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An Intercontinental Hybrid Simulation Experiment For The purpose of Seismic Assessment of a Three-span R/C Bridge

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ABSTRACT

This paper presents the challenges encountered in preparing and conducting hybrid experiments between E.U., U.S. and Canada in the framework of an FP7-funded European project focusing on the study of seismic soil-structure interaction effects in bridge structures. The test involved partners located on both sides of the Atlantic; each one assigned a numerical or a physical module of the sub-structured bridge. More precisely, the seismic response of a recently built, 99m long, three-span, reinforced concrete bridge is assessed, after sub-structuring it into five structural components (modules); four of them being numerically analyzed in computers located in the cities of Thessaloniki (Greece), Patras (Greece), Urbana-Champaign. IL (U.S.) and Toronto (Canada) while an elastomeric bearing was physically tested in Patras (Greece). The results of the hybrid experiment, the challenges met during all stages of the campaign, as well as the feasibility, robustness and repetitiveness of the intercontinental hybrid simulation test are presented and critically discussed.

Introduction

Full scale testing is a realistic way to evaluate the behavior of structures under earthquake loading, as well as to verify the effectiveness of the design or retrofy methods for new or existing earthquake-resistant structures, respectively. Notwithstanding the increasing capabilities of the structural engineering laboratories, factors related to space limitation, equipment capacity, scaling issues and the high operational and maintenance cost of the facilities themselves, often set limits to the problems that can be studied through physical experimentation. On the other hand, the advanced analytical and numerical models that are currently available, have their own limitations in capturing the actual complex seismic behavior of the structures and the phenomena

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studied. This is even more pronounced in case of complex structural behavior (such as strong material or geometrical non-linearities), non-conventional loading or boundary conditions, or significant soil-structure interaction phenomena. As a result, the analysis capabilities are inevitably limited to solving a specific set of relatively narrow problems primarily at a component level.

Given the above merits and drawbacks of the (experimental and numerical) seismic performance evaluation methods, a chalenging concept has been introduced for multi-site, on-line, computer-controlled integrated testing-analysis of complex systems. Depending on the number of the locations used for the implementation of a hybrid test, the simulation technique can be characterized as local or geographically distributed. This multi-site, Real Time Hybrid Simulation (RTHS) approach has already been developed in the United States for the assessment of complex interacting systems. It is supported by National Science Foundation, through the Network for Earthquake Engineering Simulation (NEES, www.nees.org) scheme [1]–[4] and it aims to raise the limitations related to the laboratory capacities. Within this framework, there is no need for either using a single experimental facility or for satisfying physical proximity for the multiple subcomponents. The dynamic response of full scale specimens that are discretized into sub-structures is properly controlled via purpose-specific coordination software. Two such specialized software platforms exist to date, i.e. the OpenFresco [5-6] and SimCor [7]. The components (analytical, experimental or a combination of both) are treated on different networked computers and, can thus be located anywhere in the world. Another major advantage of hybrid simulation is that it removes a large source of uncertainty compared to pure numerical simulations, by replacing structural elements with complex non-linear behavior with physical specimens tested on the laboratory test bed. Apparently, drawbacks also exist and are related to the necessity for in-depth knowledge of specialized experimental and analytical tools as well as for considerable programming effort and computational cost.

The same concept has also been successfully applied [8] for the coordination of purely numerical analysis modules (where no physical testing is performed, in contrast to the hybrid simulation application). This, so called, "*multi-platform simulation*" permits the appropriate selection and combination of different analysis packages, thus enabling the concurrent use of the most sophisticated constitutive laws, element types and features of each package for each corresponding part of the system (i.e. abutments, superstructure and supporting pile groups for instance in the case of a long bridge), depending on the foreseen inelastic material behavior, level and nature of the seismic forces and the geometry of the particular problem. As for the case of Hybrid Simulation though, the computational cost and level of expertise is relatively high compared to a conventional all-inclusive simulation package, plus, its efficiency is network-dependent.

EXCHANGE-SSI (EXperimental & Computational Hybrid Assessment Network for Ground-motion Excited, Soil-Structure Interaction systems) is an EU-funded, 7th Framework Program research project, within which, a number of earthquake engineering centers in Europe and the U.S. collaborate on the application of distributed, hybrid or multi-platform experimentation for the study of seismic soil-structure interaction effects in bridge structures. Although this geographically distributed analysis and hybrid experimentation is currently well established in the U.S. as well as within few specialized centers in Europe (primarily U.K.-NEES, JRC) and in Taiwan, the challenge here was twofold: (a) to successfully run intercontinental hybrid experiments between European and North American institutions in a fully repetitive manner by overcoming the barrier of the network connection latency introduced while transmitting data through the Atlantic, (b) to physically test a rate-dependent bridge component (i.e., bearing), as opposed to the most common case of a reinforced concrete or a steel structural member and (c) to study a comprehensive, recently constructed, bridge structure. To the best of the author's knowledge, the only similar, successful intercontinental hybrid simulation effort is the test between UC Berkeley and University of Kassel in Germany [11], involving a single component.

As the communication time step is the most critical parameter for a successful hybrid experiment, the campaign was set up carefully, initiating from a series of preparatory (numerical-only), intercontinental, multi-platform, multi-partner analyses, as well as, hybrid experiments localized at the University of Patras [9]. All partners were gradually involved in different stages and in different roles until the performance was optimized in terms of communication time. Ultimately, the bridge was divided into five structural components (modules), each one being analyzed using specific software in a different computer stations (Fig. 1) located at Aristotle University of Thessaloniki (AUTH), University of Patras (UPAT), University of Naples/Sannio (USAN), Geodynamique et Structure (GDS), University of Illinois at Urbana-Champaign (UIUC) and University of Toronto (UoT). At the final stage, the numerical module representing the left bridge bearing was replaced by the specimen and was physically tested at the University of Patras while numerical modules were established at AUTH, UPAT, UIUC and UoT. In both cases (i.e., multi-platform and hybrid experimentation) the analysis coordinator SimCor [10], developed at the University of Illinois at Urbana-Champaign was used. The description of the series of the experiments conducted, from the geographically distributed multi-platform simulation to the intercontinental hybrid experiment, as well as the limitations, challenges met and future developments are discussed in the following.

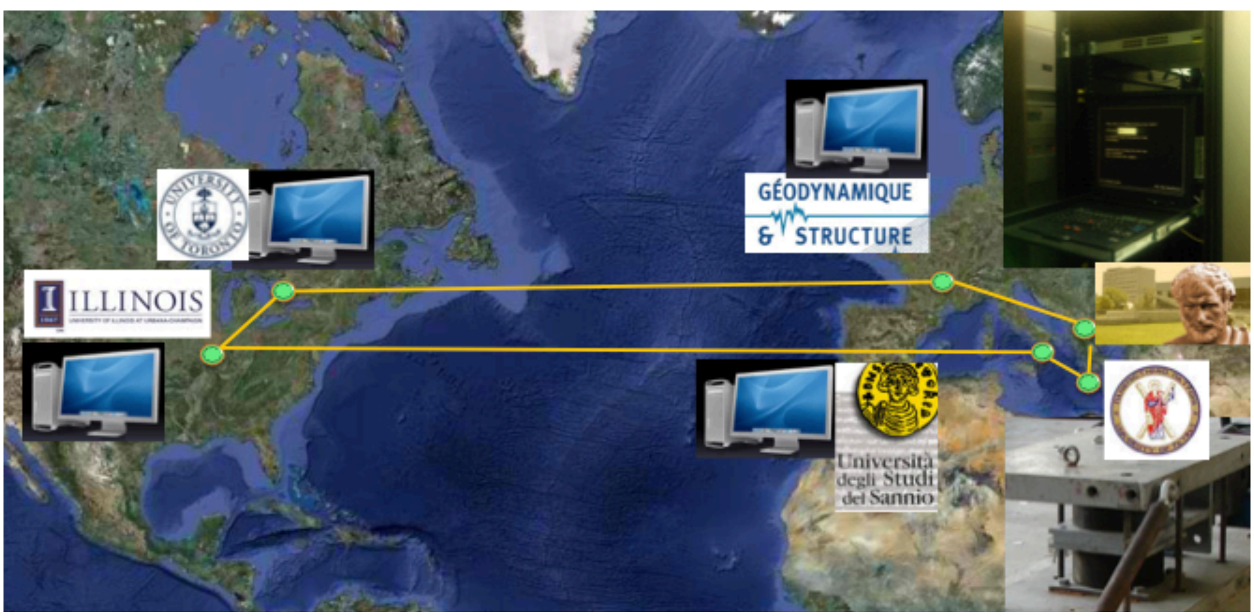

Figure 1. Geographical distribution of the numerical and experimental sub-structures involved in the intercontinental multi-platform and hybrid experiments.

Description of the Bridge Studied

A typical three-span overpass (T7) of a total length of 99.0m which is part of EGNATIA highway in Northern Greece was adopted for study. The two outer spans of the bridge have a length of 27.0m each, while the middle span is 45.0m long. The slope of the structure along the bridge axis is constant and equal to 7% with increasing altitudes towards the west abutment. The deck consists of a 10m wide, prestressed concrete box girder section, while the two piers are designed with a solid circular reinforced concrete section with diameter equal to 2.0m and are monolithically connected to the deck. The heights of the left and the right pier are 7.95m and 9.35m, respectively, while two series of 48 longitudinal bars of 25mm diameter are spaced equally around the section perimeter. The transverse reinforcement consists of an outer spiral of 14mm diameter spaced at 75mm and an inner 16mm spiral equally spaced. The deck is supported on seat type abutments of a backwall height equal to 2.0m, through two pot bearings (350mm×450mm×136mm) that permit sliding along the two principal bridge axes. Sliding joints of 10cm and 15cm length separate the deck from the abutment along the longitudinal and the transverse direction, respectively. The foundation rests on surface footings given the stiff soil formations corresponding to class B according to EC8-Part 2 or C according to NEHRP [12]). In particular, the pier footings are 9.0m long by 8.0m wide and 2.0m thick, while the footings supporting the abutments are 12.0m×4.5m×1.5m. A general overview of the bridge configuration is illustrated in Fig. 2. The bridge was designed to a peak ground acceleration of 0.16g adopting an importance factor equal to 1.0, and a behavior (or force reduction) factor equal to 2.40 according to Greek Seismic Code [23, 24] that was used at the time of construction.

Computational and Experimental Scheme

The specialized software platform SimCor [7] developed by the research group of the University of Illinois was used for coordinating the preliminary multi-platform analysis used to optimize the envisaged hybrid experiment. SimCor involves an enhanced Matlab-based script which coordinates software or hardware components supporting the NEESgrid Teleoperation Control Protocol (NTCP), as well as TCP-IP connections outside of the NEES system. Analytical models of some parts of the structure or experimental specimens representing specific parts of the same structure, are all considered as super-elements with many DOFs. Specially developed interface programs permit the interaction with different analysis software such as Zeus-NL [15], OpenSees [16], FedeasLab [17], and ABAQUS [18]. After the initialization step where the connection between the modules is achieved, the stiffness matrix of the whole structure is evaluated using predefined deformation values. The gravity forces are considered during the static loading stage where displacements due to gravity forces are imposed. Finally, SimCor performs Newmark numerical integration as it steps through the seismic record by utilizing the OS method with a modified α- parameter (a-OS method) which applies numerical damping to the undesired oscillations.

System sub-structuring

The three-span reinforced concrete bridge was divided into five different components (modules) each one analyzed in a different computer station after appropriate definition of the control points at the joint DOFs of interest. At each analysis step, a predefined displacement was imposed by the analysis coordinator and forces were measured to each specific module to establish the initial stiffness matrix of the sub-structured system. The established matrix was then used in the static and dynamic loading stage to determine the desirable target displacements. A brief description of the five modules is illustrated in Fig. 2 and is presented in the following.

- Module 1: Consists of the 99.0m bridge deck and was analyzed using the OpenSees finite element software. The superstructure is expected to remain linear and was thus modeled using linear elastic beam-column elements.
- Module 2: The left pier was numerically analyzed with OpenSees using fiber sections. The stress-strain relationships for the confined and the unconfined concrete were obtained from the Mander et al. model [19] while the uniaxial Giuffré-Menegotto-Pinto [20] material with isotropic strain hardening was used for the reinforcement bars. The median design strength of concrete and the yielding strength of reinforcing steel are 35.7 and 550MPa, respectively.
- Module 3: The right pier of the bridge was also deemed as an individual module, numerically analyzed with OpenSees using fiber sections, as previously.
- Module 4: The bearings at the left end of the deck were considered as an individual module and were first modeled as an elastomeric bearing element whose initial stiffness was calculated based on experimental results of the individually tested bearings. In the subsequent hybrid simulation, the left bearings were physically tested at the University of Patras.
- Module 5: The bearings between the deck and the right abutment were considered as an individual module also numerically analyzed using OpenSees.

UI-SimCor acted as the Analysis Coordinator in all cases.

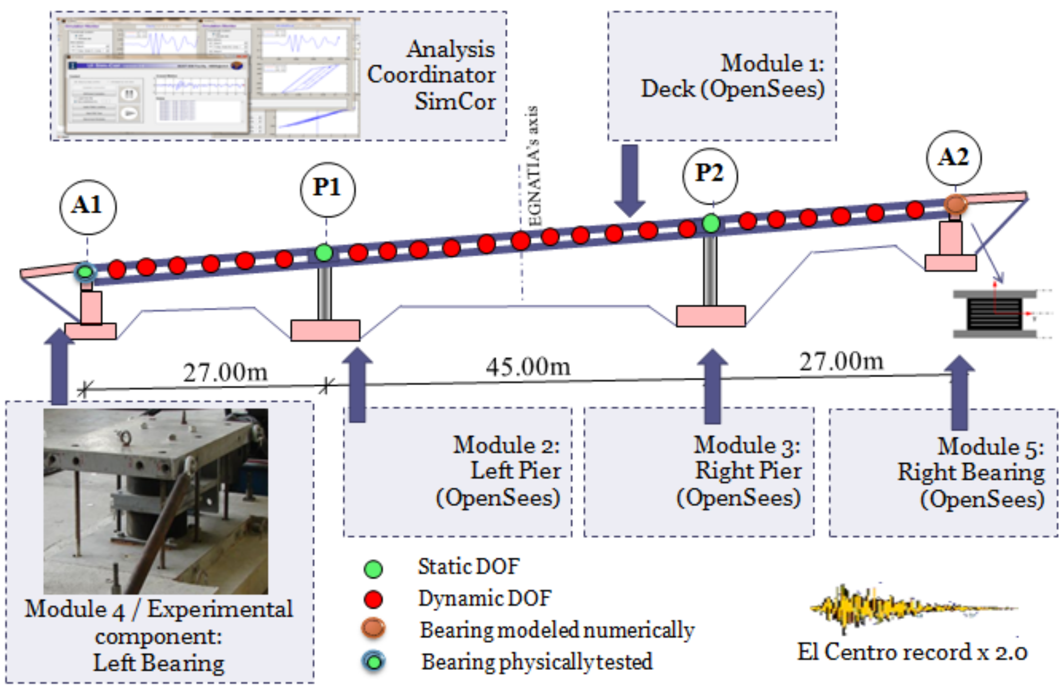

Figure 2. Layout of the bridge substructuring for the multi-platform and the hybrid simulation.

Experimental setup

The experimental setup at the Structures Laboratory of the University of Patras consisted of a pair of bearings placed in a back-to-back configuration between to stiff end plates, which were prevented from displacing or rotating (Fig. 3). A (nearly) constant vertical load of 240kN was imposed to the isolators, regardless of the level of applied shear deformation. The 350mm-in-diameter low damping rubber bearings used (ALGA, Type NB4) consisted of 7 layers of rubber with a layer thickness of 11mm and 6 steel shim plates with a thickness of 6 mm each. The total height of the bearing, including the external connection plates, was 181mm, while the total rubber height was 77mm. The prescribed shear modulus of the rubber was 0.99MPa. The measured horizontal and vertical stiffness of the bearings were estimated as: K_h = 1237kN/m and K_v = 469.6MN/m.

Preparatory computational and experimental works

Multi-platform analysis

Before proceeding with the hybrid experiment, it was deemed necessary to ensure that the multi-platform analysis yields similar results to that of the full model (i.e., the single module finite element model running on a single computer). For that purpose, the bridge was also modeled as a whole in OpenSees. Although it is not presented herein due to space limitations, an excellent match was observed between the sub-structured and the integrated finite element models independently of the geographical distribution of the multiple modules. The optimal geographical distribution and role assignment was identified through successive parametric analyses of a sample four-span, seismically isolated, reinforced concrete bridge [9] until the network latency was minimized and the analysis efficiency was improved. From the extensive parametric analyses scheme undertaken, it was seen that among the various sources of analysis delay (i.e., the geographical distribution of modules, the partners' role in the sub-structured analysis, the daytime the simulation took place, as well as pure network connection time), the latter clearly was the most dominating factor. As a result and given the rate-dependency of the bearing that was planned to be physically tested at the University of Patras careful tuning of the involved parameters was made. Finally, the optimum geographical distribution of the modules, as well as the order in which the analysis coordinator was contacting the intercontinental partner modules was identified. The execution of the experiment was also performed within the most efficient time window (12:00 and 14:00pm Greek time) found to correlate to the lowest network latency between Europe and North America.

Hybrid simulation

Although a dynamic actuator with a 1500 lt/min servovalve was employed for applying the command displacement increments, during the tests presented here the command displacement were applied in a slow, step-wise manner. Owing to the static nature of testing, strain rate effects affecting the bearing response cannot be accounted for. Nevertheless, a force correction procedure ([21], [22]) has been used in the tests performed to approximately account for this: a "corrected" force is determined as a function of the measured quantities (force, displacement, force rate and displacement rate). The exact dependence was obtained through a series of tests on similar pair of isolators (to avoid any scragging effect) at different testing velocities and for deformation levels similar to those expected during the hybrid tests.

Another issue that had to be dealt with, regards the way in which displacement commands generated by the test coordinator software are introduced as reference signals to the laboratory control system. As the majority of the controllers, even old ones, can accept external input in analog form, the approach implemented at the consortium-partner University of Toronto was used: target displacements sent out by UI-SimCor were received by purpose-built software (Network Interface for Controllers – NICON) under the Labview environment. The software directs the target value to a DAC unit and the (scaled) analog output signal is hard-wired from this unit to the controller as reference displacement or force (analog) value. Upon execution of the command signal, the opposite route was followed. The system was realized at Structures Laboratory and appropriately connected to the laboratory digital controller.

Figure 3. Experimental setup (top) and bearings tested (bottom, left) at the University of Patras along with the computational server at the University of Thessaloniki (bottom, right)

Series of multi-platform and hybrid experiments

After deciding the geographical distribution of the modules and the experimental setup of the bearings, four types of experiments were conducted among the partners, as summarized in Table 1: (a) Intercontinental multi-platform simulation (IMPS), (b) Hybrid simulation at University of

Patras (HSUPAT), (c) Hybrid simulation between University of Patras and Aristotle University (HSGR), (d) Intercontinental hybrid simulation (IHS). The ElCentro earthquake record was used for all the aforementioned experiments, with a scale factor of 1.0 and 2.0.

Comparative assessment of the dynamic response results

Due to space limitations, only indicative results of the three hybrid experiments (HSUPAT, HSGR, IHS) are presented herein. Figure 4 depicts the force-displacement loops for the experimental tested module (left bearing) for the three experiments. It is observed that, despite the system sub-structuring to modules widespread all over the world, the results of the local hybrid experiment (HSUPAT), the Thessaloniki-Patras experiment (HSGR) and the intercontinental one (HIS) are almost identical.

Table 1. Geographical distribution of the modules for all the simulations.

	IMPS	**HSUPAT**	**HSGR**	**IHS**
Module 1	*AUTH*	*UPATRAS*	*AUTH*	*AUTH*
Module 2	*UIUC*	*UPATRAS*	*AUTH*	*AUTH*
Module 3	*AUTH*	*UPATRAS*	*AUTH*	*AUTH*
Module 4	*UPATRAS*	*UPATRAS*	*UPATRAS*	*UPATRAS*
Module 5	*U of T*	*UPATRAS*	*AUTH*	*U of T*
Coordinator	*AUTH*	*UPATRAS*	*AUTH*	*AUTH*

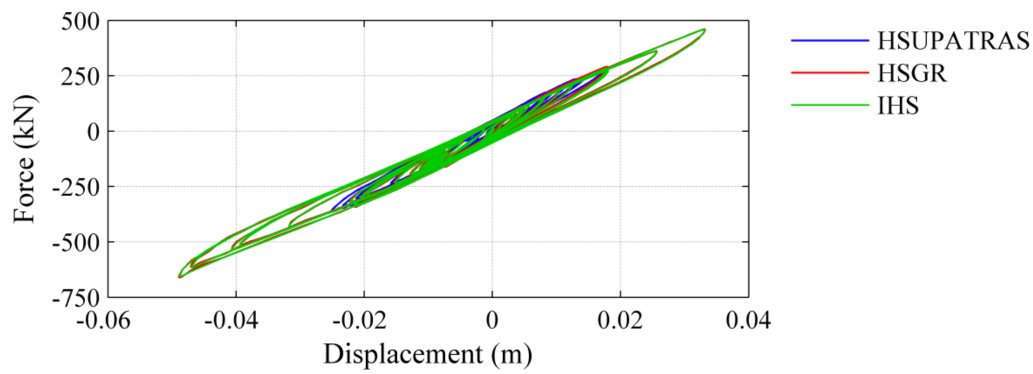

Figure 4. Comparison of the force–displacement loops for the three experiments.

It is noted herein that given the rate-dependency of the bearing that is physically tested at the University of Patras during the hybrid experimentation, the time step delay is an issue of major importance. The time step delay consists of (a) the time required for the finite element analysis at this given step or the progress of the experiment at the same time step, (b) the time required for the analysis coordinator to connect to the various modules and control forces and and displacements as well as (c) the pure networking time needed to reach the remote modules worlodwide. The disaggregation of the time step delay in the individual modules for the three experiments (IMPS, HSGR, IHS) is presented in Figure 5. It is seen that in the case of the intercontinental multi-platform simulation (IMPS), the numerical part at the most distant module from the analysis coordinator (i.e., Univ. of Illinois at Ubrana-Champaign) in Module 2 is the one that dominates the time required for every time step. As it was expected, in case of the hybrid simulations between both the Greek parnters (HSGR) and the entire group of international partners (IHS), the time step delay was primarily due to the experimentally tested component (left bearing). Network delays were kept reasonably low and the tests run successfully with only few time steps exceeding 5 seconds.

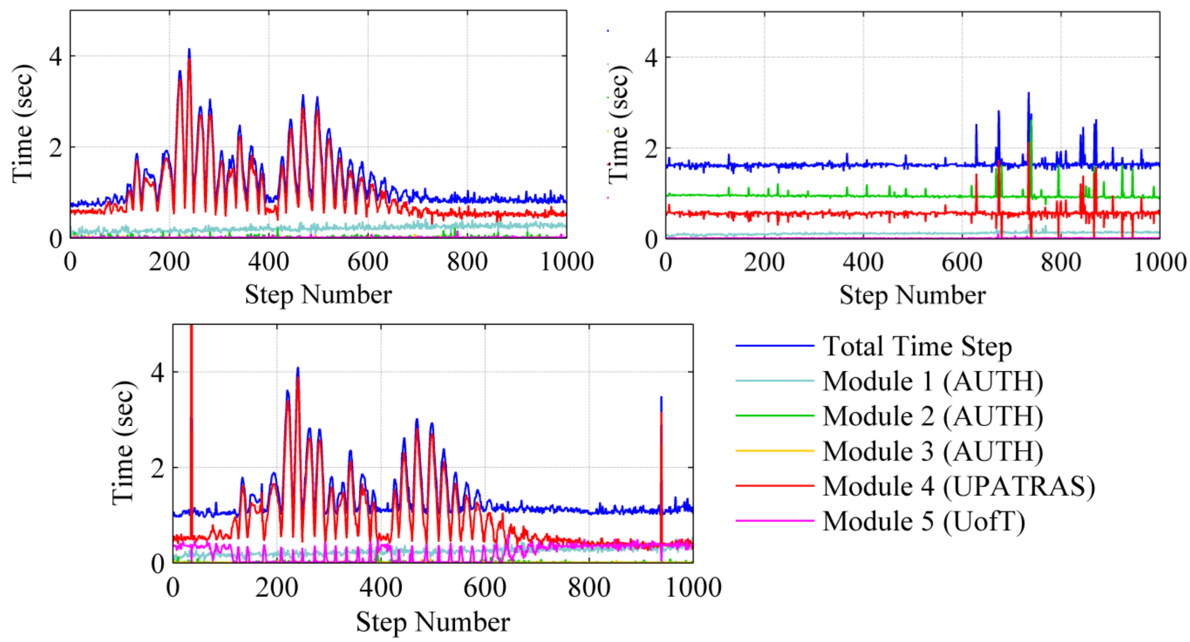

Figure 5. Time step delay for the intercontinental multi-platform simulation (IMPS, top left) hybrid simulation between Greek partners (HSGR, top right) and the intercontinental hybrid experiment (IHS, bottom).

Conclusions

This study presents the objectives, challenges and performance of an intercontinental hybrid experiment conducted between European and North American partners for the study of the seismic response of a seismically isolated, reinforced concrete bridge structure. The component that was physically tested was the left abutment bearing while the complementary superstructure components were analyzed numerically. The bridge was assessed under moderate and strong earthquake loading, through both geographically distributed, multi-platform analysis and hybrid simulations, in various combinations until the optimal role allocation was identified. Despite the rate-dependency of the bearing specimen tested and the increased network latency in linking the two sides of the Atlantic, the intercontinental hybrid experiment was accomplished and repeated successfully, highlighting the robustness, efficiency and repetitiveness of the approach.

Acknowledgments

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