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Intercontinental Hybrid Simulation for the Assessment of a three-span R/C Highway Overpass

Stathis Bousias[1], Anastasios Sextos[2], Oh-Sung Kwon[3], Olympia Taskari[4]
Amr Elnashai[5], Nikos Evangeliou[6] and Luigi Di Sarno[7]

ABSTRACT

This paper presents hybrid simulations of a three-span R/C bridge among E.U., U.S. and Canada. The tests involved partners located on both sides of the Atlantic with each one assigned a numerical or a physical module of the sub-structured bridge. Despite the network latency in linking five remote sites located on the two sides of the Atlantic (compared to previous studies in which sites were not as widely distributed) and considering the rate-dependency of the physical specimen as per Molina et al. (2002), the intercontinental hybrid simulation was accomplished and repeated successfully employing different tools, thus highlighting the robustness, efficiency and repetitiveness of the approach. Adaptations, challenges and limitations are critically discussed particularly focusing on the implications of network communication latency, the insensitivity of the sub-structuring arrangement and the accuracy of the results obtained.

1. INTRODUCTION

Hybrid simulation is a cost-effective alternative, compared to large scale shake table tests for dynamic testing of structural systems, combining physical testing with numerical simulation. In hybrid simulation, the structure is partitioned into a number of components; the unknown behavior of the most complex component is experimentally tested in the laboratory while the remainder of the emulated system is numerically analyzed in computer stations. The numerical to physical coupling is achieved via a transfer system comprising of a test frame, actuators, sensors, a controller, and an interface program which links a controller to the numerical model.

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[1] Professor, Dept. of Civil Engineering, University of Patras, Greece
[2] Associate Professor, Dept. of Civil Engineering, University of Bristol, UK & Aristotle University of Thessaloniki, Greece
[3] Associate Professor, Dept. of Civil Engineering, University of Toronto, Canada
[4] Dr. Civil Engineer, Dept. of Civil Engineering, Aristotle University of Thessaloniki, Greece
[5] Dean of Engineering, Pennsylvania State University, US
[6] Post-doc researcher, Dept. of Electrical and Computer Engineering, University of Patras, Greece
[7] Assistant Professor, Dept. of Engineering, University of Sannio, Italy

The same sub-structuring concept has also been successfully applied 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 numerical 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, boundary conditions and the geometry of the particular problem. As for the case of hybrid testing though, the computational cost and level of expertise is relatively high compared to a conventional all-inclusive simulation package. In addition, its computational efficiency is network-dependent.

The communication among the numerical and experimental components as well as the solution of the equation of motion of the entire structure is achieved via purpose-specific coordination software. To this end, specialized software platforms have been developed, e.g. *OpenFresco* (Schellenberg et al. 2009) and *UI-SimCor* (Kwon et al. 2008)]. In the former, the analysis of the numerical substructures is performed within a finite element software (*OpenSees*) and the only network communication required is that with the laboratory-tested component(s). This feature is particularly advantageous for the hybrid simulation of structures with large number of DOFs, as it keeps network communication to the minimum. On the other hand, *UI-SimCor* relies on external finite element codes and physical testing for the numerical and the experimental substructures, respectively, while solving a numerical time integration scheme and fully undertaking the task of communicating the deformation vector to all substructures thus receiving the returning measured deformation/resistance vectors. The intense network communication is particularly problematic for structures with many substructures and/or degrees-of-freedom and may even lead to process halting.

In general, most of the hybrid simulation tests have been conducted locally, where both numerical analysis and physical experimentation have been conducted within a single laboratory. However, the nature of the test lends itself to allowing substructures to be geographically-distributed between test sites across a computer network. In this context, there is no need for either using a unique experimental facility or for satisfying physical proximity for the multiple experimental or numerical components. The components (analytical, experimental or a combination of both) are treated on different networked computers and, can thus be located anywhere in the world. This multi-site approach has already been developed in the United States for the assessment of complex interacting systems. It was supported by

National Science Foundation, through the Network for Earthquake Engineering Simulation (NEES, www.nees.org) scheme (Kwon et al. 2005; Pan et al. 2005; Saouma et al. 2012; Spencer et al. 2004; Takahashi and Fenves 2006; among many others) with the aim to raise the limitations related to the laboratory capacities. Spencer et al. (2004), for instance, tested a two-bay single-story steel frame at an expanded time scale known as the Multi-Site Online Simulation Testbed (MOST) experiment. This experiment coupled two large-scale physical components in Illinois and Colorado with a computational simulation. Building on the MOST experiment, the so-called Fast-MOST test (Mosqueda 2006; Mosqueda and Stojadinović 2008) and the Multi-site soil-structure-foundation interaction test, MISST, (Elnashai et al. 2008; Spencer et al. 2006) were then conducted. The first (Fast-MOST) consisted of a six-span bridge with five remote experimental and numerical column substructures distributed within NEES facilities: namely, UC Berkeley, University of Colorado, Boulder, SUNY Buffalo, University of Illinois at Urbana-Champaign (UIUC) and Lehigh University while the latter (MISST) simulated the response of a bridge structure which was partitioned into five separate modules distributed at three of NEES equipment sites (UIUC, Lehigh University, and Rensselaer Polytechnic Institute). Similarly, a grid-based network of advanced laboratories for earthquake engineering simulation has been developed in Europe (UK-NEES), initially comprising the research laboratories at the Universities of Bristol, Oxford and Cambridge (Ojaghi et al. 2010).

Based on the examined problem and the available equipment, pseudo-dynamic hybrid tests can be executed in real time or in an extended time scale. When the rate-dependent behavior of an experimental component is of interest, as is for instance the case of rubber bearings or viscous dampers, the strain-rate dependency of the restoring forces yields the execution of the test in an extended time scale not reliable. In this case, hybrid testing must be conducted in real time (Carrion et al. 2009; Chae et al. 2014; Chen et al. 2014; Nakashima and Masaoka 1999) or at an affordable speed for the available equipment accompanied by proper compensation techniques for the restoring forces of the experimentally tested components. In this light, Molina et al. (2002) proposed a simple proportional correction of the measured forces that compensates the remaining strain-rate effect of rubber bearings due to the unrealistically slow speed of the test; the correction factor being obtained by means of a characterizing test on the specific rubber isolators, which were of interest in the particular test. Several other Real Time Distributed Hybrid Tests (RTHT) have been carried out highlighting the challenges and current limitations for studying the rate-dependent dynamic coupling (Chen and Ricles 2009; Dion et al. 2010; Ojaghi et al. 2014; Schellenberg et al. 2014).

In case that rate-dependent problems studied by means of remote sites that are geographically distributed at a great distance, the inevitable additional time delay in communication introduces a considerable degree of uncertainty, which is further hindered by the lack of a systematic study for the exploration of possible network implications. This is further amplified by the fact that, despite the increasing number of geographically distributed tests within US or Europe, the number of wide range international hybrid tests is rather limited. Takahashi et al. (2008) performed a geographically distributed test for a two-span continuous bridge between UC Berkeley and Kyoto University in Japan. The strong nonlinear behavior of the C-bent RC and the steel pier of the bridge were experimentally tested at the two laboratories, leading to a very stable set of tests involving strongly nonlinear behavior. More recently, a continuous intercontinental test was conducted between University of Kassel in Germany and UC Berkeley in the US (http://openfresco.berkeley.edu/2012/09/kassel-berkeley/). The experimental substructure of the test consisted of a friction device (Dorka 1995) and a fixed Tuned-Mass-Damper (TMD). The computational portion of the hybrid model consisted of a single degree of freedom mass with viscous damping. Computations were executed at UC Berkeley and the experimental substructure was located at the University of Kassel. Due to the average network communication time of 0.2 sec between the two sites and the uncertainty in the network lag, the 0.01 sec of numerical integration time was executed in 1 sec of real-time, which resulted in the time scale factor of 100.

Along these lines, the objectives of this paper are to:

- systematically study the effect of remote host distance on the feasibility of executing hybrid simulation at the system level among long-separated sites
- investigate the feasibility of implementing hybrid simulation tools and procedures that are not tailored to the existing equipment in Europe, and
- demonstrate the stability and accuracy of an intercontinental multi-platform and/or hybrid test for the case of a real bridge with rate-dependent behavior concentrated on its elastomeric bearings while considering soil-embankment-abutment-bridge interaction (Taskari and Sextos 2015).

The bridge studied was partitioned into five structural components (modules), each one being analyzed using specific software in different computer stations (**Figure 1**) located at Aristotle University of Thessaloniki, Greece (AUTH), University of Patras, Greece (UPATRAS), University of Sannio, Italy (USANNIO), University of Illinois at Urbana-

Champaign, U.S. (UIUC) and University of Toronto, Canada (UofT). At the final stage, the numerical module representing the left bridge bearing was replaced by a physical specimen tested at the Structures laboratory at University of Patras. In both cases (i.e. multi-platform simulation and hybrid testing) *UI-SimCor* (Kwon et al. 2007, 2008) was used as the simulation coordinator. The description of the series of the experiments, from the geographically-distributed multi-platform simulation to the intercontinental hybrid simulation, as well as the limitations, challenges met and adaptations required towards a robust, intercontinental hybrid testing are discussed in the following.

Figure 1. Geographical distribution of the numerical and experimental sub-structures involved in the intercontinental multi-platform simulation and hybrid testing. All sites connect to the coordinator located at AUTH.

2. DESCRIPTION OF THE BRIDGE

The particular structure is a three-span (27-45-27m) reinforced concrete (R/C) overpass of a total length of 99.0 *m,* which is part of EGNATIA highway in Northern Greece. The slope of the deck along its axis is constant and equal to 7% with increasing altitudes towards the west abutment. The deck is a 10 *m* wide, prestressed concrete box girder section, while the two piers are designed with a solid circular reinforced concrete section with diameter equal to 2.0 *m* and are monolithically connected to the deck. The heights of the left and the right pier are 7.95 *m* and 9.35 *m*, respectively. Two series of 48 longitudinal bars of 25 *mm* diameter are spaced equally around the section perimeter, while the transverse reinforcement consists of an outer spiral of 14 *mm* diameter spaced at 75 *mm* and an inner 16 *mm* spiral equally spaced. The deck is supported on two elastomeric bearings (350 ×450 ×136mm) with a shear modulus (*G*) equal to 1.0 *MPa*, which is supported on seat type abutments with a backwall height equal to 2.0 *m*. Sliding joints of 10 *cm* and 15 *cm* length separate the deck from the abutment along the longitudinal and the transverse direction, respectively. Given the stiff soil formations corresponding to class *B* according to EC8-Part 2 (CEN 2005) or *C* according to

NEHRP [FEMA440, 2004], surface footings of 9 *m* × 8 *m* × 2 *m* and 12 *m* × 4.5 *m* × 1.5 *m* are designed for the foundation of the piers and the abutments, respectively. A general layout of the bridge configuration is illustrated in **Figure 2**. The bridge was designed for a peak ground acceleration of 0.16 *g* adopting an importance factor equal to 1.0, and a behavior (or force reduction) factor equal to 2.40 according to Greek Seismic Code (Earthquake Planning and Protection Organization (EPPO) 2000; Ministry of Public Works of Greece 1999) that was used at the time of construction.

Figure 2. General overview of the bridge configuration.

3. IMPLEMENTATION AND VERIFICATION OF HYBRID TESTING

3.1 System sub-structuring

For the purpose of this study, the five components (modules), were picked to correspond to the bridge deck, the left pier, the right pier, as well as the left and right abutment bearing. Each component was numerically analyzed or experimentally tested as described in the following section. **Figure 3** illustrates the bridge sub-structuring scheme used for the multi-platform simulation and the hybrid testing.

The specialized software platform *UI-SimCor* (Kwon et al. 2008) developed by the research group of the University of Illinois was used for coordinating the simulation. *UI-SimCor* involves an enhanced MATLAB-based script which coordinates software or hardware components through TCP-IP connections. 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* (Elnashai et al. 2002) *OpenSees* (McKenna et al. 2002), *FedeasLab* (Filippou and Constantinides 2004), and *Abaqus* (Hibbit and Sorenson 2006). After the initialization step where the network connection between the modules is established, the stiffness matrix of the entire structure is evaluated using predefined deformation values. The gravity forces are applied during the static loading stage where displacements due to gravity forces are imposed. Finally, *UI-*

SimCor performs Newmark numerical integration as it steps through the seismic record by utilizing the operator-splitting (OS) method with a modified α- parameter (a-OS method), which introduces numerical damping to suppress the high-frequency spurious oscillations.

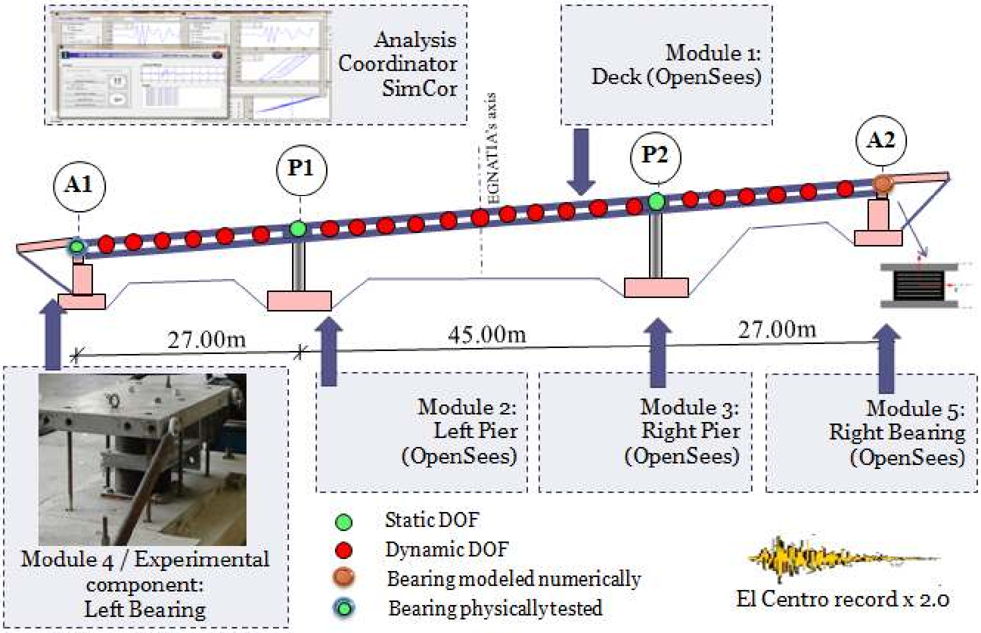


Figure 3. Layout of the bridge sub-structuring for the multi-platform simulation and hybrid testing.

3.2 Experimental substructure module

The physical module comprised the elastomeric bearings located at the left end of the bridge. The experimental setup installed at the Structures Laboratory of the University of Patras employed a pair of bearings placed one on top of the other (back-to-back configuration) and inserted between stiff end plates – the latter were prevented from displacing or rotating (**Figure 4**). A nearly constant vertical load of 240 *kN* was imposed to the isolators, regardless of the level of applied lateral deformation. The 350 *mm*-in-diameter low damping rubber bearings used (ALGA, Type NB4) consisted of seven, 11 *mm*-thick layers of rubber and six steel plates each of a thickness of 6 *mm*. The total height of each bearing, including the external connection plates, was 181 *mm*, while the total rubber height was 77 *mm*. The prescribed shear modulus of the rubber was 0.99 *MPa*. The measured horizontal and vertical stiffness of the bearings were estimated as: $K_h = 1237$ *kN/m* and $K_v = 469.6$ *MN/m*.

Although a dynamic actuator (with a 1500 *l/min* servo valve supplied by a 600 *l/min* pump) was employed for applying command displacement increments, during the tests presented here the command displacement were applied in a slow (relatively to actual seismic velocity), step-wise manner. Owing to the quasi-static nature of the test, strain rate effects affecting the response of the elastomeric bearing cannot be accounted for by applying realistic strain rate. Thus, the force correction procedure proposed by Molina et al. (2002) was adopted to approximately account for the increase in force due to the strain rate effect; the measured force was adjusted as a function of measured quantities (force, displacement, force rate and displacement rate) to yield a rate-dependent force estimate. Such calibration was realized by subjecting a pair of identical isolators (different to those used in the final test, to avoid any effect of scragging) to different testing velocities and for deformation levels similar to those expected during the hybrid tests. From these tests it was possible to obtain a relationship for the "corrected" force based on other measured quantities. The corrected force was then returned to the numerical integration scheme for advancing the solution to the next step.

Figure 4. 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).

3.3 Numerical substructure modules

OpenSees analysis platform was used for the numerical analysis of all the numerical modules. Each module was modeled separately with the following assumptions:

Module 1. Bridge deck: The deck is expected to remain linear and thus was modeled with elastic beam-column elements.

Modules 2 and 3: Left and Right Pier: The left pier was modeled with nonlinear beam-column fiber elements. The stress-strain relationships for the confined and the unconfined concrete were obtained from the literature (Mander et al. 1988), while the uniaxial Giuffré-Menegotto-Pinto (Taucer et al. 1991) 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 550 *MPa*, respectively. Soil-structure interaction was considered at the pier footing. The dynamic impedance at the footing-soil interface was derived according to Mylonakis et al.(2006), as a product of the static stiffness K, times the dynamic stiffness coefficient $k(\omega)$ where ω is the frequency of interest. In this case, ω was assumed to be equal to the first natural cyclic frequency of the examined bridge. The radiation damping coefficient $C(\omega)$ was then derived for the same cyclic frequency. The derived values for the dynamic stiffness and dashpot coefficients are presented in Figure 5.

Modules 4 and 5: Left and Right Bearings: The hysteretic behavior of the bearings is considered with the use of nonlinear translational springs, with a horizontal effective stiffness determined by the shear modulus of the elastomer (G), the full cross-sectional area (A) and the total thickness of the rubber layers (t_r), i.e. $K_{eff} = GA/t_r$. The yield force (F_y) and displacement (D_y) of the bearing was determined assuming a value for the maximum shear strain equal to 2.0 and a value of 2.0 for the elastic (K_1) over the inelastic stiffness (K_2) ratio (Naeim and Kelly 1999).

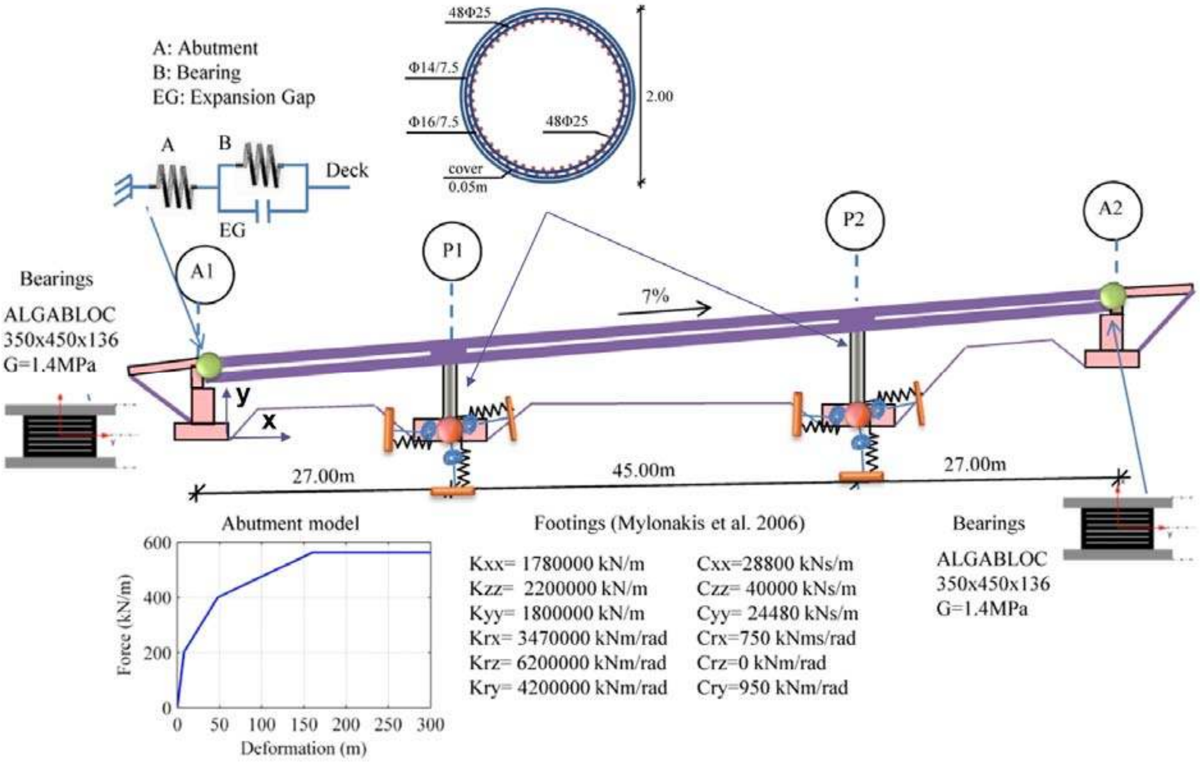


Figure 5. Overview of the numerical model employed for the purposes of multi-platform simulation. Sub-structuring is identical to that of Fig. 3, however, all modules are purely numerical.

3.4 Analysis coordinator

UI-SimCor acted as the Analysis Coordinator. Each module was analyzed in a different computer station after appropriate definition of the control points at the joint dynamic degrees of freedom (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. An indicative plot of seismic response of the individual bridge components under the N-S component of the ground motion (PGA: 0.32g) recorded at a site in El Centro, California, during the Imperial Valley earthquake of May 18, 1940, is depicted in Figure 6. Given that the intensity of the particular earthquake record exceeded the design level, strongly nonlinear response was observed in all piers and bearings.

3.5 Verification of hybrid simulation

Before proceeding with the hybrid simulation, 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).

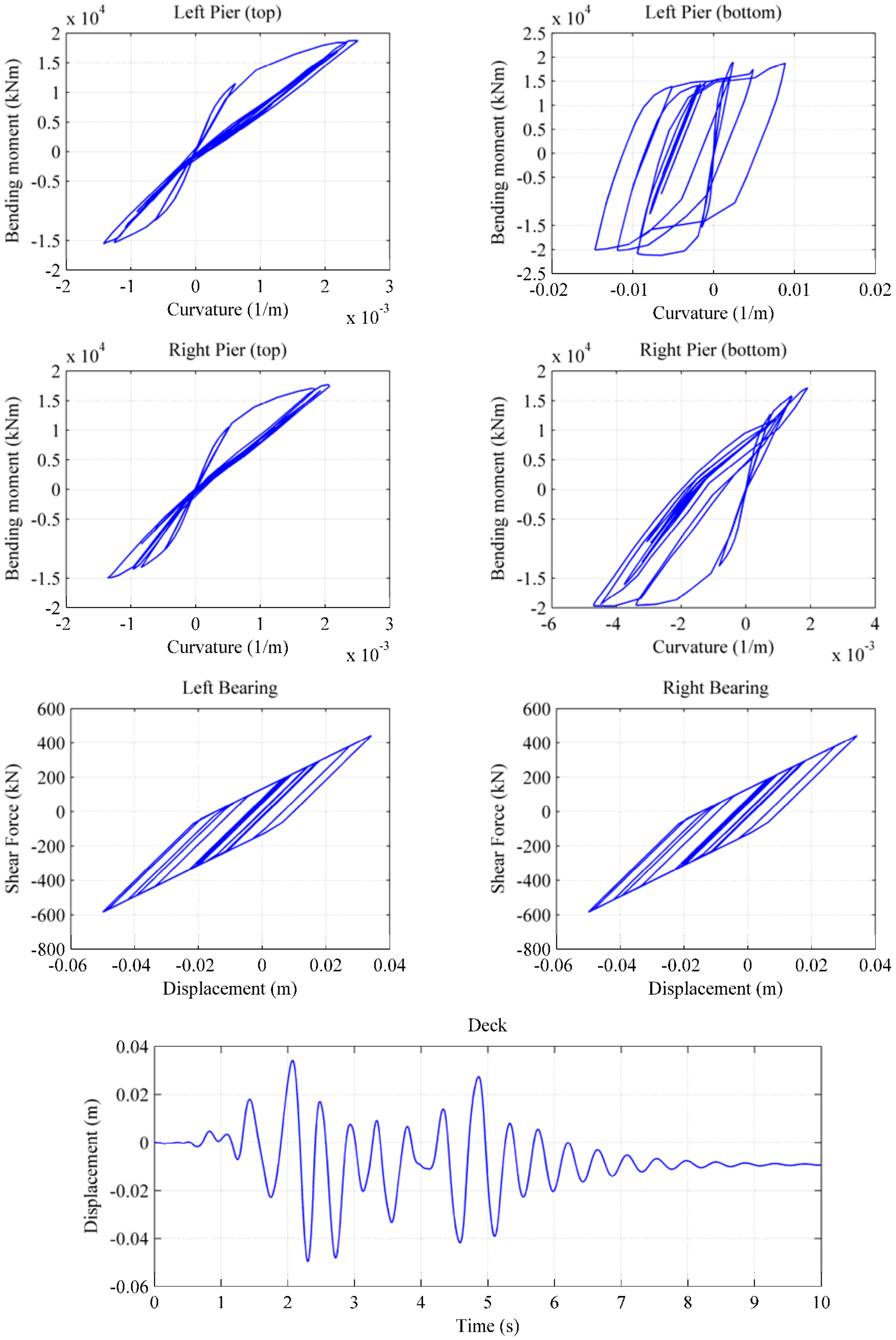


Figure 6. Seismic response of individual bridge components (piers, bearings, deck) under the El Centro earthquake.

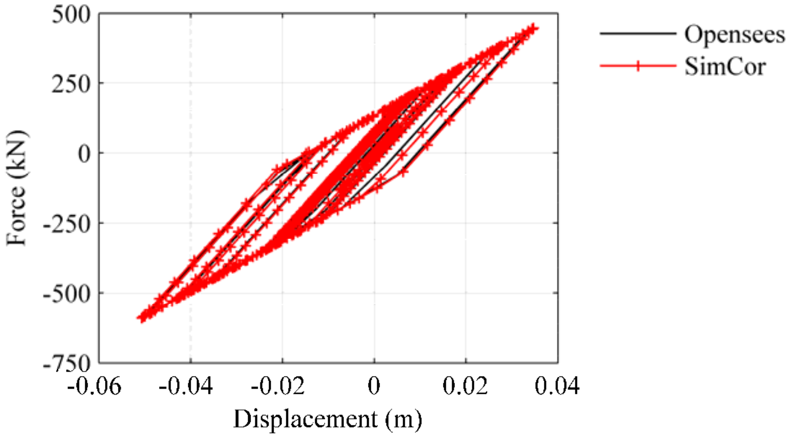


Figure 7. Comparison of the force-displacement loops between the full and the sub-structured model.

For that purpose, the bridge was also modeled as a whole in OpenSees. An excellent match was observed between the sub-structured and the integrated finite element models independently of the geographical distribution of the multiple modules as shown in Figure 7. The optimal geographical distribution and role assignment for each remote site was identified through successive parametric analyses of a sample four-span, seismically isolated, reinforced concrete bridge (Taskari and Sextos 2013) 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 uncertainties associated with analysis delay (i.e., the geographical distribution of modules, the possibly different role of each partner site in the sub-structured analysis, the day and time the simulation took place, as well as pure fluctuation of network connection time), the latter was found to be clearly dominant. Moreover, it was seen that more than 50% of this latency can be attributed to crossing the Atlantic. In fact, seven to ten hops and approximately 60 – 110 *ms* were required on average to reach the last European hop, involving commonly but not exclusively, the route among Thessaloniki-Frankfurt-Amsterdam-Paris at a 2800 *km* physical distance, thus effectively wasting more than 40 - 70 *ms*, before connecting to the first transatlantic hop in Toronto.Given the above network latency and the rate-dependency of the problem studied, careful tuning of the bearing setup which was physically tested at the University of Patras was required. 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. Based on the sensitivity studies conducted, the execution of the experiment was performed within the most efficient time window that lead to the lowest network latency between Europe and North America 10:00am and 12:00pm GMT, naturally correlated to nighttime in the east coast of the United States.

3.6 Communication between controller and UI-SimCor

Another issue that had to be dealt with is the way in which displacement commands, generated by the simulation coordination software, are introduced as reference signals to the laboratory control system. To show the potential and applicability of the approach in labs with different hardware platforms, two approaches for implementing hybrid simulation in control systems of substantially different capabilities were realized at the Structures Laboratory of the University of Patras (Figures 8-9).

The smoothest way to introduce reference displacements to the host controller is when the latter supports network communication. If this is the case, then the main concern is security because with controllers functioning within a local laboratory network, risks maybe encountered when they are exposed to a public network through which the reference signals are received, Figure 8. Thus, any scheme for implementing hybrid simulation in modern controllers should deal with the problem of riskless introduction of reference command signals from the public to the local network. For this purpose, a MATLAB-based parenthetic application (StrulabAPI) was built, running on a machine in the public network, but communicating with both the remote server running *UI-SimCor* (via a network card configured on the public network) and the control application (master controller) in the laboratory (via a second network card on the same machine, but configured on the local network). The StrulabAPI application receives - through the public network - the target displacement command from *UI-SimCor* and updates - through the local network - the command displacement in the dual memory blocks of the master controller application. Any updating of the dual memory is instantly seen by the control unit operating the actuator (Fig. 8) and proceeds in applying the displacement command received. Any modifications which need to be realized on the target displacement received from *UI-SimCor* is performed within StrulabAPI: these may include scaling (if the specimen is in different scale with respect to the analytical substructures) and geometric transformation (in case the reference coordinate system of the target displacement does not coincide with the current actuator axis). More details can be found in Bousias et al. (2014).

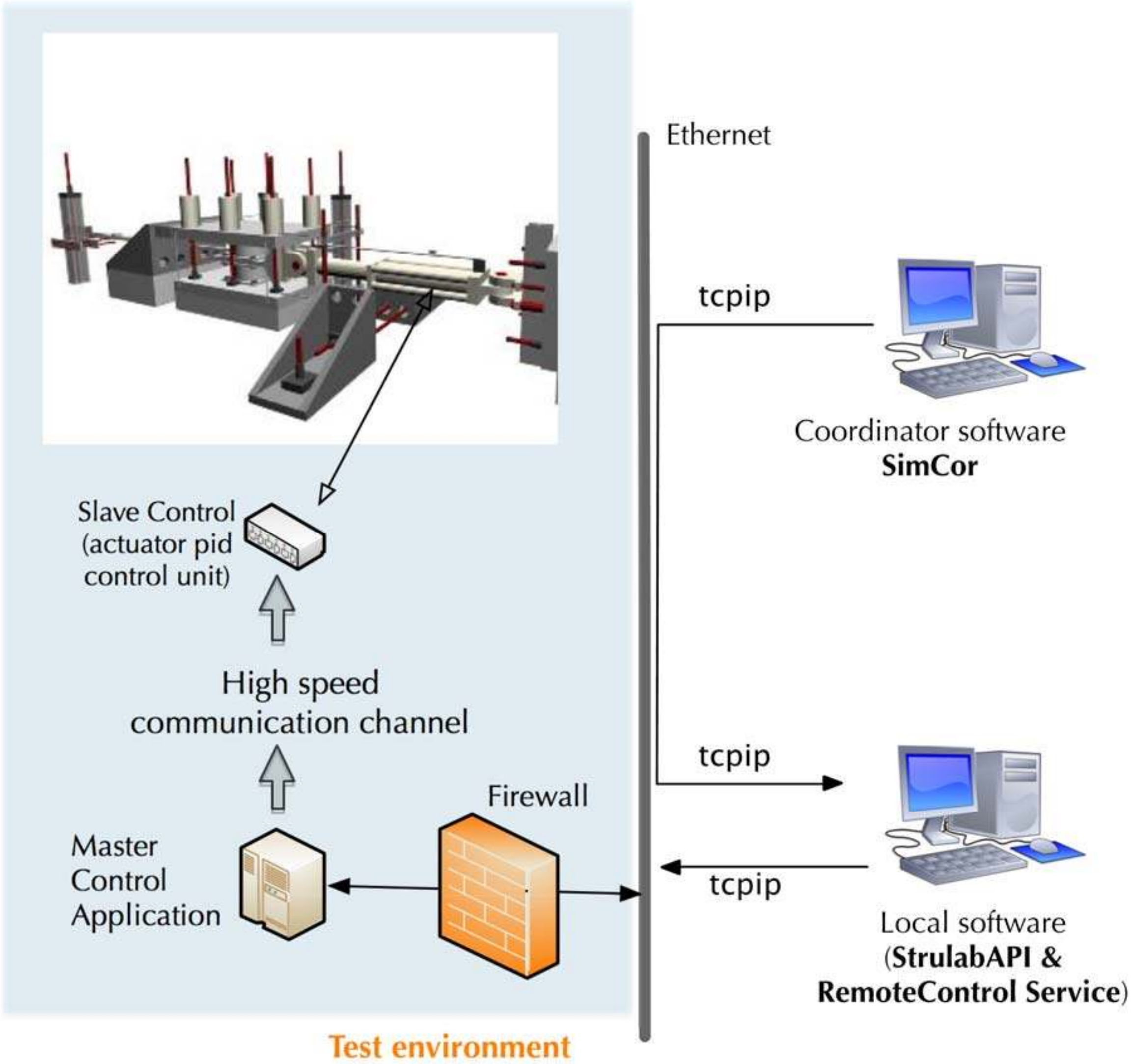


Figure 8. General configuration of the controller-specific communication scheme.

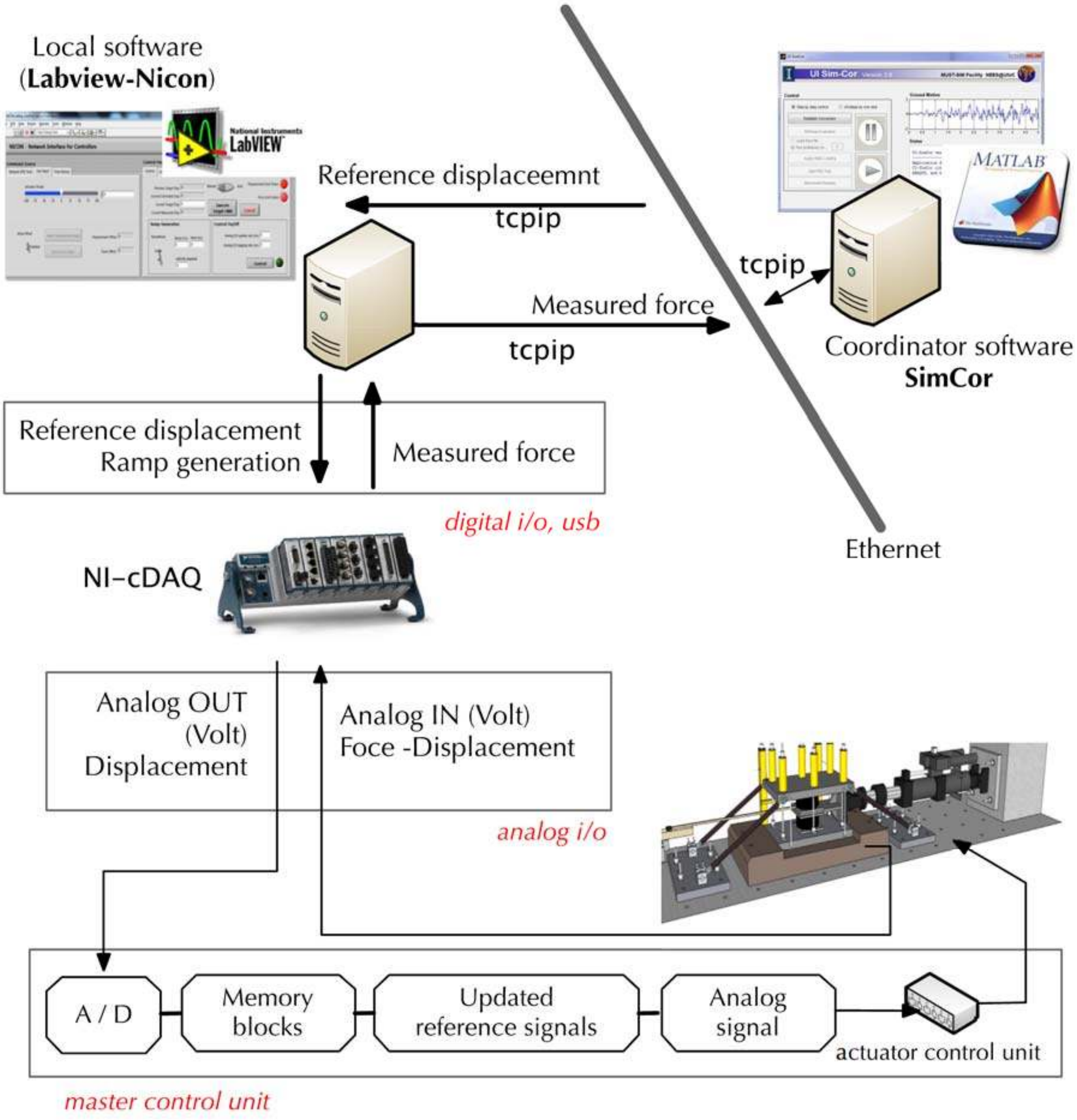
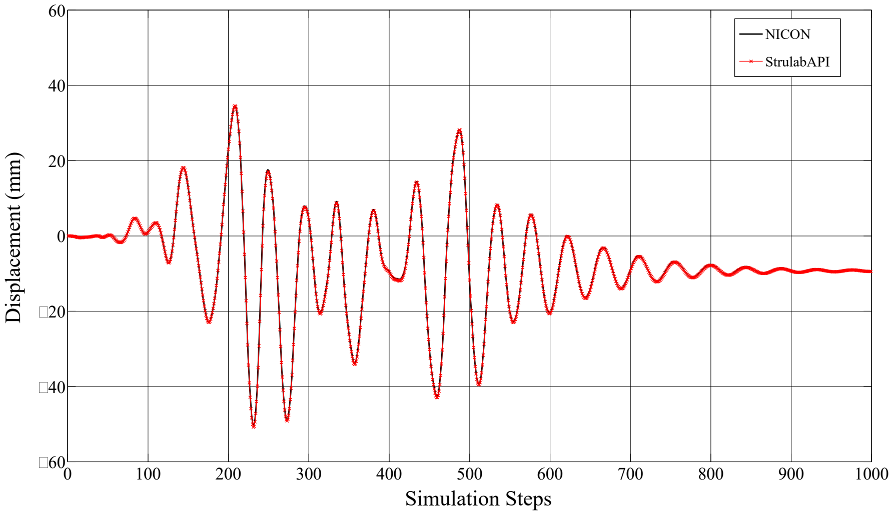
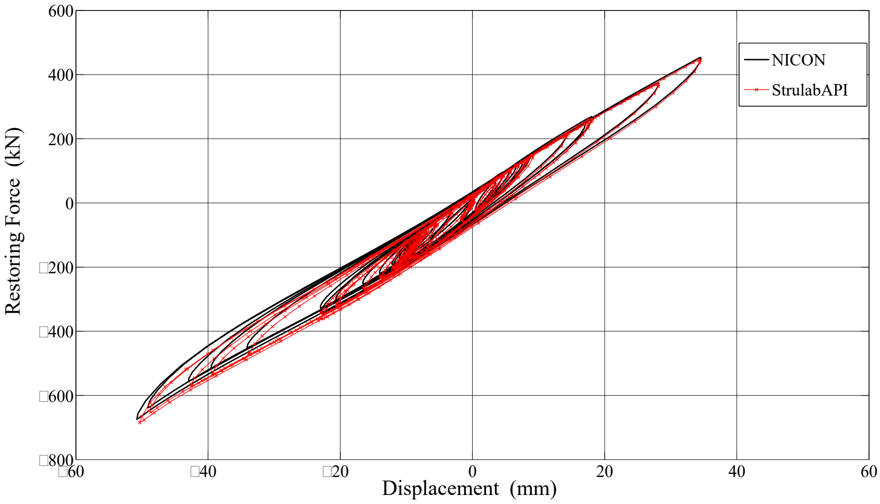


Figure 9. General configuration of the analog-input scheme.

For controllers without networking capabilities, as is the case for most controllers in structural laboratories, the analog-input option, which is available in almost all of them, may be explored: i.e. the capability to accept external input in the form of an analog signal. The approach developed at the consortium-partner University of Toronto was used: target displacements sent out by *UI-SimCor* were received by a purpose-built application [Network Interface for Controllers – *NICON,* (Kammula et al. 2014; Zhan and Kwon 2015)] in *LabVIEW* environment.



(a)



(b)

Figure 10. Experimental component: (a) displacement, and (b) force-displacement response.

The displacement command received (in digital form) from the network is directed by NICON to a digital–to–analog (DAC) unit and the scaled analog output signal is hard-wired from this unit to the analog input terminal of the actuator controller, as reference displacement (or force) value, Figure 9. Upon execution of the command signal, the opposite route is followed: the measured reaction force is directed (in analog form) to an analog–to–digital converter (ADC) with the resulting digital signal being sent to the simulation coordination software via the *NICON*. No compensation due to the network (varying) time was introduced in the experimental module as all rate-dependent effects on the force response of the isolator were compensated via the characterization process.

Displacement (Figure 10(a)) and force-displacement response (Figure 10(b)) obtained from each approach, i.e. the “analog-in” (NICON) and the Matlab script (StrulabAPI), are compared. It is shown that displacements obtained by the two approaches practically coincide and force-displacement loops compare very well – the asymmetry in the force-displacement response is due to bearing damage owing to previous tests. However, what is not depicted in these figures is that steps are completed faster in the analog-input” (NICON) approach – this is elaborated in the following section along with other time-related issues.

4. HYBRID SIMULATION CASES AND RESULTS

4.1 Hybrid simulation cases

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, namely, (a) Intercontinental multi-platform simulation (IMPS), (b) Hybrid simulation at the University of Patras only (HSUPAT), (c) Hybrid Test between University of Patras and Aristotle University (HTGR), and (d) Intercontinental Hybrid Test (IHT). The El Centro earthquake record was used for all the aforementioned experiments. A total number of 1000 steps were executed while the time step was set equal to 0.01sec.

Table 1. Alternative configurations and roles among the geographically distributed remote sites.

	IMPS	**HTUPAT**	**HTGR**	**IHT**
Module 1	*AUTH*	*UPATRAS*	*AUTH*	*AUTH*
Module 2	*UIUC*	*UPATRAS*	*AUTH*	*UIUC*
Module 3	*USANNIO*	*UPATRAS*	*AUTH*	*USANNIO*
Module 4	*UPATRAS*	*UPATRAS*	*UPATRAS*	*UPATRAS*
Module 5	*U of T*	*UPATRAS*	*AUTH*	*U of T*
Coordinator	*AUTH*	*UPATRAS*	*AUTH*	*AUTH*

4.2 Comparison of results from different analysis cases

Figure 11 depicts the force-displacement loops for module 4 (left bearing) and the first three simulations (HSUPAT, HTGR, IHT). It is observed that, despite the system sub-structuring to sites widespread all over the world, the results of the local hybrid simulation (HSUPAT), the Thessaloniki-Patras hybrid test (HTGR) and the Intercontinental Hybrid Test (IHT) lead almost identical results.

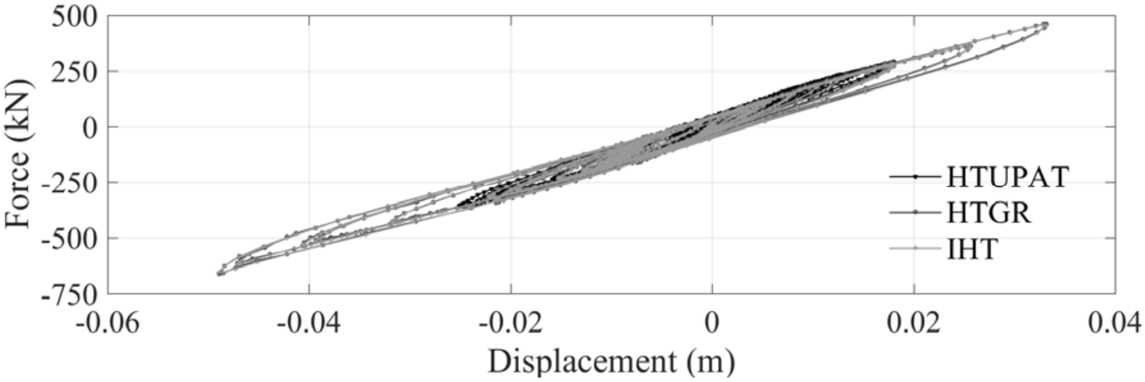


Figure 11. Comparison of the force–displacement loops for the three experiments.

4.3 Observed distribution of communication delays

To study the sensitivity of the total time t_{tot} required for completing each step on various network-related and analysis parameters, the individual sources of delay had to be identified and measured for each one of the n=5 remote sites involved and their four different configurations summarized in Table 1, namely (a) the time, t_1, required for the finite element analysis at a given step, (b) the time required to communicate target commands to each substructure, $t_{2,n}$, (c) the time $t_{3,n}$ for completing the individual (numerical or experimental) operations at a sub-structure level of the respective remote site; (d) the time, $t_{4,n}$, required for the analysis coordinator to receive measured values and (e) t_{net} the pure networking (internet) time spent in transmitting the data along the various to remote modules worldwide.

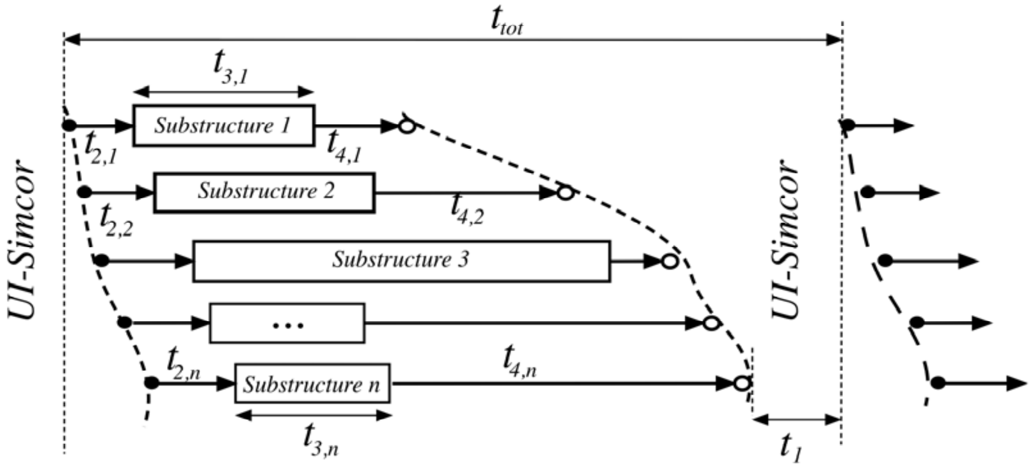


Figure 12. Schematic representation of operations and time duration within each time step

The disaggregation of the time step into individual modules for the three main cases of multi-platform simulation (IMPS), and hybrid testing at a national (HTGR) and intercontinental level (IHT) is presented in Figure 12. It is noted that the time indicated in the graphs for each one of the *n* modules (remote sites) is the sum of communication and operation time, $t_{2,n}+t_{3,n}+t_{4,n}$.

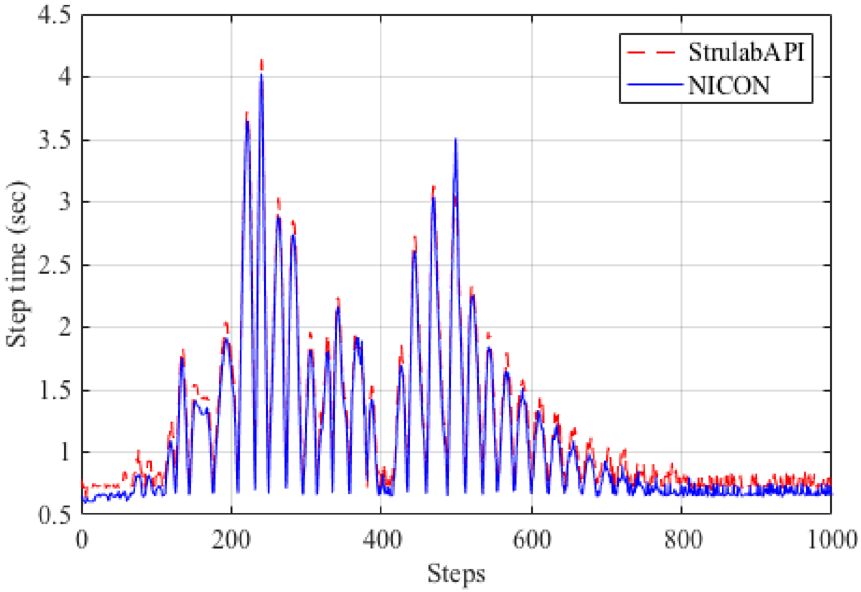
For the Intercontinental Hybrid Test (IHT) in particular, the total time required by the experimental substructure (n=4) to complete a step, including its forward/backward communication to/from the analysis coordinator, $t_{2,4}+t_{4,4}$, as well as the time required for physically imposing the required step displacement, $t_{3,4}$ is shown in Figure 13 (top). The time measured for both controller approaches (i.e., analog input and controller-specific) is also presented. A slight advantage of systematically shorter times is observed for the "analog-input" approach (NICON) over the controller-specific (StrulabAPI) one, which can be primarily attributed to facts: first, NICON is a LabVIEW-based script and is thus a multi-thread application with higher computational efficiency. Secondly, the system (elapsed) time is better estimated in NICON, as timing of signals is assigned when the respective value is available in the memory.

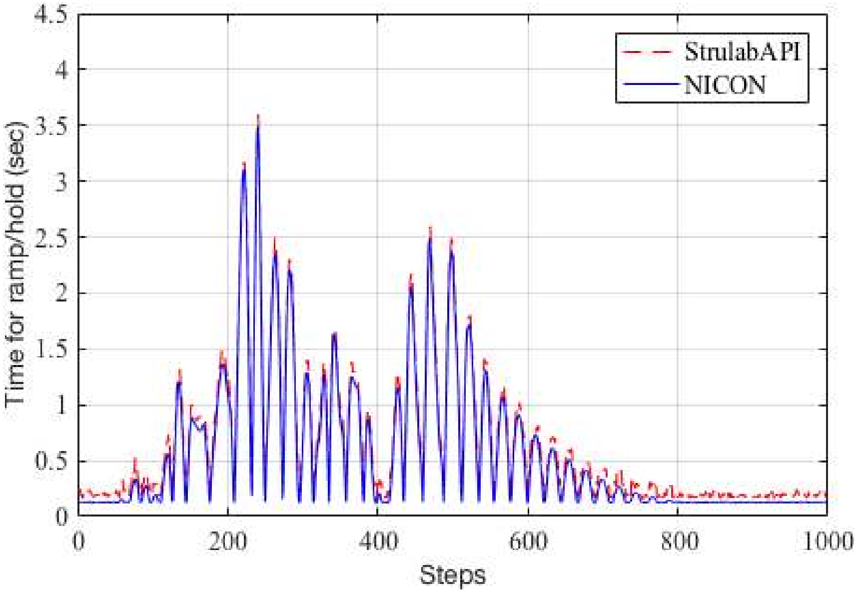
Figure 13 (middle) depicts the time, $t_{3,4}$, exclusively required to realize the command displacement: it comprises the time for displacement ramp generation and application, eventual hold periods and, in the case of StrulabAPI approach, successive attempts at 10ms intervals to acquire respective displacement/force measurements. For the selected substructure discretization the experimental part is by far the major contributor to the overall per-step delay. Notably, the per-step duration varies in each step from around 0.2 *sec* to 3.5 *sec*, a fact that can be attributed to displacement amplitude received at each step (i.e., having fixed the max piston velocity at 2 *mm/sec*, larger displacement steps of the order of 8 *mm* require more time, which was measured 3.5 *sec*, in this case).

Subtracting the respective times in Figure 12 (middle) from those presented in Figure 12 (top) it is possible to estimate the pure network communication time, which is illustrated in Figure 13, bottom - network delays shown to be reasonably low and in the range of 0.5-0.7 sec.

The two approaches employed for realizing the hybrid simulation found almost equivalent, except for some instances in which the "analog-input" approach shows unexpected delays, e.g. between 3.62 *sec* $< t <$ 3.82 *sec* and for $t = 4.95$ *sec*. These delays are due to network communication and are revealed when the time required by the analysis engine, t_1, (time-difference between receiving the response from the last module, n=5, until the next command to the first module, n=1, is sent) and the ramp/hold time in the experimental module are subtracted from the total time step duration. Even though the sporadic presence of this delay is not expected to introduce any major error in the response of the bridge at a system level, its unpredictable nature highlights the necessity for further studies to identify and minimize network latency particularly when the remote sites are widely separated, rate-dependent phenomena are involved and RTDS is pursued.

Another interesting aspect is the time required for the analysis coordinator *UI-SimCor* to communicate with each one of the five modules (substructures) for the three main configurations of the intercontinental multiplatform simulation (IMPS), the national hybrid testing (HTGR) and the Intercontinental Hybrid Testing (IHT). It is noted that in this case communication time refers not only to the network delays but also to the required time for the numerical analysis or the execution of the experiment to proceed by one time step as well as the "waiting" time of each module until *UI-SimCor* sends/ receives data in a series way (predetermined order of modules).





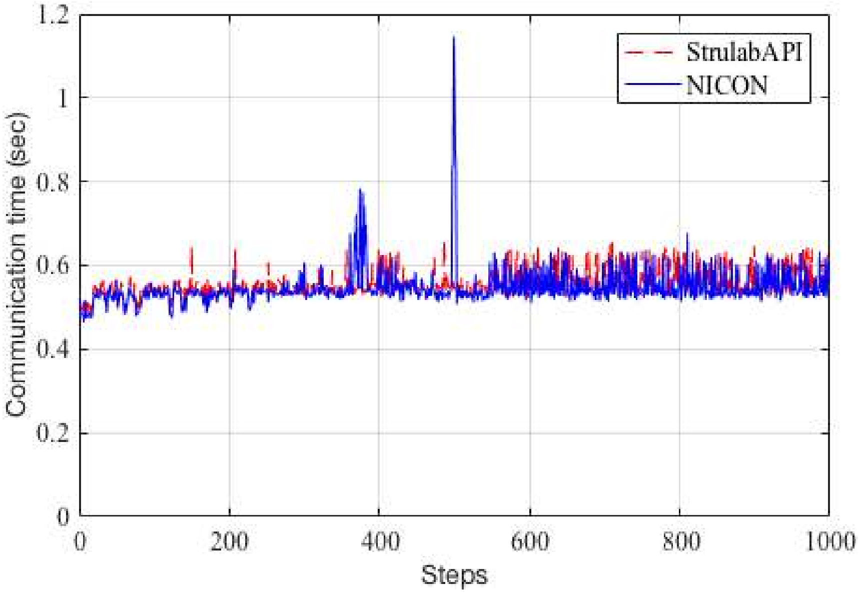


Figure 13. IHT: per step duration in the experimental module: total time, $t_{2,4}+t_{3,4}+t_{4,4}$ (top); ramp-and-hold duration per step, $t_{3,4}$ (middle); communication time per step, $t_{2,4}+t_{4,4}$ (bottom).

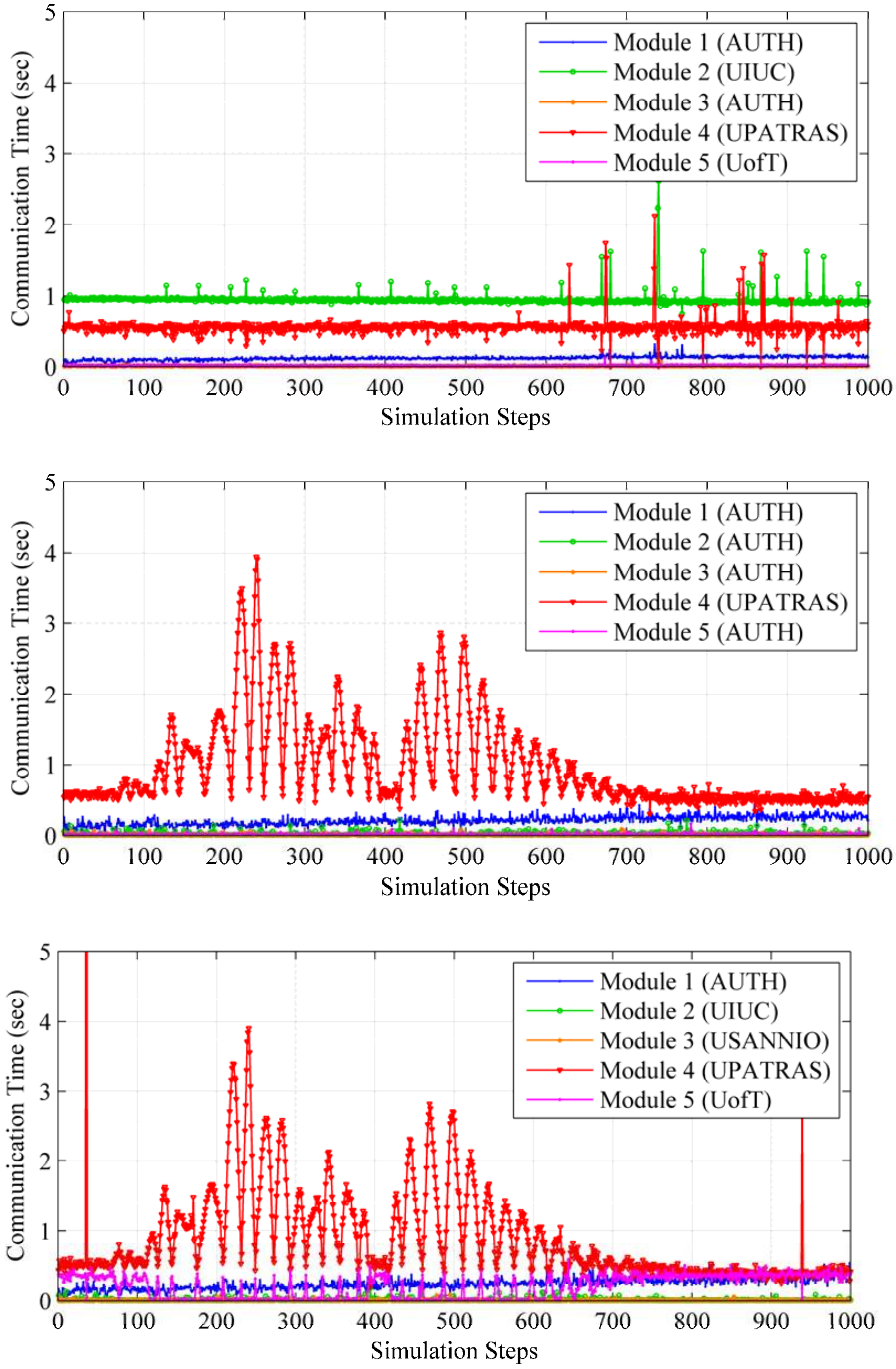


Figure 14. Communication time $(t_{2,n}+t_{3,n}+t_{4,n})$ for the Intercontinental Multi-Platform Simulation (IMPS, top), Hybrid Test between Greek partners (HTGR, middle) and the Intercontinental Hybrid Test (IHT, bottom).

Table 2. Statistical distributions and sources of variation for the communication time of each module for the IHT.

Modules	**Location of remote sites**	**Distribution observed**	**Distribution parameters (sec),** $t_{2,n}+t_{3,n}+t_{4,n}$	**Network delay,** $t_{2,n}+t_{4,n}$	**Experimental delay,** $t_{3,n}$	**CPU Time,** $t_{3,n}$
Coordinator	AUTH	-	-			
Module 1 (Deck/Elastic)	AUTH	Normal	μ=0.21 σ=0.06	-	-	x
Module 2 (Left Pier, Nonlinear)	UIUC	Log-normal	μ=0.35 σ=0.12	x	-	x
Module 3 (Right Pier, Nonlinear)	USANNIO	Log-normal	μ=0.32 σ=0.16	x	-	x
Module 4 (Left Bearing, Nonlinear)	UPATRAS	Log-normal	μ=0.78 σ=0.52	x	x	
Module 5 (Right Bearing, Nonlinear)	UofT	Log-normal	μ=0.28 σ=0.11	x	-	x

As shown in Figure 14, in the case of multi-platform simulation (IMPS), the numerical part at the most distant module from the analysis coordinator (i.e., Univ. of Illinois at Urbana-Champaign) in Module 2 required more time to communicate with *UI-SimCor* per time step, which is natural since the analysis coordinator was running in Europe. This is also an indication that the roles between different remote sites and particularly that of the coordinator should be very carefully selected based on preliminary parametric studies.

For the two national and intercontinental hybrid tests (Figure 14 middle and bottom), it is evident that the experimentally tested component (left bearing, Module 4), needed more time to establish communication with *UI-SimCor,* which is also quite anticipated since the time measured includes the execution of the experimental step.

A final issue that was studied is the variation of time delay along the entire duration of the Intercontinental Hybrid Test (IHT). This is deemed an important information as highly dispersed times required to accomplish a time step are deemed prohibitive for studying problems that are strongly rate-dependent. The statistical distribution of the communication time per step of the individual modules for the Intercontinental Hybrid Test was then examined considering three sources of variation, namely, network delay, experimental delay and CPU time of the numerical analysis, the latter including the effect of nonlinear soil, pier or bearing response under stronger ground motions in the involved sites. **Table 2** summarizes the observed distributions and the sources of variation for the communication of all modules this test as well as the sites where the response was nonlinear.

It is seen that the communication time of Module 1 (i.e. numerically analyzing the bridge deck) follows a normal distribution (with mean value μ=0.21sec and standard deviation σ=0.06sec). For this very example, since *Module 1* is numerically analyzed locally and the deck remains elastic during the hybrid test, the only source of variation is attributed to the CPU procedures in the computer station used for the coordination and the analysis of the hybrid simulation. Naturally, the coefficient of variation C.O.V. of the time required per step is kept reasonably low (0.28). Mean times and standard deviations are higher for sites running numerical analysis of substructures that exhibit nonlinear response as also shown in Table 2, corresponding to cov values between 0.35-0.50, while following a rather uniform distribution. As anticipated, the communication time of the experimental component (i.e. *Module 4*: left bearing), which integrates experimental and communication sources of variation, follows a log-normal distribution with μ=0.18 and σ=0.52.

6. CONCLUSIONS

This paper investigates the effect of remote host distance on the feasibility, accuracy and performance of hybrid simulation among long-separated sites. Both geographically distributed multi-platform analysis and hybrid simulations were performed for the case of a real three-span reinforced concrete bridge between European and North American partners. Two different approaches employed for implementing hybrid simulation. In the first, a fully featured controller was employed, while in the second the "analog-input" approach was selected. The component that was physically tested was the bearing located at the left bridge abutment, while the complementary superstructure components were numerically analyzed.

It is concluded from this study that an intercontinental experiment among five sites can be performed successfully (at a time expansion of 150-250 times), thus highlighting the increasing capabilities of geographically distributed hybrid simulation. It was also proven feasible to implement tools and procedures that are not tailored to the existing equipment in Europe after appropriate hardware and software adaptations at the local host.

From a technical point of view, the two approaches employed for realizing the hybrid simulation (i.e., fully featured controller versus "analog-input" method) were almost equally efficient, except for some instances in which the latter showed unexpected delays. These delays are due to network communication and are uncovered when the time required by the analysis engine and the ramp/hold time in the experimental module are subtracted from the total time step duration.

Clearly, the distance among remote hosts remains a crucial factor considering future Real-Time Hybrid Testing experiments particularly for studying rate-dependent physical problems among sites at great distance. This is because the time expansion tolerance of rate sensitive components or devices is counteracted by the network latency, which can only be reduced at a certain degree (particularly in terms of signals crossing the Atlantic).

On the other hand, the observation that the communication time followed certain distributions around the mean might be a useful tool in compensating for the related uncertainty while designing similar experiments. Overall, the intercontinental hybrid experiment was accomplished and repeated successfully, highlighting the robustness, efficiency and repetitiveness of the approach. However, further research is needed to minimize uncertainties, and optimize the efficiency of the communicating algorithms both at the site level and for the coordination of the multiple sites.

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