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Advanced Hybrid Simulation Application Platform

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***Abstract*—The design of complicated structures for high level performance under accidental actions has been a scientific challenge in the field of civil engineering, with social and economic implications. The method of hybrid simulation lends itself as an efficient tool in unveiling the nonlinear response of structural systems. The present research aims to evaluate the technical aspects of a hybrid simulation (HS) implementation platform, making use of the current knowledge but paving the way to future extensions in multi-physics problems.**

***Keywords*—hybrid simulation, substructures, control system, earthquake engineering, multi-hazard**

I. Introduction

New structures are expected to satisfy the ever-increasing level of performance requested by users, as failing to service their complicated functions has significant social and economic implications. New methods of construction, innovative materials and the requirements for structures' enhanced performance/quality (in structural, environmental, maintenance, durability, sustainability and resilience terms), challenge modern engineering. The computational tools available fail to offer reliable models representing accurately the complicated, non-linear response of structures (cracking, residual deformation, stiffness degradation due to cyclic loading, strength degradation due to fire effects, strength increase due to strain rate effects, redistribution of forces due to accidental loss of support) and it is not uncommon that existing models are used beyond their calibrated range of application. In addition, codes of practice lag behind in incorporating new knowledge.

Although experimental testing is expected to provide reliable answers to research questions, its use is rather limited: existing facilities cannot cope with the increased and differentiating needs for testing – especially at full-scale due to issues linked to testing scaled-down specimens – while the cost of building new facilities is prohibitive.

An effective solution to the aforementioned issues has been the better use of existing testing facilities via a new approach: sub-structured testing. A structure is discretised in individual components (*substructures*) in such a way that numerical modelling is employed only for the sub-structures the response of which is relatively well known through analytical tools (*numerical substructures*), while the rest sub-structure(s) are physically tested in the lab (*physical substructures*).

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The approach has been generalized and nowadays termed as Hybrid Simulation (HS), to include all of its many possible configurations.

II. Hybrid Simulation method

In hybrid simulation method, a simulation coordinating software manages the status and the flow of information among sub-structures; in addition, it may (or may not) perform the task of numerically integrating the differential equations describing the problem at hand (for seismic testing, the equations of dynamic equilibrium). The structure may be decomposed in numerical only, experimental only, or numerical and experimental sub-structures. At each loading step, the value of the target displacement to be executed is delivered to every substructure via network and the corresponding force is received as feedback. Obviously, attention has to be paid that the boundary conditions among the substructures closely represent the actual ones. For the physical substructures, servohydraulic actuators are employed to apply the target displacement to specimens (and return the respective reaction forces), while structural analysis software is used to return the reaction force from each numerical sub-structure. This unified (numerical-experimental) approach, combines realism, flexibility and thrift, using laboratory infrastructure selectively and appropriately for the problem at hand, in order to maximize effectiveness.

The outmost advantage of hybrid simulation comes into picture when structures need to be tested at full scale, while available laboratory facilities fall short in satisfying this demand. The need for testing at full scale derives from the inability to satisfy similitude requirements for scaled models, from the complicated nature of the structure or from the strongly nonlinear nature of the response of some structures. Hybrid simulation with sub-structuring is also the method of choice in those cases that the response of a particular part of the structure is only of interest, while the rest can be satisfactorily modelled numerically.

One important asset of hybrid simulation is that discretizing the structure into a distributed system of sub-structures, the individual components (be it numerical or physical specimens) can be treated simultaneously – via network – at different, even geographically distributed, research facilities. Depending on capabilities available at each facility (e.g. in-house developed software, experience in specialized numerical techniques, specific laboratory devices and facilities, capability of applying specific type of loading on specimens), each research group treats independently and with the most appropriate tools the (numerical or physical) sub-structure assigned to it. At each time step, the deformation at the interface of sub-structures is sent to be applied to every substructure and the respective reaction force is expected. Various simulation coordinator software have been developed for the implementation of hybrid simulation method, such as

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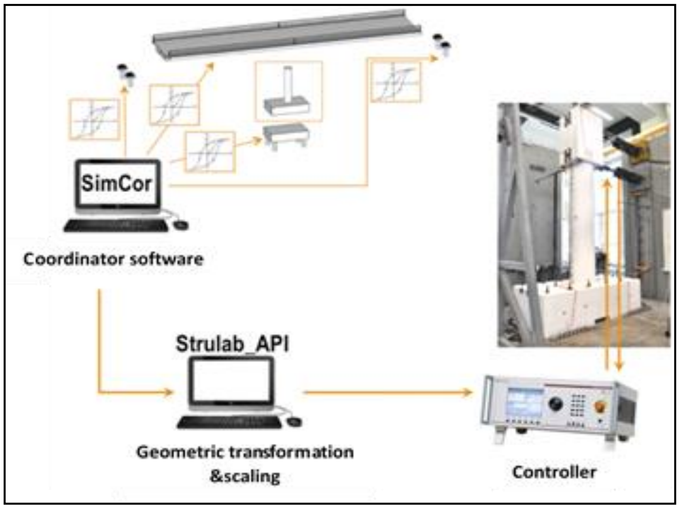

Figure 1. Hybrid simulation bridge scheme.

OpenFresco (Open-source Framework for Experimental Setup and Control) and UI-SimCor) (Fig. 1).

Hybrid simulation has the potential to cope with real engineering issues which vary from the response of bridge piers to multi-physics coupled phenomena, e.g.:

- Thermomechanical problems.
- Soil – structure interaction problems.
- Structures subjected to offshore hazards (tsunamis) or offshore structures suffering sea waves and wind.
- Response of energy effective systems mounted on buildings under seismic loading.

III. Practical issues in HS

Even though hybrid simulation has been very efficient at the field of Earthquake Engineering, its application to other scientific fields is not straightforward, mainly due to the coupling between the different loading types applied simultaneously. Examples of such cases are fires induced to structures during or after an earthquake, the response of bridge seismic protection systems (bearings) at low temperatures, the soil-structure interaction, the response of pressurised energy networks crossing seismic faults and wind-plus-wave loading on offshore structures.

In addition to the existent gap in theoretical knowledge for expanding HS to fields beyond earthquake engineering, application of HS presents complex technical issues and requires specialised competences. It is for this reason that the method is applied in only a limited number of facilities worldwide. As multi-faceted tools are employed in HS, i.e. simulation coordinator software, compatible numerical analysis software, communication protocol, servohydraulic control systems, etc., the user is facing many technical issues. For widening the range of application of HS, not only users should be exempted from the overburden incurred, but further developments are necessary for expanding the application of the method to cases of different actions and their combinations

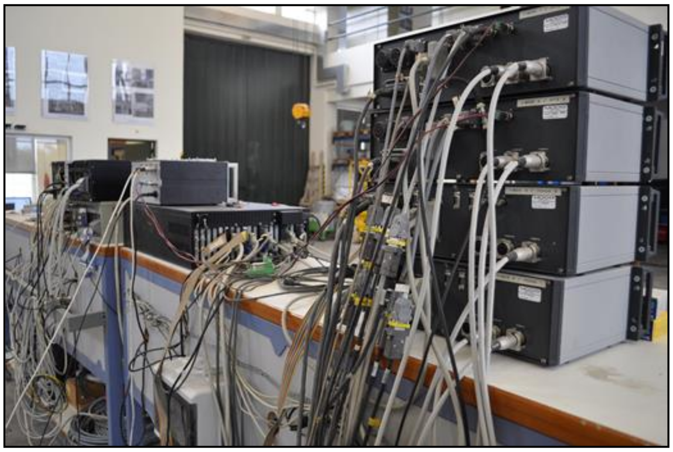

Figure 2. Typical cabling of actuator control system.

/coupling thereof (e.g. earthquake and fire). It is worth noting that, except for some special cases in earthquake engineering, numerical analyses software do not a priori support network communication liaising with the coordinator software and laboratory control systems (which respect certain limitations). Research groups assemble the hybrid simulation platform by selecting available tools (often developing new ones) and combining them with the control testing system in the host lab. The Structures Laboratory (Strulab) in Patras, Greece has been using so far, a hybrid simulation application platform comprising:

- simulation coordinator software: UI-SimCor
- numerical analysis software: Opensees
- custom made cards control software for actuator controllers: JRC
- real-time operating system (ETS) for actuator control software.

The above configuration cannot meet the requirements of expanding the application of hybrid simulation method and also is technically hard to use (Fig. 2).

The work presented here describes the investigation and implementation for a new HS system that will be more versatile and technically easier to assemble.

IV. Multi-hazard testing platform

In order to upgrade the current hybrid simulation application platform to be efficiently extended to other than earthquake engineering problems, such as multi-hazard problems, multi-physics problems, multi-scale problems, one should determine the requirements that the enhanced system should fulfil.

Theoretical thermomechanical problems in structures (e.g. fire and static/seismic loading) were used as reference on how hybrid simulation method could be improved to cope with problems related to various multi-physics actions on structures. Knowledge of structural response under fire falls short regarding the representation of the interaction phenomena between the structural response (including force redistribution) and fire evolution and its effects on material properties. Current knowledge is mainly based on tests on individual members exposed to standardized (non-real) temperature curves and with no concern for any interaction with the rest structure – very few experimental results on full- or large-scale specimens are available. This implies that the actual risk structures bear under fire cannot be accurately estimated. To that end and for developing performance-based strategies to fully evaluate the structural response for fire phenomena, current experimental capabilities should be advanced.

A main issue concerning thermomechanical problems in structures is multi-physics coupling. In general, substructures are mechanically (via displacements and corresponding reaction forces) and thermally (via temperature and corresponding heat flow) coupled. In thermomechanical problems, the fire evolution analysis – the temperature spreading from the fire source to the surrounding structural elements – precedes. Subsequently, the information is transferred to the stage of thermomechanical response analysis, which includes thermal response analysis (calculation of conductivity and radiation at the surface of the structural members and the heat spreading towards their core) and static response analysis. Coupling of fire evolution analysis and thermomechanical response analysis may be a unidirectional (the fire evolution analysis is completed first and afterwards the information is sent to the thermomechanical response analysis) or bidirectional procedure (the temperature and displacement fields of thermomechanical response analysis modify the state at the surface of the elements and that change is taken into account at each step of the fire evolution analysis). An obstacle in the implementation of the second and more proper approach (bidirectional procedure) comprises differences in the discretization of the structural elements – sparse at the stage of fire evolution analysis and dense at the stage of thermomechanical response analysis: the data exchange becomes difficult and the time scale between the fire evolution analysis and the thermomechanical response analysis is different. In addition, not only the physical substructure but also the numerical one has to be exposed in heat loads requiring proper software. Also, the physical substructure has to transfer to the numerical one the heat flow at their interface via proper laboratory equipment.

The time scale of testing the physical substructure should fulfill the limitations set by the different evolution rate of fire (minutes) and the dynamic phenomenon (e.g. earthquake in seconds) and by the changes at the boundary conditions as the fire evolves. The latter demands an almost real time execution of the hybrid simulation - considering creeping phenomena due to high temperatures – unless alternative approaches are developed, given the present laboratory equipment inadequacy.

From the software point of view, the simulation coordinator software has to transfer to all the substructures the information related to gas temperature, the radiation and mass conductivity at the fire space. To continue the analysis there are two options: the thermal and mechanical analysis of the numerical substructure take place within the same software (e.g. Abaqus, Safir software) with all the appropriate information provided by the fire evolution analysis, or the thermal effect can simply be considered either as causing no mechanical deformation corresponding to calculated nodal forces or as causing change of mechanical characteristics of the material. The first approach is closer to reality, but very few software can fulfil it (supporting network service), while the second is rough enough but also flexible, as operations can be performed within the analysis software.

V. Advanced HS platform

The issues mentioned above, lead to the requirements that both hardware and the software of the advanced hybrid simulation platform should satisfy.

A. Hardware

The intended expansion of hybrid simulation method in new scientific directions requires availability of advanced tools (hardware), communication protocols and control/coordinator software.

Most of the existing laboratory facilities either do not possess the appropriate equipment or their servohydraulic actuator control system is out of age, consisting of custom-made electronic components, lacking flexibility, capability of expansion, network communication, reliability and testing quality. The main disadvantages of existing hardware can be summarized as:

- low quality of signals, due to digital-to-analog conversion away from signal source
- extended, analog type, wiring with high noise to transmitted signal ratio
- inability of internal communication between the units controlling each actuator
- limitation in the number of actuator control units supported by main testing controller

To overcome the above obstacles, state-of-the art components were acquired: power supply, analog input/output, digital output, loadcell and optical encoder signal conditioner etc., offering efficient support of Ethernet protocol with real time response down to I/O level (EtherCAT type), capability of real time testing (reduction of delays) and cost effectiveness. Utilizing these components, control units were assembled and positioned on the servohydraulic actuators, reducing the distance between signal sources (force, displacement, servovalve voltage, valve on/off etc.) and point signal conditioning (amplification and AD conversion). A single digital bus facilitates internal communication among all the actuator control units (no matter the number) and the master controller software (Fig. 3).

The new philosophy, the capability of self-diagnosis offered by the components, the high-speed communication level, the standardized industrial components and simplified

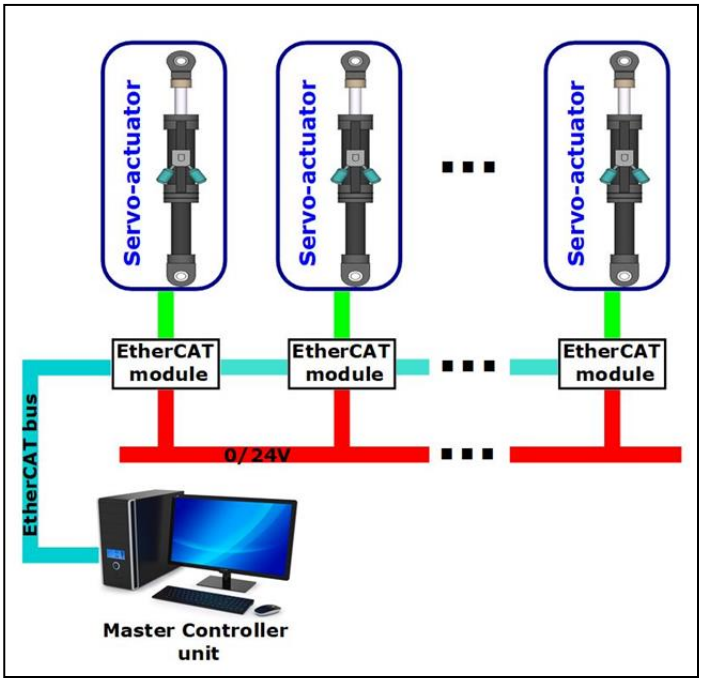

Figure 3. Schematic complete configuration of advanced HS platform.

cabling (Fig. 4) will relieve users from potential problems usually observed in complicated structural tests.

B. *Operating system and software*

The real time feature should be the dominant characteristic of a modern controller software. That is achieved placing the master controller software and the control software of each actuator on the same CPU. The master controller software is executed on a machine with real time operating system for multicore processors (Windows Embedded Compact) to reduce the control time step to 1ms. To enhance user-friendliness, the new master controller software was upgraded as well as the data acquisition system interface.

The simulation coordinator software is not affected by the modifications mentioned above, as it treats both numerical and physical substrutures as network nodes (via IP addresses). The communication between coordinating software and main controller is achieved by custom-made software (Matlab).

An issue concerning the numerical substructures, is how to deal with the considerable computational effort required by some types of substructures, e.g analysis of large area soil medium, heat diffusion analysis in structural elements, while ensuring that will not cause delays in the communication with the rest substructures (particularly the experimental ones being susceptible to relaxation phenomena). For such type of sub-structures it is recommended that the numerical substructures should be held in parallel processing computational systems using open access software (e.g. Opensees-SP). The reliability of the HS platform developed is currently under extensive verification testing.

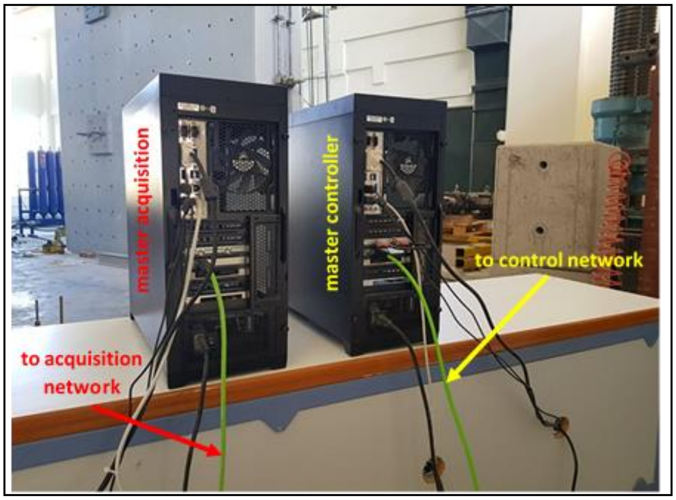

Figure 4. Typical cabling of enhanced acquistion and control system.

VI. Conclusions

To deeply comprehend the response of large scale, complicated structures, hybrid simulation method has been accepted as the most appropriate tool, especially in Earthquake Engineering for which the method was initially developed and been applied for quite some years. In HS structures are discretized in numerical and physical components (substructures) with the research interest focusing on the latter – this approach optimizes the combined use of available reliable software and laboratory facilities. The present research aims in developing a roadmap for the expansion of hybrid simulation method in multi-physics and multi-hazard problems and in creating an application platform built by robust industrial hardware of high quality, relevant control and simulation coordinator software simplifying – to the extent possible - the use of HS and making it applicable to a wider range of problems.

The benefits of developing an advanced hybrid simulation platform, are:

- the capability of expanding hybrid simulation to complicated structures exposed to actions beyond seismic, combined or not (e.g. thermo-mechanical problems),
- the advanced capabilities of HS: testing time step closer to real-time testing combining the communication protocol with real-time operating system and standardized modules,
- the enhancement of the reliability of application of HS by using equipment based on widely approved industrial standards and modern automation technology,
- a reliable and useful testing platform with flexible architecture, adaptability to demanding requirements, reduction of noise-to-signal ratio, internal communication via robust digital bus, enhanced simulation coordinator system with single way of

communication and precise synchronization of the distributed units,

- an application platform open to further development,
- multi-processing computer systems, compatible with the advanced software used in analysing structures of high computational effort.

The implementation of an advanced platform for large-scale structural experimental tests will maintain the recent research activity and broaden the research interest in cutting-edge scientific fields with wide range of applications.

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