developed is analysed with the use of advanced earthquake motion scenarios that account for complex and coupled wave propagation phenomena.
- the vast experience gained so far in earthquake engineering fields and especially, site response and wave propagation can be directly implemented into FE analysis without any additional simulation or computational effort.
- a good balance is achieved between FE modelling complexity and ground motion refinement, thus leading to more realistic numerical simulations.
- such a modular procedure for developing more realistic loading cases could be easily extended to other engineering disciplines and/or different loading sources (i.e. wind, blast, traffic loading etc).
- by grouping the functionalities into different modules of clarified key responsibilities, the overall structure can be broken down into stand-alone procedures at any stage of design, while individual researchers and software developers can extend the particular modules continuously and independently of each other. Similar applications can be built much faster, and be easily maintained.
- APDL, a very powerful programming environment (but with inevitably limited visual capabilities) is used exactly at its field of application (i.e. as the advanced command interpreter to ANSYS) while the efficient and user-friendly interface of a VB platform is used for calculation and APDL lines generation. As a result, the implementation of a computer interface leads to the automatic preparation of the APDL file easier, significantly faster and most importantly, without the requirement of previous programming or APDL knowledge by the potential user.
- Parametric analyses are performed quickly and effortlessly, a fact that it is of paramount importance due to the multi-parametric nature of the response of a bridge to asynchronous excitation.
- The procedure and the tools developed can be used even in the framework of advanced hybrid computational-experimental investigation of complex structures which is the current state-of-research worldwide [23].

Conclusions

In this paper, an object-oriented framework for integrating available computer programs for the generation of more realistic eartquake ground motions is presented, by coupling, through the APDL scripting language, a comprehensive algorithm for the generation of multiple support excitation scenarios, a module complying with the (simplified) latest Eurocode 8 provisions and the finite element development environment of ANSYS. It is suggested that for particular cases, the implementation of the developed scheme can reveal potential structural weakness and highlight conditions under which the assumption of synchronous bridge excitation could lead to the significant underestimation of both displacements and member forces.



Analysis Log

```
start of CYCLE 1
Maximum Acceleration after Baseline Correction = 116.089
m/sec2
Observed at 6.06 sec
Target PGA = 92.736 in/sec2
start of CYCLEPIER 1
X = m
Y= m
Angle of incidence 0
Distance= 50m
```

Spectrum Type
- ● Elastic
- ○ Design

Spectrum Type
- ● Type 1
- ○ Type 2

Maximum Peak Ground Acceleration 0.24

Soil Category B

Damping 5%

Importance Factor 1.2

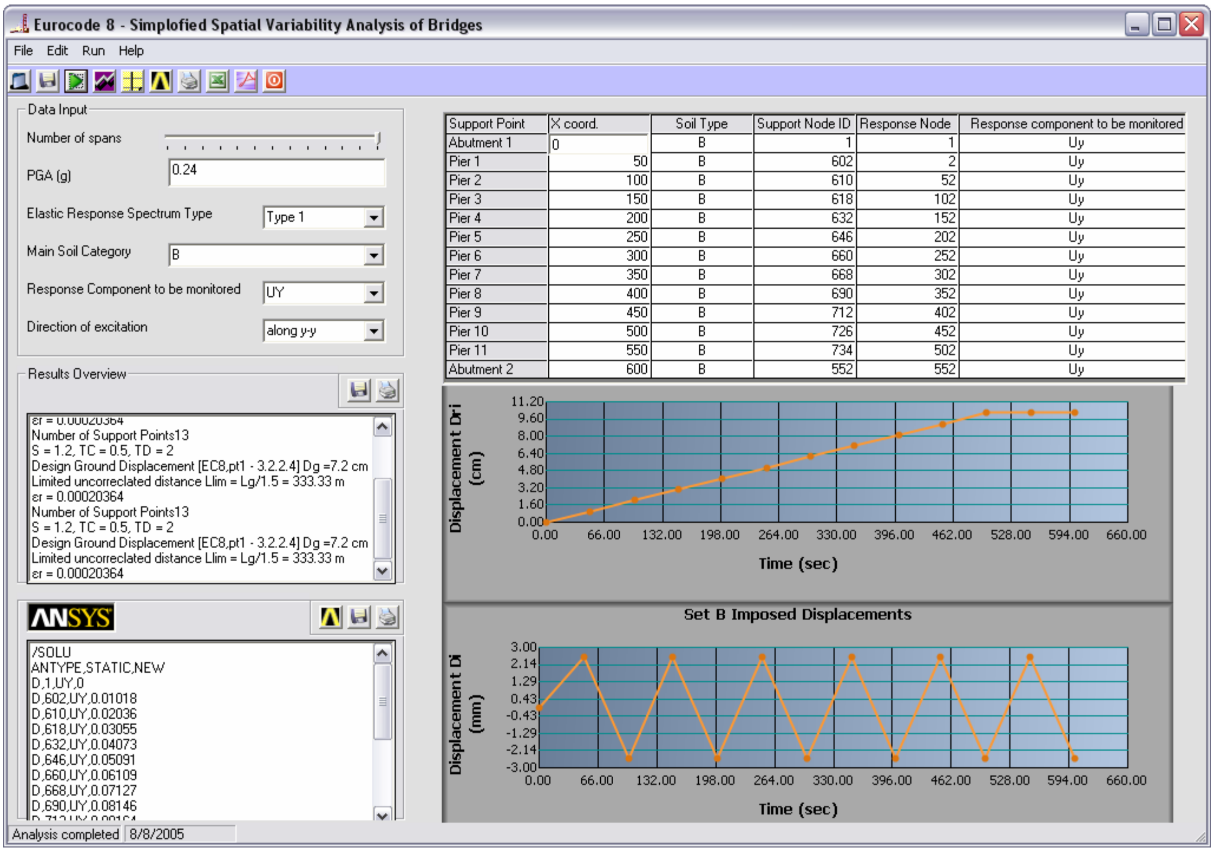
Maximum Peak Ground Acceleration a=0.24 g
Maximum Spectral Acceleration S(T) =0.864 g
Soil Category = B
Damping Factor n= 1
Importance Factor = 1.2

0	0.346
0.01	0.38
0.02	0.415
0.03	0.449
0.04	0.484
0.05	0.518
0.06	0.553
0.07	0.588
0.08	0.622
0.09	0.657
0.1	0.691
0.11	0.726
0.12	0.76
0.13	0.795
0.14	0.829
0.15	0.864
0.16	0.864
0.17	0.864
0.18	0.864
0.19	0.864
0.2	0.864
0.21	0.864
0.22	0.864
0.23	0.864
0.24	0.864
0.25	0.864

Export Decimals 5

Analysis completed 8/8/2005

Figure 3: User interface for Spatial Variability Analysis of Bridges (ASING, ver. 2.1)



Data Input

Number of spans

PGA (g) 0.24

Elastic Response Spectrum Type: Type 1

Main Soil Category: B

Response Component to be monitored: UY

Direction of excitation: along y-y

Support Point	X coord.	Soil Type	Support Node ID	Response Node	Response component to be monitored
Abutment 1	0	B	1	1	Uy
Pier 1	50	B	602	2	Uy
Pier 2	100	B	610	52	Uy
Pier 3	150	B	618	102	Uy
Pier 4	200	B	632	152	Uy
Pier 5	250	B	646	202	Uy
Pier 6	300	B	660	252	Uy
Pier 7	350	B	668	302	Uy
Pier 8	400	B	690	352	Uy
Pier 9	450	B	712	402	Uy
Pier 10	500	B	726	452	Uy
Pier 11	550	B	734	502	Uy
Abutment 2	600	B	552	552	Uy

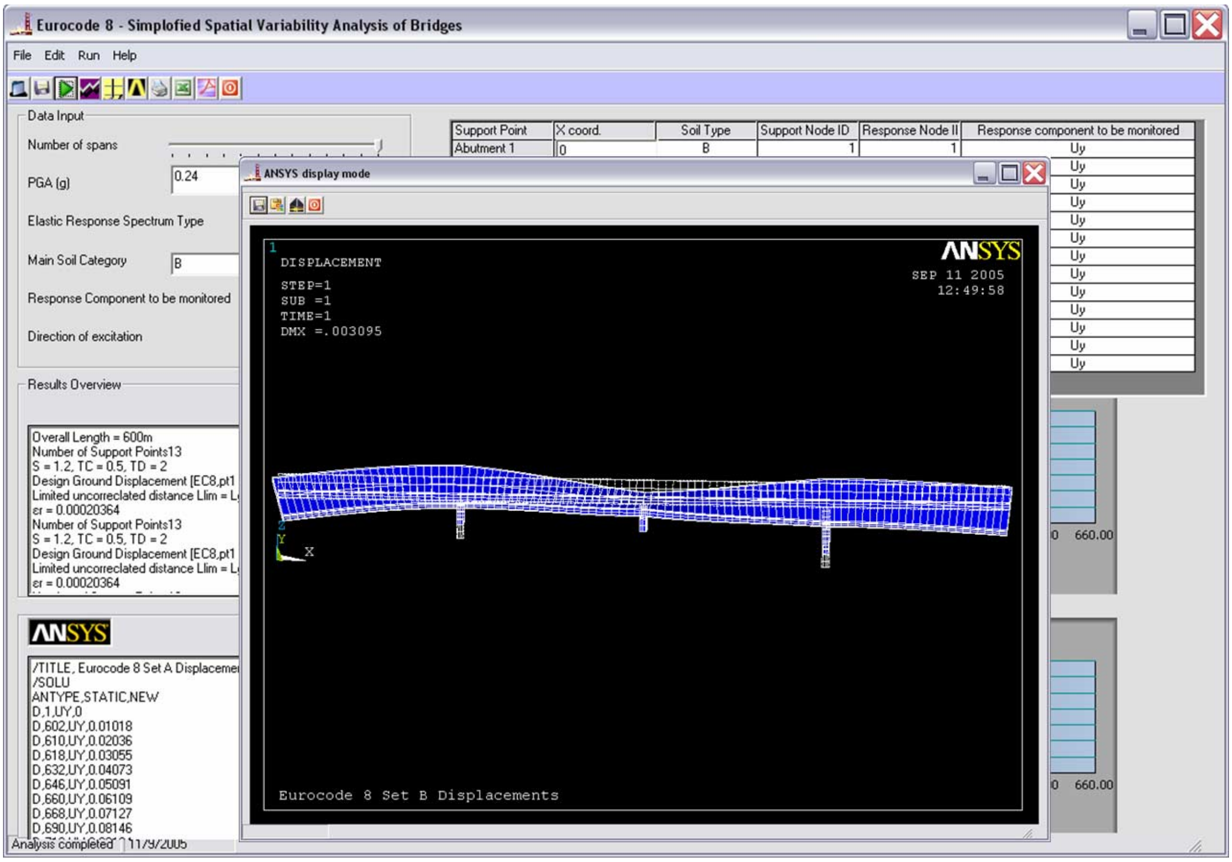
Results Overview

```
Number of Support Points13
S = 1.2, TC = 0.5, TD = 2
Design Ground Displacement [EC8,pt1 - 3.2.2.4] Dg =7.2 cm
Limited uncorreclated distance Llim = Lg/1.5 = 333.33 m
εr = 0.00020364
Number of Support Points13
S = 1.2, TC = 0.5, TD = 2
Design Ground Displacement [EC8,pt1 - 3.2.2.4] Dg =7.2 cm
Limited uncorreclated distance Llim = Lg/1.5 = 333.33 m
εr = 0.00020364
```

```
/SOLU
ANTYPE,STATIC,NEW
D,1,UY,0
D,602,UY,0.01018
D,610,UY,0.02036
D,618,UY,0.03055
D,632,UY,0.04073
D,646,UY,0.05091
D,660,UY,0.06109
D,668,UY,0.07127
D,690,UY,0.08146
```

Analysis completed 8/8/2005

Figure 4: User interface for Spatial Variability Analysis of Bridges (EC8 – SSVAB module)



Data Input

Number of spans

PGA (g): 0.24

Elastic Response Spectrum Type

Main Soil Category: B

Response Component to be monitored

Direction of excitation

Results Overview

Overall Length = 600m
Number of Support Points13
S = 1.2, TC = 0.5, TD = 2
Design Ground Displacement [EC8,pt1
Limited uncorreclated distance Llim = L
εr = 0.00020364
Number of Support Points13
S = 1.2, TC = 0.5, TD = 2
Design Ground Displacement [EC8,pt1
Limited uncorreclated distance Llim = L
εr = 0.00020364

```
/TITLE, Eurocode 8 Set A Displaceme
/SOLU
ANTYPE,STATIC,NEW
D,1,UY,0
D,602,UY,0.01018
D,610,UY,0.02036
D,618,UY,0.03055
D,632,UY,0.04073
D,646,UY,0.05091
D,660,UY,0.06109
D,668,UY,0.07127
D,690,UY,0.08146
```

Analysis completed 11/9/2005

Support Point	X coord.	Soil Type	Support Node ID	Response Node II	Response component to be monitored
Abutment 1	0	B	1	1	Uy
					Uy
					Uy
					Uy
					Uy
					Uy
					Uy
					Uy
					Uy
					Uy
					Uy
					Uy
					Uy

```
1
DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =.003095
```

SEP 11 2005
12:49:58

Eurocode 8 Set B Displacements

Figure 5: Visualization of the bridge deformed shape when subjected to the EC8 Set B prescribed imposed displacements

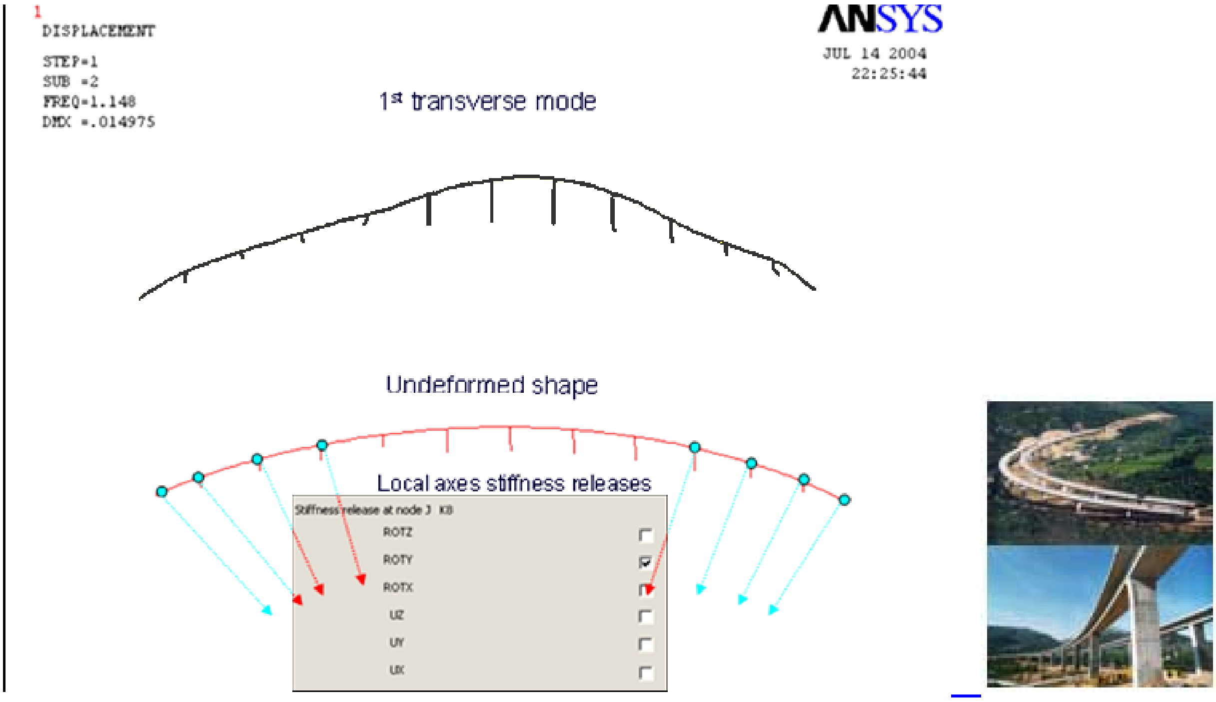


Figure 6: Application to the Krystallopigi Bridge

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