

Partitioned time integration methods for hybrid simulators



O. S. Bursi & G. Abbiati

Department of Mechanical and Structural Engineering, University of Trento, Italy

B. Wu & G. Xu

School of Civil Engineering, Harbin Institute of Technology, China

SUMMARY

The seismic performance assessment and retrofit of a concrete bridge by means of a testing program was conceived within the RETRO TA research activity of the European project SERIES. In detail, an old under designed 400m span viaduct was considered as Case Study. In this paper, initially numerical tools devoted to test the effectiveness of the seismic retrofit of the bridge by means of continuous-time hybrid simulations are presented. To this end, two implementations of a partitioned time integration method together with the OpenFRESCO software are proposed. The Numerical Substructure characterized by strong nonlinearities is simulated by means of the well-known OpenSEES FE code, whilst the Physical Substructure will be tested at the Joint Research Centre of Ispra, Italy. Since fast tests are deemed necessary to estimate the behaviour of rate-dependent isolation devices, a feasible accommodation of delay is provided. Finally, a procedure aimed at simulating damage of the whole structural system by means of identification and model-updating is suggested.

Keywords: Hybrid simulations; PM method; OpenFRESCO; OpenSees; xPC-Target; Real-time; Delay overcompensation; Model updating

1. INTRODUCTION

A full scale testing program is foreseen in the RETRO TA project, a research program of the European SERIES project (Taucer 2011). The case study consists of an old concrete viaduct shown in Fig. 1 where two independent roadways are supported by 12 couples of portal piers.



Figure 1. Longitudinal view of the Rio Torto viaduct

The linear distributed dead load of the deck is approximately 170kN/m per roadway. The length of bays varies between 29 and 33m. Six Gerber saddles interrupt the reinforced concrete beams of the deck which is connected to the piers by means of two vertical steel bars. Each pier is composed of two circular columns of variable diameter comprised between 1.20m÷1.60m. The two columns are connected at various heights by one or more transverse beams endowed with rectangular cross section as illustrated in Fig. 2. The height of the piers varies between 13.80 -near the abutments- to 41.00m -in the middle part of the bridge-. Each pier bears a vertical load varying between 5600 to 7140 kN. In order to achieve the seismic-performance requirements imposed by Italian seismic standards, which fully comply with Eurocode 8, the installation of a couple of isolation devices -one per column- for each pier portal frame interposed between the cap beam and the deck was proposed. Therefore, two isolation systems, i.e yielding-based and friction-based bearings were currently designed and characterized.



Figure 2. Views of the Rio Torto viaduct: a) portal piers and b) concrete decks

In this perspective, a coordinated effort between some RETRO TA partners is undergoing to improve the quality of pseudo-dynamic tests. Some of these actions are summarized in this paper. Initially, the OpenSEES FE model of the bridge is described. Then, hybrid simulations with dynamic substructuring are selected to prove the effectiveness of the seismic retrofit. Preliminary results from numerical simulations of the emulated structure subjected to natural accelerograms highlighted the nonlinear response of several piers; so, the OpenSEES software was adopted to emulate the Numerical Substructure (NS). The test configurations relevant to the Physical Substructure (PS) are then presented. In this context, the PM interfield-parallel integration algorithm (Pegon and Magonette, 2002, Bursi et al., 2008) is adopted to apply the continuous-time testing method. Two implementations of the PM method based on OpenFRESCO are proposed. The connection between the integration algorithm and both the NS and PS is carefully analysed. Moreover, because isolation devices might be subjected to strain rate, fast hybrid simulations are deemed necessary. To this end, two feasible delay overcompensation strategies are suggested (Wu et al., 2012). Finally, a way to take into account the non-linear behaviour of piers belonging to the NS during testing is proposed.

2. PRELIMINARY NUMERICAL SIMULATIONS AND CYCLIC TESTS

One of the two roadways of the viaduct was modelled by means of OpenSEES (Paolacci and Giannini, 2011). Nonlinear fiber beam elements were adopted; the Kent-Scott-Park model was employed to model the concrete behaviour (Kent and Park, 1971) whilst the contribution of its tensile strength was neglected (Marefat et al., 2009). Conversely, the Menegotto-Pinto model was adopted for steel reinforcements (1973). The piers were considered fully constrained at the bottom, whilst the abutments at both sides were released along the longitudinal (X) direction. Only the flexural behaviour was taken into account; as a result, both the non-linear shear behaviour of transverse beams and the influence of fix-end rotation effects owing to strain-penetration of steel bars were neglected. Some mode shapes corresponding to periods of 1.15s and 1.01s, respectively, are shown in Fig. 3.

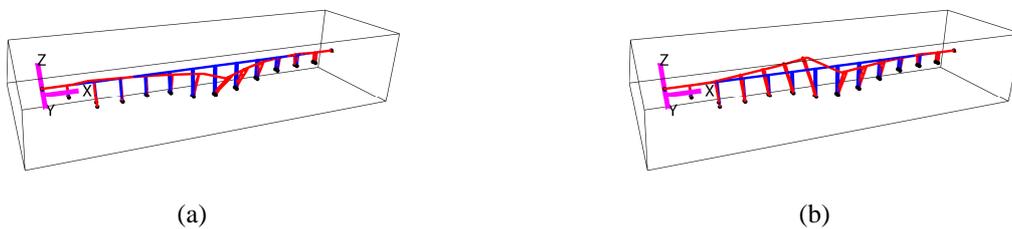


Figure 3. FE model and mode shapes of the Rio Torto viaduct: a) period $T=1.15s$; b) period $T=1.01s$.

To estimate the seismic vulnerability of the bridge, some preliminary nonlinear time-history analyses were carried out. A nonlinear response of piers was observed whilst the deck remained linear. Maximum PGA values and relevant limit states are summarized in Table 1.

Table 1. PGA values for different limit states

	Damage limit LS	Life safety LS	Collapse prevention LS
PGA	0.174g	0.308g	0.352g

A series of experimental tests were carried out at Roma Tre on three 1:4 scale mock-ups of the 12th portal frame pier (Paolacci and Giannini, 2011). In order to characterize their nonlinear hysteretic behaviour, a cyclic horizontal displacement was applied at the cap-beam level of the mock-ups by means of hydraulic actuators. Specimen failure always occurred by cracks opening both at the top and at the bottom of piers, followed by collapse of transverse beams. Experimental results allowed for a proper tuning of fibre-based elements of OpenSEES.

3. SET-UP FOR HYBRID SIMULATIONS

The performance of the bridge and of the retrofitting system, which is characterized by strongly nonlinear hysteretic behaviour, can be estimated by means of continuous-time hybrid simulations.

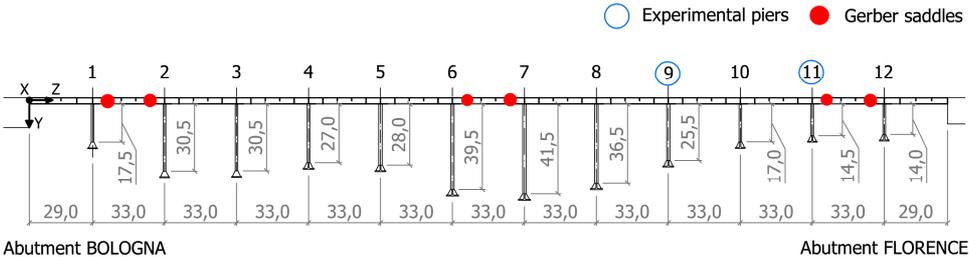


Figure 4. Structural scheme and main dimensions (in m) of the Rio Torto viaduct

Fig. 4 highlights piers 9 and 11; together with relevant Gerber saddles; these piers will be experimentally tested in the laboratory of Joint Research Center at Ispra in a scale 1:2.5. A FE-based OpenSEES model will emulate the remainder of the structure. Differently from the FE model already implemented and described in Section 2, it will be characterized by plastic hinges as well as localized hysteretic behaviour. In fact, the solution time of the NS is crucial and must be of the same order of magnitude of the controller time-step, which lasts few milliseconds. Fiber models of piers may require some minutes of computation and so they are not feasible to this end.

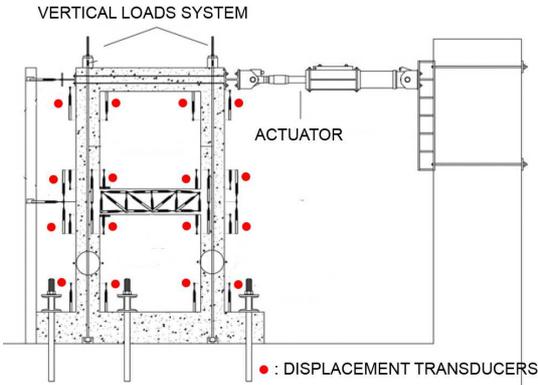


Figure 5. Experimental set-up relevant to a pier subject to test

Fig. 5 and 6 depict the experimental set-ups conceived for the PSs. With reference to piers, actuators are connected at the cap-beam level. Conversely, isolation devices and relevant actuators are placed at the floor level. For the time being, the NS is approximately characterized by 200 DoFs.

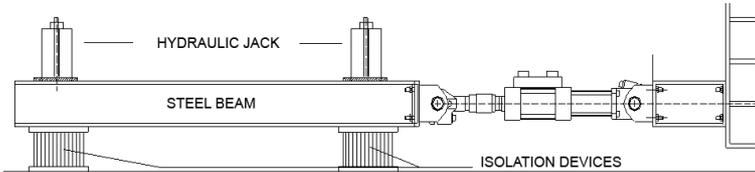


Figure 6. Experimental set-up relevant to isolation devices

4. THE PM METHOD

The PM method is an interfield parallel partitioned integration algorithm originally formulated for continuous Pseudo Dynamic (PsD) testing by Pegon and Magonette (2002); it allows for the coupling of implicit and explicit time integrators dealing with different time-step lengths for each subdomain. The PM method was further numerically and experimentally investigated by Bonelli et al. (2008), who proved its favourable stability and consistency properties. The proposed implementation of the algorithm considers Newmark integration schemes for both subdomains A and B. Fig. 7 shows the task sequence for the case with substepping, i.e. $ss = 2$.

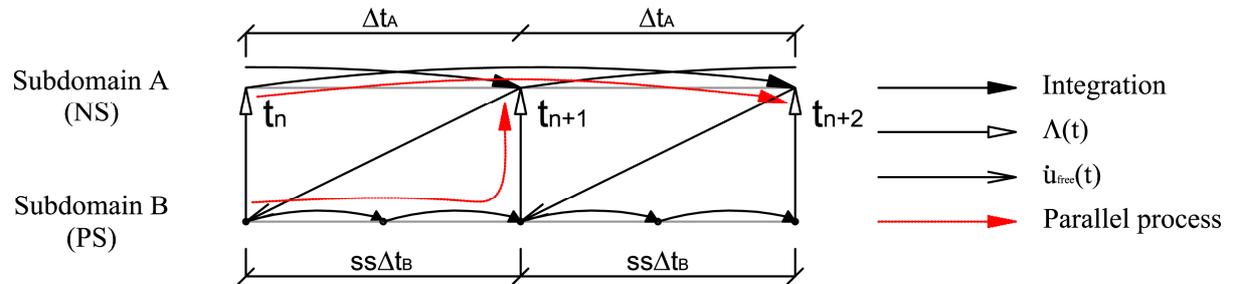


Figure 7. Task sequence of the PM method

The NS is characterized by strong nonlinearities and is simulated by means of the well-known OpenSEES FE software available within the SimDomain Experimental Control class of OpenFRESCO. In order to compute the transient analysis of the whole emulated system, Newmark-based time integration algorithms are available from the same OpenSEES FE framework. Because the computational burden is not compatible with the fine time step of the controller, such monolithic algorithms fail in the case of complex NS characterized by several DoFs. Therefore, two ways to take advantage of the partitioned PM method without any change of the original source code of OpenFRESCO are proposed herein: Implementation #1 - the Matlab software is employed to implement the PM method, whilst the OpenSEES framework is exploited to simulate NS; furthermore, the OpenFRESCO software manages the data transfer between Matlab and the experimental control system. A predictor-correct finite-state algorithm running on the xPC-Target machine keeps actuators moving during the Matlab computation; Implementation #2 - a Simulink model of the PM algorithm is implemented on a real-time xPC-Target machine, whilst the OpenSEES framework is exploited to emulate NSs on the Host-PC; furthermore, the Generic Client Element Simulink block manages the data transfer between the xPC-Target and the Host-PC. OpenFRESCO connects finite element models with control and data acquisition systems to standardize the deployment of such tests on structural systems. To this end, OpenFRESCO can act as: i) middleware for a wide variety of computational software packages, including: OpenSEES, MatLAB, Simulink, LS-DYNA, Abaqus and UI-SimCor; ii) interfaces with many popular experimental control and data acquisition systems manufactured by dSpace, MTS, SCRAMNet, Shore Western, etc. The main classes provided by the framework of OpenFRESCO are: - *Experimental Site*: it provides the communication methods for distributed testing over TCP/IP, NHCP, or UDP protocols; - *Experimental Setup*: it represents a software abstraction of the actual experimental set-up in the laboratory; - *Experimental Control*: it defines the interface to different control and data acquisition systems in the laboratories. It is used to construct the xPC-Target Experimental Control Object. These classes extend the Tcl/Tk framework and are managed by Tcl scripts. The *SimAppSiteServer* service provides the connection via TCP/IP protocol. Further details of Implementations are given herein.

4.1. Implementation #1

By using OpenFRESCO, trial displacements calculated within MatLAB by the PM algorithm are sent both to the PS and NS, respectively, and the corresponding reaction forces are measured back to MatLAB, in order to compute the next displacement command. To this end, the Middle-tie server architecture is adopted. The PM MatLAB algorithm communicates with OpenFRESCO by the

TCPsocket.mexw32 mex file via TCP/IP protocol. The corresponding experimental equipment is shown in Fig. 8.

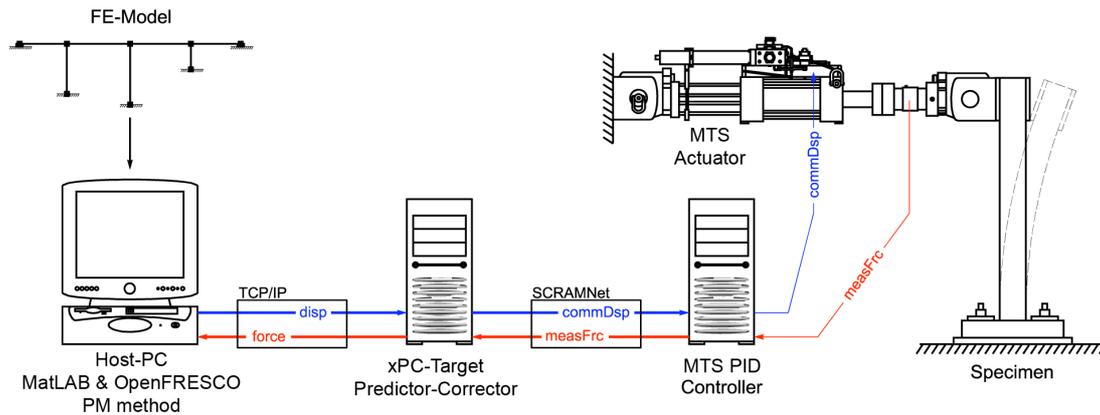


Figure 8. Arrangement of the experimental equipment

MatLAB and OpenFRESCO codes are implemented in the Host-PC, and the Predictor-Corrector model runs on the xPC-Target real-time machine. The NS is analysed by the OpenSEES framework on the Host-PC whilst the PS is handled by MTS controller. The block diagram of Fig. 9 depicts the architecture of the hybrid simulation.

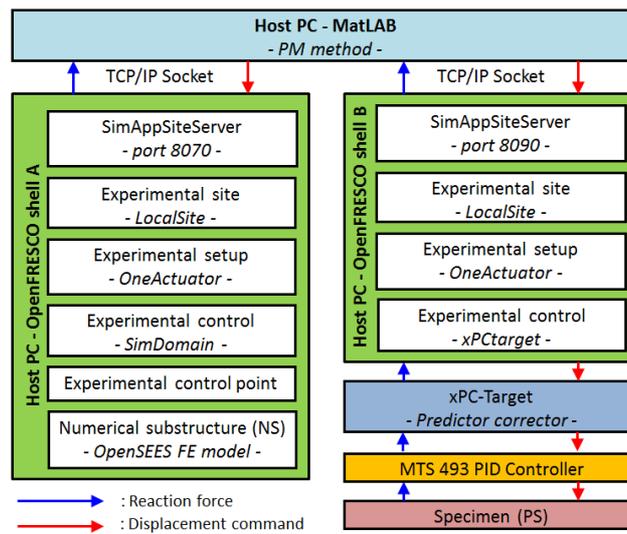


Figure 9. Block diagram relevant to Implementation #1

The xPC-Target acts as a link between the Host-PC and the MTS controller. The Shared Common RAM Network (Scramnet) GT200 shares memory between xPC-Target and MTS controller. The Scramnet is a real-time communications network, based on a replicated, shared memory network. The control signal, such as displacement command, written locally to the xPC-Target computer is instantaneously copied to the controller computer in the network, and the measured signal, such as reaction force, written locally to the controller computer is instantaneously copied to the xPC-Target computer in the network. The xPC-Target is accessed from the Host-PC through an Ethernet connection and runs a Simulink predictor-corrector model. The predictor-corrector is an event-driven algorithm that keeps the actuator moving during the MatLAB computation. As shown in Figure 10, the displacement command sent to the actuator is extrapolated by means of Lagrange polynomials from the previous time step solutions -extrapolation task- (Shellenberg, 2008) until the displacement solution at time t_1 is not available; since the time integration task is accomplished by the Host-PC, the displacement command is interpolated over the last four displacement solution -interpolation task-.

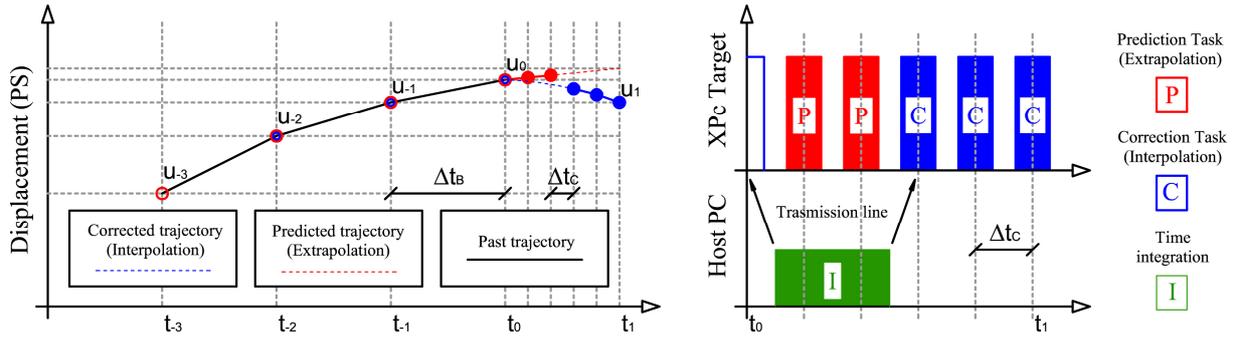


Figure 10. Predictor-corrector task sequence in OpenFRESCO

The *Experimental Control SimDomain* object, together with the *Experimental Control Point*, allow for simulation of an actual experimental specimen by handling a set of DoFs of the emulated OpenSEES FE model. They can also be used to test an experimental set-up and a network communication to ensure that all non-experimental aspects of a hybrid simulation are properly set before conducting an actual experiment (Schellenberg et al., 2009). This implementation was tested on a split-mass SDoF system at the University of Trento shown in Fig. 11a. The PS corresponded to the subdomain B and consisted in a HE 140A steel profile with an effective height of 1.35m. A PsD and a fast-time test with time scale of 10 and 1, respectively, were conducted. Both columns were considered clamped at the base and hinged to the truss. The properties of the analysed system read,

$$m_A = m_B = 5.31 \cdot 10^4 \text{ kg}, k_A = 2.10 \cdot 10^6 \text{ N/m}, k_B = 1.94 \cdot 10^6 \text{ N/m}, c_A = c_B = 3.34 \cdot 10^4 \text{ Ns/m}$$

An equivalent numerical damping of 5 per cent was added to the system. The corresponding specimen set-up is shown in Fig. 11b

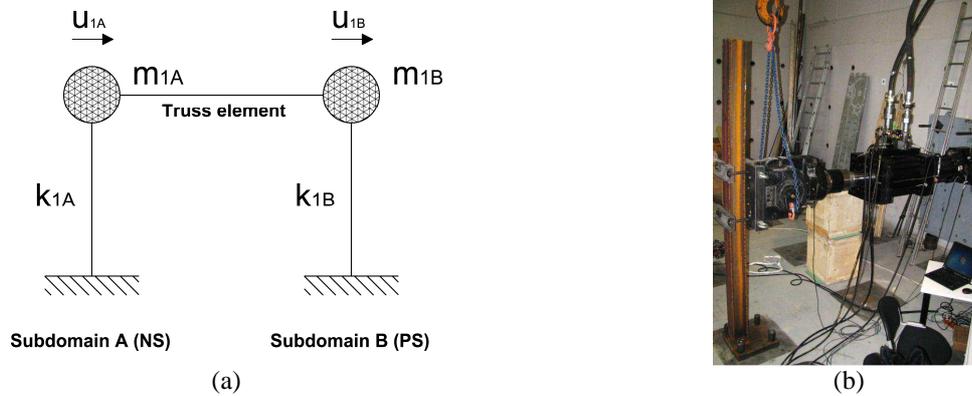


Figure 11. a) Emulated SDoF system b) Test set-up of the PS

Table 2 summarizes the parameters of the time integration schemes adopted for both the PsD test and the Fast-Time test.

Table 2. Time integration schemes setting

Subdomain	Integration scheme	Δt	γ	β
A	Implicit-Newmark	20 ms	1/2	1/4
B	Explicit-Newmark	20 ms	1/2	0

The system was subject to the NS component of the 1940 El Centro earthquake record with a PGA of 0.20m/s^2 . The NS was simulated by the SimDomain Experimental Control class of OpenFRESCO.

With regard to the pseudo-dynamic test, the time scale was chosen to be 10, which means that each laboratory time step lasted 0.20s whilst the integration time step was chosen to be 0.02s.

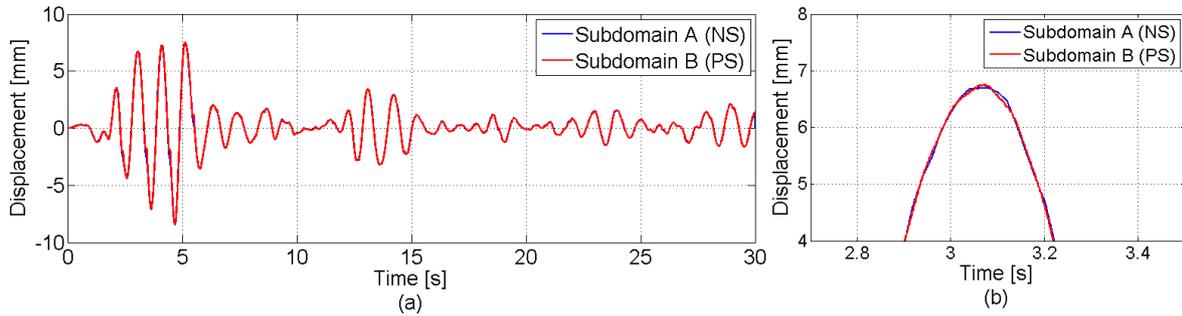


Figure 12. Displacement response at the interface DoF and relevant zoom

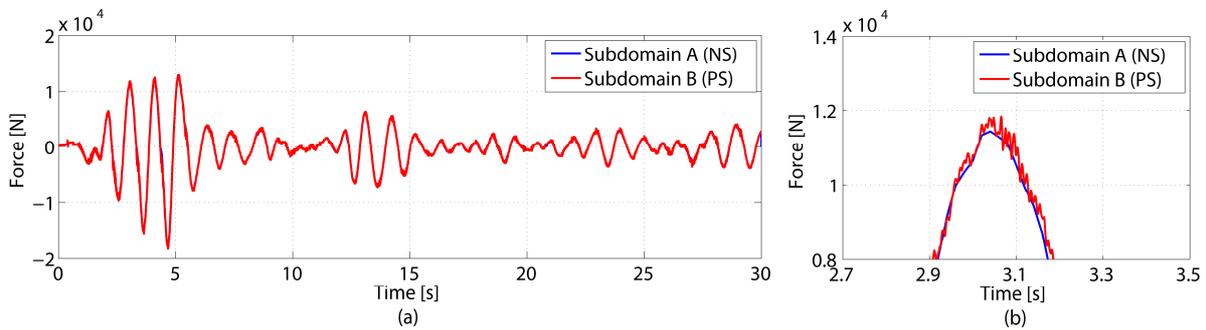


Figure 13. Reaction force at the interface DoF and relevant zoom

The displacement response of the coupled system is shown in Fig. 12. The numerical solution agrees with the physical one. The same conclusion can be drawn for the reaction force depicted in Fig. 13 although the signal from the load cell was characterized by a greater noise than the numerical solution. Also a fast time test was conducted. See Abbiati et al. (2012) for further details.

4.2. Implementation #2

A Simulink model of the PM algorithm is implemented on a real-time xPC-Target machine, whilst the OpenSEES framework is exploited to emulate the NS on the Host-PC; furthermore, the Generic Client Element Simulink block provided by OpenFRESCO manages the data transfer between the xPC-Target and the Host-PC. The relevant arrangement is shown in Fig. 14. With respect to the previous implementation, there is no need to employ any predictor-corrector algorithm: the continuous-time testing is achieved thanks to the subcycling capabilities of the PM method, which synchronizes the PS integration time step with the controller time step.

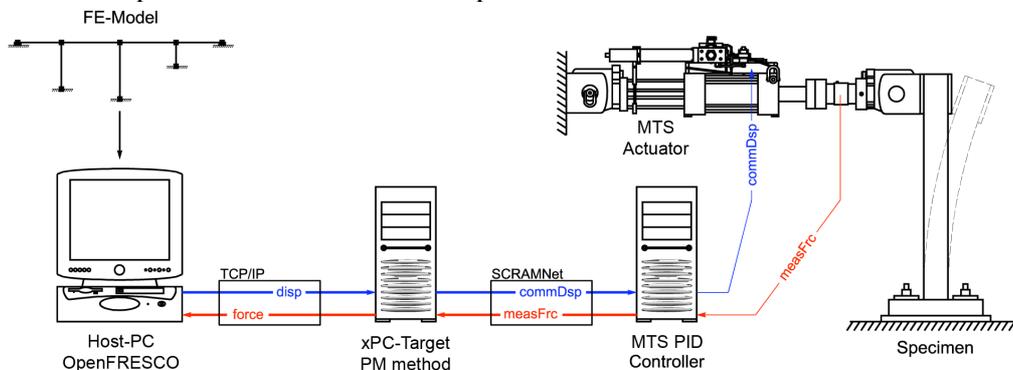


Figure 14. Arrangement of Implementation #2

The PS is handled by the MTS controller. Fig. 15 describes the implementation of the second architecture proposed by means of a block diagram. The TCP/IP protocol manages the data transfer between the xPC-Target, the MTS controller and the Host-PC.

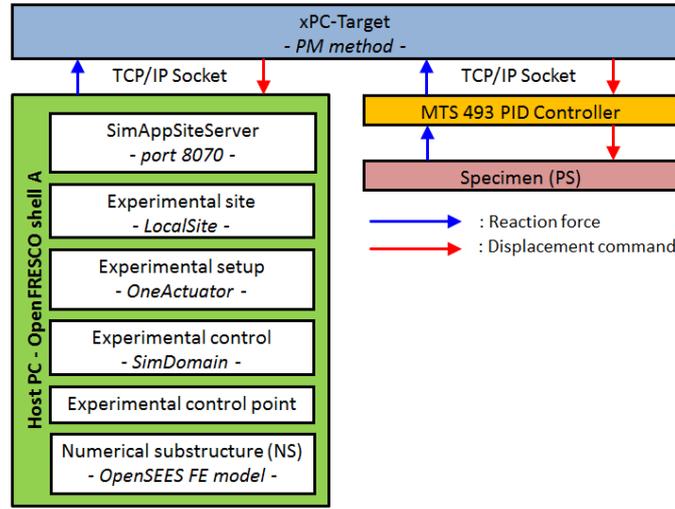


Figure 15. Block diagram relevant to Implementation #2

5. DELAY COMPENSATION WITH THE PM METHOD

Since real-time tests are deemed necessary to accurately estimate the possible behaviour of rate-dependent isolation devices, a feasible accommodation of the delay overcompensation strategy is provided. Here, we propose the novel delay overcompensation method introduced by Wu et al. (2012). The idea of delay compensation in the time domain is to send the displacement command at least a delay τ in advance the expected time needed to achieve the desired displacement. Delay compensation is based on the delay estimation and a structure response prediction. The idea behind the new compensation technique is to assume that the delay is bounded by $\tau_{c,i}$ and $\tau_{c,s}$; by its upper limit $\tau_{c,s}$, the displacement command is overcompensated in order to let the desired displacement x_d at time t_n to be achieved earlier than it should be. The corresponding reaction force f_d is then interpolated and fed back to the NS. To this end and in agreement with Fig. 16 an optimal instant $t_{op,n}$ must be defined; it occurs when the measured displacement $x_m(t)$ matches the desired displacement $x_d(t_n)$.

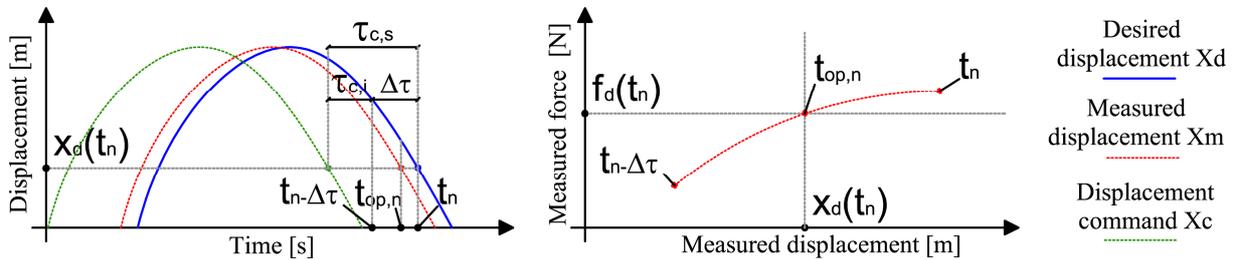


Figure 16. Delay overcompensation scheme

The optimal problem can be formulated as follows:

$$t_{op,n} = \arg \min_t |x_m(t) - x_d(t_n)|, t \in [t_n - \Delta\tau, t_n] \quad (1)$$

Evidently, as long as the desired displacement $x_d(t_n)$ matches the chosen measured displacement $x_m(t)$, exact delay compensation is achieved, which means that the measured force f_d corresponds to the desired displacement $x_d(t_n)$ without errors owing to prediction methods and actuator control. To accommodate this technique within the PM algorithm, two strategies of displacement forward predictor are proposed. The first technique is standard and it was already proposed by Horiuchi et al. (1996). The actuator commands are extrapolated over the last few solutions of the PS by means of Lagrange polynomials.

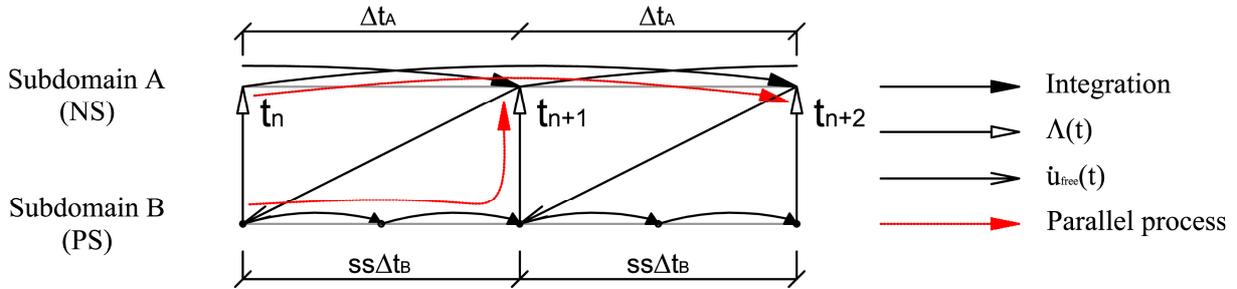


Figure 17. Task sequence of the PM method

As shown in Fig. 17, subcycling in the PS enables for complex NS characterized by nonlinear behaviour and several DoFs. As further advantage, none of predictor-corrector algorithms are still necessary. The second technique employs the predictive capabilities of the PM method. In greater detail as shown in Fig. 18, the switching of NS and PS allows for the predictive part of the PM algorithm to overcompensate the displacement command.

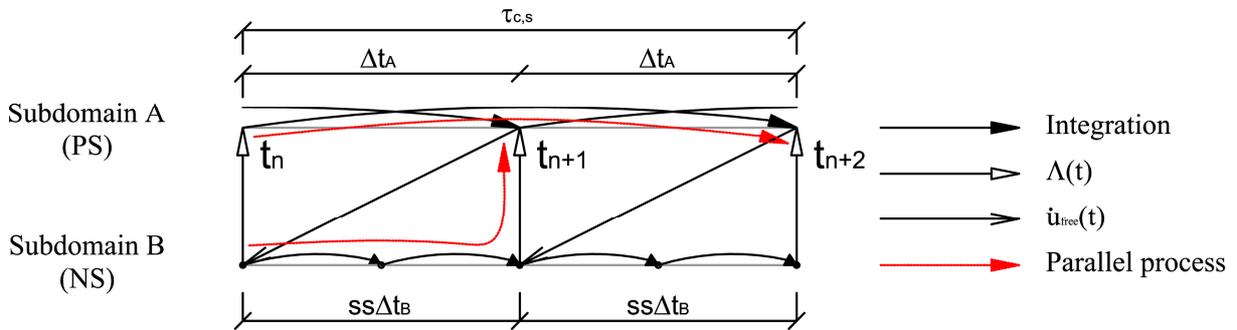


Figure 18. Modified task sequence of the PM method

The coarse time step adopted for the PS must be assumed equal to half of the overcompensation time $\tau_{c,s}$. In this case, the fine time step is adopted to integrate the NS. Subcycling in the subdomain B can improve the accuracy of the NS, when the initial stiffness operator is employed in the integration, e.g. when the Operator-Splitting method is exploited. Since the coarse time step is adopted for the PS, a predictor-corrector algorithm must be used in order to keep the actuator continuously moving during the computation.

6. OFFLINE IDENTIFICATION AND TUNING PROCEDURE

As highlighted by Paolacci et al (2011) during the seismic event most of the damage is concentrated within the piers, whilst the deck remains almost linear. A procedure to take into account the degradation of piers belonging to the NS is proposed hereinafter. The basic idea is to perform hybrid simulations at increasing PGA levels, in order to identify the increasing nonlinear behaviour and update the NS accordingly. A recursive procedure, consisting of alternating offline identification and tuning tasks follows. The identification task is accomplished by means of time-frequency

identification techniques combined with parametric identification (Bursi et al., 2012). The offline identification task deals with differential equations in discretized form that cannot be treated by typical FE element codes, but must be solved with proper numerical tools. This type of tools are not suitable for real-time implementation, hence the need for an offline FE- model tuning.

7. CONCLUSIONS

The case study of the Rio Torto viaduct was presented within the framework of the RETRO TA research activity. Initially, the results of previous investigations about the vulnerability assessment of the bridge and its dynamic behaviour, conducted by means of FE OpenSEES models and experimental cyclic tests were summarized. In order to evaluate the effectiveness of the seismic retrofit proposed, a set-up for hybrid simulations was presented. In this respect, to adopt the continuous-time testing strategy, two possible implementations of the PM method were proposed. Some relevant experimental test was shown. Since isolation devices can be characterized by rate-dependent behaviour, the architectures proposed were devised to take into account actuators delay by means of a novel overcompensation strategy. Finally, to simulate damage occurring during seismic events within emulated piers, an offline recursive identification-tuning procedure working at different PGA levels was suggested. Numerical simulations of the whole hybrid test campaign will be the subject of the forthcoming research activity. As outlook, further investigation will be conducted to improve the PM algorithm, in order to avoid numerical energy dissipation at the interface among subdomains.

ACKNOWLEDGEMENT

The authors greatly acknowledge the support of Shawn You of MTS and the financial support from the European Union through the SERIES projects (Grant number: 227887). Nonetheless, opinions are those of the author.

REFERENCES

- Abbiati G., Bursi O.S., Molinari M., Xu G. (2012) Use of Partitioned Time Integration Schemes for Parallel Simulations of Hybrid Systems. Proc. of the 5th European Conf. on Struct. Control, Genoa, 18-20 June.
- Bonelli A., Bursi O.S., He L., Magonette G., Pegon P., (2008). Convergence analysis of a parallel interfield method for heterogeneous simulations with substructuring. *I. J. for Num. Meth. Eng.*, 75, 7, 2008, 800-825.
- Bursi, O.S., Ceravolo, R., Erlicher, S., Zanotti Fragonara, L., Identification of the hysteretic behaviour of a partial strength steel-concrete moment-resisting frame structure subject to pseudo-dynamic tests, *Earthquake Engineering & Structural Dynamics*, 27 FEB 2012 | DOI: 10.1002/eqe.2163.
- Horiuchi T., Nakagawa M., Sugano M., Konno T. (1996). Development of real-time hybrid experimental system with actuator delay compensation, Proc. 11th World Conf. on Earthquake Eng., Acapulco, paper 660.
- Kent DC, Park R. (1971) Flexural members with confined concrete. *J. Struct Division, ASCE*, N. 97, 1969–1990.
- Marefat M.S., Masood S., Shirazi H., Rostamshirazi R., Khanmhamadi M., (2009). Cyclic Response of Concrete Beams Reinforced by Plain Bars, *Journal of Earthquake Engineering*, 13:463-481.
- Menegotto M, Pinto PE. (1973) Method of Analysis for Cyclically Loaded R.C. Plane Frames Including Change in Geometry and Non-Linear Behavior of Elements under Combined Normal Force and Bending. Proc. of IABSE Symposium on Resistance and Ultimate Deformability of Structures Acted on by Well Defined Repeated Loads, Vol.13, 1973; 15–22.
- Paolacci F., Giannini R., (2011). An experimental and numerical investigation on the cyclic response of a portal frame pier belonging to an old reinforced concrete viaduct, *Earthquake Engineering & Structural Dynamics*, DOI: 10.1002/eqe.1175
- Pegon P. and Magonette G., (2002). Continuous PSD testing with nonlinear substructuring: presentation of a stable parallel inter-field procedure. Technical Report 1.02.167, E.C., JRC, ELSA, Ispra, Italy.
- Schellenberg, A., 2008, "Advanced Implementation of Hybrid Simulation," Dissertation, University of California, Berkeley.
- Schellenberg A., Kim H. K., Takahashi Y., Fenves G. L., and Mahin S. A., 2009. OpenFRESCO Command Language Manual. Version: 2.6.
- Taucer F., (2011). Seismic Engineering Research Infrastructures for European Synergies: Activities of the Joint Research Centre in large scale experimental testing within the framework of the Eurocodes, 7th International conference on structural defects and rehabilitation, 2-4 June, Fortaleza, Brazil.
- Wu B., Wang Z. and Bursi O.S., (2012), Actuator dynamics compensation based on upper bound delay for real-time hybrid simulations, *Earthquake Engineering and Structural Dynamics*, submitted.