Enhancing the collaboration of earthquake engineering research infrastructures

Georgios Tsionis, Fabio Taucer, Artur Pinto

2015
This publication is a Science for Policy report by the Joint Research Centre, the European Commission’s in-house science service. It aims to provide evidence-based scientific support to the European policy-making process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of this publication.

**JRC Science Hub**
https://ec.europa.eu/jrc

JRC99510

EUR 27648 EN

© European Union, 2015

Reproduction is authorised provided the source is acknowledged.

How to cite: Georgios Tsionis, Fabio Taucer, Artur Pinto; Enhancing the collaboration of earthquake engineering research infrastructures; EUR 27648 EN; doi:10.2788/021850

All images © European Union 2015

**Abstract**

**Towards stronger international collaboration of earthquake engineering research infrastructures**

International collaboration and mobility of researchers is a means for maximising the efficiency of use of research infrastructures. The European infrastructures are committed to widen joint research and access to their facilities. This is relevant to European framework for research and innovation, the single market and the competitiveness of the construction industry.
# Table of contents

Executive summary ........................................................................................................................ iii

1. Introduction .............................................................................................................................. 1

2. Roadmap towards enhanced collaboration of research infrastructures .............................. 3

  2.1 Collaboration of European research infrastructures ....................................................... 3

  2.2 International collaboration of research infrastructures ..................................................... 5

  2.3 Collaborative research agreements .................................................................................... 7

3. Priority topics for transnational access to research infrastructures .................................... 9

4. Applications of real-time hybrid simulation ........................................................................ 11

5. Conclusions .......................................................................................................................... 15

References ..................................................................................................................................... 17

List of abbreviations and definitions ......................................................................................... 19

List of tables ................................................................................................................................. 21

Annex – presentations at the EU-USA-Asia workshop on hybrid testing ............................... 23
Executive summary

Policy context
The preparation and implementation of the ESFRI together with the provision of transnational access to research infrastructures so that scientists can use them to conduct top-level research, are aligned with the 2014-2020 European framework for research and innovation and the Innovative Union Flagship Initiative. Transfer of knowledge and innovation to the European industry in the construction sector will support its competitiveness in the European and global marketplace. Besides, there are significant opportunities for industry in smart, sustainable and inclusive economy and the construction sector in particular can make a substantial contribution in responding to climate change and other environmental and societal changes. Furthermore, innovation and a strong knowledge base are important for the single market, which is the foundation for Europe’s industrial strength and productive capacity and create jobs.

Key conclusions
It is important for the European earthquake engineering research community to establish a long-term strategy for the use of the research infrastructures with focus on wider transnational access, transfer of knowledge and innovation to industry (particularly small and medium-sized enterprises) and international collaboration. In this respect, they should exploit the possibilities offered by the European Strategy Forum for Research Infrastructures and the Horizon 2020 programme, and seek active support from the member states of the European Union. Further to developing a holistic vision on earthquake engineering, new collaborative research projects should contribute to the creation of growth and jobs, seek a wider involvement of industry, and facilitate international collaboration and mobility of researchers. Scientific topics to be considered should aim at excellence and innovation, should be relevant to the policy priorities of the European Union, as expressed also in the JRC priority nexuses, and should contribute to the next generation of European standards for structural design.

There are ambitious programs for earthquake engineering research in the USA, South Korea and Taiwan, with funds that are up to 10 times higher than what is available in Europe. Moreover, these countries have a long-term vision for research, with a time frame of 10 or 20 years, as opposed to the European framework programmes for research that cover only four-year projects. It is evident that research infrastructures worldwide recognise the importance of addressing risk in a multi-hazard dimension (i.e. wind, tsunami, fires and earthquakes).

Hybrid cyber-physical simulation is an example of the highly-innovative achievements of earthquake engineering research facilities. While technical issues such as improving the accuracy of experiments and the testing of real- and large-scale specimens require further development, there is notable interest for the application of the method in other sectors, for instance wind, fire and marine engineering, which presents opportunities for the development of tools for the mitigation of risks due to multiple natural hazards.

Main findings
The earthquake engineering community has an impressive record of research projects that produced excellent results as regards innovation, transnational access and international collaboration. The European research infrastructures, in particular, manage to maintain their important role at world level despite the fact that they receive significantly less funding than their international partners.

International collaboration and mobility of researchers is a reality and a means for maximising the efficiency of use of research infrastructures. It needs to be further
enhanced on the side of European infrastructures, for instance through the European Strategy Forum for Research Infrastructures, the Group of Senior Officials and bi- or multi-lateral collaboration agreements. Important aspects are the access to the infrastructures and to the generated experimental data through a user-friendly platform. The EU-USA-Asia workshop on hybrid cyber-physical simulation demonstrated that the earthquake engineering infrastructures have made significant progress in the subject and researchers in other fields have a strong interested in exchange of knowledge. There is potential for further synergies, in view of the development of methodologies, techniques and tools to address the mitigation of risk of the built environment to multiple natural hazards.

Related and future JRC work

Future work regarding networking and advancement of earthquake engineering research infrastructures will focus on the opening of access to the ELSA facility and the preparation of collaborative research projects with European and international partners within Horizon 2020, ESFRI and the collaborative research agreements.

Quick guide

This report examines the current state of the collaboration of earthquake engineering research infrastructures and the outlook for future joint activities among European and international partners. Because of their particular requirements, i.e. the need to perform large-scale experiments making use of highly-specialised equipment, few facilities exist and their efficient use to the benefit of all researchers and the society at large, calls for a better coordinated framework for transnational access and international collaboration. The hybrid testing method is an example of the common achievements of the earthquake research community, which attracts significant interest from other engineering disciplines.
1. Introduction

The RINET institutional project of the Joint Research Centre (JRC) focuses on networking of research infrastructures and advancing innovative aspects of safety and sustainability in the construction sector. The project pursues four objectives:

i) to build up a sustained platform for collaboration of research infrastructures in earthquake engineering in the European Union, encompassing the objectives of the European Strategy Forum on Research Infrastructures (ESFRI), and focusing on safety and sustainability in the building sector;

ii) to establish a framework for collaboration with leading networks and research infrastructures outside the European Union;

iii) to develop new technologies and standards for the efficient and joint use of research infrastructures;

iv) to evaluate innovative technologies, such as robotics and hybrid cyber-physical testing.

The preparation and implementation of the ESFRI together with the provision of transnational access to research infrastructures so that European scientists can use them to conduct top-level research, in collaboration with industry, are well aligned with the 2014-2020 European framework for research and innovation [1] and the Innovative Union Flagship Initiative [2]. Transfer of knowledge and innovation to the European industry in the construction sector will support its competitiveness in the European and global marketplace [3]. Besides, there are significant opportunities for industry in smart, sustainable and inclusive economy and the construction sector in particular can make a substantial contribution to responding to climate change and other environmental and societal changes [4]. Furthermore, innovation and a strong knowledge base are important for the single market, which is the foundation for Europe’s industrial strength and productive capacity and create jobs [5].

The European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre enjoys an excellent reputation for the long experience and sustained commitment in facilitating scientific and research collaboration in earthquake engineering and advanced testing methods. ELSA seeks to include all relevant European stakeholders and is uniquely positioned to establish collaboration with international partners.

The present report extends a previous one on the RINET project [6] to cover the recent activities relevant to the elaboration of a roadmap to promote the collaboration of research infrastructures within the European Union and with international partners (China, Japan, South Korea, Taiwan and the USA), the identification of priority topics for transnational access to large-scale infrastructures and to recommendations on innovative technologies for the efficient use of research infrastructures. The hybrid testing method is an example of the common achievements of the earthquake research community, which attracts significant interest from other engineering disciplines.
2. Roadmap towards enhanced collaboration of research infrastructures

This Chapter presents the discussions and outcome of a workshop that was organised at the JRC on the 7th of October 2015 to discuss the future collaboration between research infrastructures on earthquake and structural dynamics. Researchers from Europe, the USA, South Korea, China and Taiwan discussed their recent experience and outlook for future collaboration in the field, while participants from DG Research and Innovation and the JRC presented the European Strategy Forum on Research Infrastructures and the opportunities within Horizon 2020 and the open access to JRC research infrastructures. Table 1 lists the titles and authors of the presentations.

Table 1. Presentations at the meeting on the future collaboration of earthquake engineering research infrastructures

<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>The SERIES FP7 project</td>
<td>S. Bousias, University of Patras, Greece</td>
</tr>
<tr>
<td>The Network for Earthquake Engineering Simulation</td>
<td>S. Dyke, Purdue University, USA</td>
</tr>
<tr>
<td>The Korea Construction Engineering Development Collaboratory Management Institute</td>
<td>C.-Y. Kim, Myongji University, South Korea</td>
</tr>
<tr>
<td>The International Joint Research Laboratory of Earthquake Engineering</td>
<td>W. Lu, Tongji University, China</td>
</tr>
<tr>
<td>International collaboration of the National Center for Research on Earthquake Engineering</td>
<td>K.-C. Tsai, NCREE, Taiwan</td>
</tr>
<tr>
<td>European Strategy Forum on Research Infrastructures</td>
<td>M. Ribeiro, DG Research and Innovation, European Commission</td>
</tr>
<tr>
<td>Research infrastructures work programme in Horizon 2020</td>
<td>L. Saracco, DG Research and Innovation, European Commission</td>
</tr>
<tr>
<td>Open access to JRC research infrastructures</td>
<td>F. Taucer, Joint Research Centre, European Commission</td>
</tr>
</tbody>
</table>

2.1 Collaboration of European research infrastructures

The SERIES\(^1\) project was funded by the 7th Framework Programme and brought together 23 partner institutions from 11 countries. It was made up of networking, joint research and transnational access activities. The project provided transnational access to 27 projects and to more than 250 users over a period of four and a half years.

The European Strategy Forum on Research Infrastructures is an initiative of member states of the European Union. It is one of the main pillars of the European Research Area initiative and the European Commission provides the secretariat. Member states may propose new projects for inclusion in the ESFRI roadmap and commit to support the construction and operation of national infrastructures that have an added value at European level, e.g. through ministries and funding agencies for research. ESFRI has

---

\(^1\) www.series.upatras.gr
provided to date funding for 48 projects of infrastructures with a strategic vision over a 10-20 year period and updates regularly the roadmap.

A European Research Infrastructure Consortium (ERIC) is a legal form designed to facilitate the joint establishment and operation of research infrastructures of European interest. It may be used by institutions outside ESFRI and allows the participation of infrastructures from third countries. Most distributed infrastructures have opted for ERIC, while single-sited ones have opted for ERIC or transnational agreements.

There are five calls in the 2016-2017 work programme of Horizon 2020 on excellent science:

- development and long-term sustainability of new pan-European research infrastructures;
- integrating and opening research infrastructures of European interest;
- e-infrastructures;
- fostering the innovation potential of research infrastructures;
- support to policy and international cooperation.

The call on ‘Integrating and opening research infrastructures of European interest’ includes a topic on integrating activities for advanced communities and in particular for research infrastructures for earthquake hazard. The projects proposed to the call should address networking, transnational access and joint research activities and aim at bringing an added value with respect to previous projects.

The JRC plans to open its research infrastructures for access to external users. The framework for access is being finalised by Directorate A in collaboration with the internal Working Group on JRC-ESFRI relations, and comprises two modes of access: relevance- and market-driven. The former foresees an open call for proposals and a peer review by a user selection committee on the basis of the scientific and socio-economic relevance of proposals, their excellence, originality and feasibility. The latter applies when access is defined through an agreement between the user and the JRC which foresees a full fee for the use of the facilities. Pilot projects for access, in particular at the European Laboratory for Structural Assessment, will run already in 2016.

The discussion of the representatives of the European research infrastructures regarding the future collaboration is summarised below:

- It is important to submit a proposal for the 2018 update of the ESFRI roadmap. For this, the way to obtain the necessary support from member states should be further discussed. It is appropriate to examine also the possibilities for collaboration with the European Plate Observing System, although it deals mainly with seismic hazard.
- The group of earthquake engineering infrastructures intends to submit a proposal to the 2014 call for research infrastructures for earthquake hazard, with focus on transnational access to the experimental facilities, and preferably together with the engineering seismology community.
- Any new project should articulate a holistic future vision on earthquake engineering, contribute to the creation of growth and jobs, seek a wider involvement of industry and in particular small and medium-sized enterprises, technology transfer and facilitate international collaboration, which is highlighted in the Horizon 2020 calls for scientific excellence.
- Scientific topics that may be considered in the planned proposal include early warning systems, remote sensing, geological monitoring, infrastructure networks, resilience to multiple hazards, applications at urban level (smart cities) and the use of advanced web protocols for a distributed (international) database of experimental data.

The ELSA Unit, through its participation in the JRC Internal Working Group on JRC-ESFRI relations, will facilitate the development of a proposal of the European research infrastructures in earthquake engineering for inclusion in the next ESFRI roadmap. This proposal will bring together national and European funds to support a long-term strategy for the earthquake engineering research infrastructures, with focus on efficient use of
the facilities, validation of data and testing protocols, and sharing of data with the entire user community in Europe and worldwide.

An important action to strengthen the collaboration of research infrastructures is the updating of the virtual database developed within the SERIES project. The European earthquake engineering laboratories have different infrastructures, capabilities, working languages, hardware and software platforms, which complicate the dissemination and reuse of information. The SERIES database [7] provides access to multiple distributed sources of information by using a single, centralised gateway. It essentially created the infrastructure for data integration between 22 laboratories with a common data structure and data exchange methods. The database may be complemented with semantic web technologies to facilitate the integration of different data sources and the interoperability with other similar databases worldwide. This new flexible data management system will contribute to the greater dissemination of experimental results, the sharing of software systems and the development of intelligent decision-support systems.

2.2 International collaboration of research infrastructures

In its 10 years of operation in the USA, the George E. Brown, Jr. Network for Earthquake Engineering Simulation² (NEES) created a network of 15 laboratories that gave access to 422 projects and to more than 200 researchers (mostly PhD, MSc and undergraduate students), producing more than 5000 publications. The facilities provided funding for their full operational costs and offered tele-presence. The experimental data were uploaded in the database developed by the network and were widely used worldwide. Examples of the impact of NEES include code changes on tsunami effects, making available high-performance computing facilities to a large number of users and providing the necessary information for the development of next-generation structures. Outreach activities, such as webinars on the use of the project results, media coverage and museum projects, were a significant component of the network. During the course of the project, NEES established formal agreements with international partners. For the period 2015-2019, the Natural Hazards Engineering Research Infrastructure will supersede NEES, focusing on multiple hazards (wind, tsunami and earthquake) and experimental facilities for rapid post-disaster response.

The Korea Construction Engineering Development Collaboratory Management Institute³ (KOCED CMI) was launched in 2004 by the Ministry of Land, Transport and Maritime Affairs of South Korea. The objective is to establish a comprehensive base for construction-related testing, research and education with the ultimate goal of strengthening South Korea's international competitiveness in construction industries and technologies. The first phase (2004-2009) was dedicated to the construction of test facilities for earthquake, wind, coastal and harbour engineering, and the development of the cyberinfrastructure. The second phase (2009-2024) foresees the construction of six additional facilities (structure extreme conditions, impact, collision; climate change; hydraulic model testing; weather conditions on roads; vehicle driving simulation; noise, air and ventilation conditions in buildings). KOCED CMI plans a shared use of its infrastructure with international researchers. A formal agreement for collaboration between the JRC and KOCED CMI is being finalised.

The International Joint Research Laboratory for Earthquake Engineering⁴ brings together five earthquake engineering research infrastructures: Tongji University in China, the European Laboratory for Structural Assessment of the JRC (as observer), the Pacific Earthquake Engineering Research Center in the USA, EUCENTRE in Italy and the Tokyo

---

² https://nees.org
³ http://eng.koced.or.kr
⁴ www.ilee-tj.com
Institute of Technology in Japan. It addresses resilience with a multi-disciplinary focus and receives funding from the Ministry of Education of China for 12 international projects with an average of 100,000 USD per project.

The National Center for Research on Earthquake Engineering in Taiwan has been sharing its research infrastructures at national level since 18 years, with a support of around 10 million USD per year from the government. NCREE has actively collaborated with the University at Buffalo and the University of Ottawa, as well as with NEES, and deems the exchange of international students very important.

The discussion regarding the past experience and future international collaboration of earthquake engineering research infrastructures is summarised below:

- There are ambitious programs for earthquake engineering research in the USA, South Korea and Taiwan, with funds that are five to 10 times higher than what was made available to the SERIES project. Moreover, these countries have a long-term vision for research, with a time frame of 10 or 20 years, as opposed to the European framework programmes for research that cover only four-year projects.
- Each NEES laboratory ran on average three projects per year, as opposed to one project per year in SERIES, and received funding for the full operation of the laboratory, as opposed to the limit of 20% imposed by the 7th Framework Programme for SERIES. This demonstrates the high efficiency of European laboratories in meeting the budget constraints and their high potential to capitalise on possible increased funding.
- Most international research infrastructures recognise the importance of addressing risk in a multi-hazard dimension (i.e. wind, tsunami, fires and earthquakes) and with particular consideration for energy and transport infrastructures.
- Outreach, education and training of young researchers have proven to be one of the main outcomes of the sharing of research infrastructures.
- In response to the strong request from funding authorities and building on their past experience, research infrastructures intend to strengthen the collaboration and exchange of researchers with international partners.

Before the 7 October meeting, an EU-US-Asia workshop on hybrid testing took place in Ispra on 5 and 6 October 2015 (see Chapter 4). The objectives were to bring together researchers from different geographic and academic backgrounds to discuss challenges and to provide opportunities for researchers to establish and strengthen international collaboration. An initial agreement was made for the publication of the workshop proceedings in the Geotechnical, Geological and Earthquake Engineering series of Springer or a number of papers in a special issue of the Bulletin of Earthquake Engineering. As a follow-up of the workshop, the JRC is organising together with Purdue University a special session on ‘Hybrid cyber-physical simulation: state-of-the-art and future prospects in USA and Europe’ at the 16th World Conference on Earthquake Engineering that will take place in Chile on 9-13 January 2017. Until the deadline for submission, eight abstracts were submitted to the special session. With the aim of maximising the outcome of the conference, contacts were taken with the organisers of special sessions with similar topics to coordinate and merge the sessions.

The European Commission is part of the Group of Senior Officials (GSO) together with Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russia, South Africa, UK, and USA. The GSO was formed to take stock and explore cooperation between infrastructures. It elaborated a framework for global research infrastructures [8] which distinguishes three types of facilities of global interest (single-sited, globally distributed and national facilities) and defines a set of common principles for their development and operation. The framework addresses also issues of project and funding.

---

5 [www.ncree.org](http://www.ncree.org)
management, merit-based access, international mobility, clustering of infrastructures, data exchange, etc. The JRC should examine the scope of proposing its unique research infrastructures as facilities of global interest.

2.3 Collaborative research agreements

The ELSA Unit has established collaborative research agreements (CRA) with major international research infrastructures in earthquake engineering, as shown in Table 2. The general objective of the CRAs is to contribute to understanding and resolving scientific issues in the field of earthquake engineering (e.g. hybrid testing and resilience of buildings and civil infrastructures to natural hazards) and to ensure that discoveries, inventions and creations are utilized in ways most likely to benefit the public.

Table 2. Collaborative research agreements in the field of earthquake engineering

<table>
<thead>
<tr>
<th>Partner institution</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tongji University, China</td>
<td>20/01/2014 - 19/01/2019</td>
</tr>
<tr>
<td>Building Research Institute, Japan</td>
<td>26/05/2014 - 25/05/2019</td>
</tr>
<tr>
<td>Purdue University, USA</td>
<td>Negotiation concluded</td>
</tr>
<tr>
<td>Korea Construction Engineering Development Collaboratory Management Institute, Korea</td>
<td>Negotiation concluded</td>
</tr>
<tr>
<td>Cyprus University of Technology, Cyprus</td>
<td>Negotiation concluded</td>
</tr>
</tbody>
</table>

In the framework of the collaborative research agreements, the following visits were exchanged:

- Prof Julio Ramirez and Prof Shirley Dyke from Purdue University visited the JRC on the 22nd of May 2014. The possibility to establish a CRA and the organisation of an EU-USA workshop on hybrid testing were first discussed during this visit.
- The JRC was represented at the initiation of the International Joint Research Laboratory of Earthquake Engineering partnership in July 2015. The full members of ILEE are Tongji University, University of California – Berkeley, Tokyo Institute of Technology and EUCENTRE. It is a cooperation initiative with the goal to network large laboratories in hope of quick and fluent knowledge and skills transfer. The main subject of the research will be earthquake resilient civil and infrastructure engineering (buildings, bridges, lifelines, energy facilities and geotechnics).
- Prof Chul-Young Kim and Prof Jae-Yeol Cho visited the JRC on the 3rd of July 2015 as representatives of the Korea Construction Engineering Development Collaboratory Management Institute. The visit focused on exchange of information on the research facilities of the two sides and the advancement of the collaborative research agreement between JRC and KOCED CMI.
- The JRC was invited to deliver an invited presentation at the Global Session of the 2015 Convention of the Korean Society of Civil Engineers. The title of the presentation was ‘European research infrastructures for earthquake engineering and structural dynamics: Achievements and future challenges’. The participation to the conference was complemented by a visit to three major earthquake engineering research facilities of KOCED and to the Collaboratory Management Institute.
- A delegation of the Building Research Institute of Japan, composed of Mizuo Inukai, Tadashi Ishihara and Tomohisa Mukai visited the JRC on the 19th of October 2016 for the first management panel on collaboration research between JRC-IPSC and the Building Research Institute. Information about the past activities was exchanged. It
was decided to focus future collaboration on the harmonisation of building codes and testing methods.
3. Priority topics for transnational access to research infrastructures

In the framework of the JRC Organisational Development and the Enlargement and Integration Strategy, ELSA is preparing to provide wider access to its research infrastructures. The objective is to foster innovative research and development, dissemination of knowledge, improve related methods and skills, training and foster collaboration at European level. Moreover, wider access will promote interaction with a wide range of social and economic actors, including industry and public services, for a more efficient use of the scarce experimental facilities available in Europe.

Access will be provided following an open call for proposals and the evaluation of submitted proposals with regard to a number of criteria including:

- scientific and technical value and interest;
- originality and innovation;
- relevance to priority topics of the JRC Research Infrastructures;
- importance for European standardisation;
- importance for European integration and cohesion;
- importance for sustainable growth and European competitiveness;
- importance for a resilient Energy Union with a forward-looking climate change policy;
- relevance to JRC thematic priority areas (Nexus);
- availability of similar infrastructures in any of the users’ countries;
- previous use of research infrastructure by any user;
- synergies and complementarities with existing research projects and ESFRI research infrastructures;
- dissemination plan;
- cost and feasibility according to research infrastructure;
- quality of proposing team.

Further to the previous criteria, the work performed within the transnational access should be of relevance to JRC thematic priority areas. The ten priority nexuses that will form the basis for the future activities that the JRC should develop are designed to support European Union policy makers in devising and implementing policies to respond to the identified societal challenges. They are:

- economy, finance and markets;
- energy and transport;
- education, skills and employment;
- food, nutrition and health;
- natural resources and climate;
- people and governance in multicultural societies;
- civil security;
- migration and territorial development;
- data and digital transformation;
- innovation systems and processes.

Energy and transport are relevant to the activities of the ELSA research infrastructure as concerns inter alia energy efficiency in buildings, the effects of climate change on structures and the structural safety of components of networks for the production and distribution of energy (including nuclear reactors of current and new generation, on- and off-shore wind turbines, pipelines and terminals for (shale) gas, etc.).

The civil security nexus is also highly relevant for transnational access projects dealing with the protection of critical infrastructures and with mitigation and management (e.g. emergency preparedness and response) of disaster risk due to natural and man-made hazards.

The above-mentioned topics were selected to match the Commission priorities related to: i) jobs, growth and investment (by boosting the competitiveness of the construction
sector and providing support to small and medium-sized enterprises), ii) the energy union (by focusing on energy efficiency of new and existing buildings) and iii) the internal market (by the contribution to innovation and standards for the construction industry). In addition, they serve a number of objectives of the strategy for upgrading the single market [9] and in particular the removal of barriers to innovation for small and medium-sized enterprises, the modernisation of the standards system and the removal of barriers for construction products.

Projects of transnational access should make an important contribution to European standardisation, through pre-, peri- and co-normative research in support of the next generation of Eurocodes. The Commission Recommendation on the implementation and use of the Eurocodes [10] calls for scientific and research cooperation with the JRC to ensure an ongoing increased level of protection of buildings and civil works, specifically as regards the resistance of structures to earthquakes and fire. The Mandate for the amendment and extensions of scope of the Eurocodes [11] foresees the following topics:

- assessment, re-use and retrofitting of existing structures;
- requirements for robustness;
- structural glass;
- atmospheric icing of structures;
- actions from waves and currents on coastal structures;
- adaptation of the Eurocodes to take into account the relevant impacts of climate change;
- performance-based and sustainability concepts in design and construction;
- serviceability for buildings and bridges;
- fatigue verification.

The need to develop further additional rules in the Eurocodes, covering FRP structures and tensile surface structures, may be examined in the future.
4. Applications of real-time hybrid simulation

An EU-US-Asia workshop on hybrid testing took place in Ispra on 5 and 6 October 2015. It was jointly organised by the JRC, Purdue University and the University of Connecticut. The objectives of the workshop were to bring together researchers from different geographic and academic backgrounds to discuss challenges in real-time hybrid simulation, increasing the broader knowledge of the community and driving future research successes; to assist in the expansion of real-time hybrid simulation beyond seismic applications; and to provide opportunities for researchers to establish and strengthen international collaboration.

The workshop was organised in five sessions with the following topics: stability and accuracy of hybrid tests; applications in earthquake engineering; complexity of the numerical components in hybrid simulation; large-scale hybrid simulation; applications beyond earthquake engineering. There were 27 presentations given by researchers from Europe, the USA, China and Taiwan, as shown in Table 3. Handouts of the slide presentation are given in an Annex to this report.

The participants were asked in advance to consider a list of questions and address these in their presentations:

- What is your process for planning and preparing to conduct a hybrid simulation test?
- How (what measures) and when (before, during, after) is stability of a test assessed?
- How (what measures) and when (before, during, after) is accuracy of a test assessed and how are the resulting errors dealt with?
- What are the current limits of model complexity and how are you addressing these?
- What efforts have you undertaken (or plan/hope to begin) to improve the acceptance of hybrid simulation in the overall testing community?

The workshop comprised also working group discussions on three of the above topics, in particular stability and accuracy requirements to achieve testing needs, complexity of the numerical components and acceptance of real-time hybrid simulation by the broader experimental testing communities. The co-chairs of the discussion sessions reported back to the participants before a concluding round-table discussion.

The first session focused on the development of methods to predict, before the test, and assess, during the test, the accuracy and stability of the hybrid simulation method. Past and future applications in earthquake tests in Europe, the USA, China and Taiwan were presented in the second and fourth sessions. The third session was dedicated to specific problems related to the complexity of the numerical components in hybrid simulation.

A number of innovative applications in earthquake engineering and other fields were presented at the last session, including the automotive industry, wind turbines and a framework for distributed hybrid testing which makes use of an automated procedure based on an online interface between software, hardware and operational procedures implemented in different laboratories. Also, the possible application of hybrid testing on complex infrastructure networks within urban areas, with the aim to reduce the epistemic uncertainty regarding the networks and to consequently improve their performance, was discussed with reference to the UK Collaboratorium for Research in Infrastructure and Cities.

Regarding structural fire engineering, the substructuring method used in earthquake engineering has been successfully applied in fire testing with the establishment of a powerful experimental tool for analysis of structural elements. Future developments will focus on the connection to a Finite Element Method software for the simulation of the numerical substructure with nonlinear response and the improvement of force measurements via pressure transducers.
<table>
<thead>
<tr>
<th>Stability and accuracy of hybrid tests</th>
<th>G. Abbiati &amp; B. Stojadinovic, ETH Zurich, Switzerland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty propagation and global sensitivity analysis in hybrid simulation using polynomial chaos expansion</td>
<td>G. Abbiati, ETH Zurich, Switzerland; O. S. Bursi, University of Trento, Italy; I. Lanese &amp; A. Pavese, EUCENTRE, Italy</td>
</tr>
<tr>
<td>Verification of different approaches in implementing hybrid simulation</td>
<td>S. Bousias, University of Patras, Greece</td>
</tr>
<tr>
<td>Reliability assessment of real-time hybrid simulation in presence of actuator tracking error</td>
<td>C. Chen, San Francisco State University, US</td>
</tr>
<tr>
<td>Real time hybrid simulation: stability, performance and execution</td>
<td>S. Dyke, Purdue University, US</td>
</tr>
<tr>
<td>Dynamic similitude design approaches for small-sized model of multi-tower high-rises with isolated conservatory on the top</td>
<td>W. Lu, Tongji University, China</td>
</tr>
<tr>
<td>Minimising hybrid testing errors by optimal test rig design and control</td>
<td>A. Plummer, University of Bath, UK</td>
</tr>
<tr>
<td>Applications in earthquake engineering</td>
<td></td>
</tr>
<tr>
<td>Towards real-time hybrid testing of RC frame panels with masonry infills</td>
<td>A. A. Correia, A. Campos Costa &amp; P. Candeias, National Laboratory for Civil Engineering, Portugal</td>
</tr>
<tr>
<td>Development of multi-axial real time hybrid simulation</td>
<td>G. Fermandois-Cornejo &amp; B. F. Spencer Jr., University of Illinois, Urbana-Champaign, US</td>
</tr>
<tr>
<td>MDOF hybrid shake table testing for bridge and building structures</td>
<td>A. Schellenberg, UC Berkeley, US</td>
</tr>
<tr>
<td>Hybrid tests of a full-scale two-story reinforced concrete frame with buckling restrained braces</td>
<td>K.-C. Tsai, A.-C. Wu &amp; K.-J. Wang, National Taiwan, National Taiwan, University &amp; National Center for Research on Earthquake Engineering, Taiwan</td>
</tr>
<tr>
<td>Complexity of the numerical components in hybrid simulation</td>
<td></td>
</tr>
<tr>
<td>Hybrid simulations of complex isolated bridges enhanced with parallel time integrators and model updating</td>
<td>G. Abbiati, ETH Zurich, Switzerland; O. S. Bursi, University of Trento, Italy; I. Lanese &amp; A. Pavese, EUCENTRE, Italy</td>
</tr>
<tr>
<td>Integration algorithms for hybrid simulation of structural response through collapse</td>
<td>G. Mosqueda, UC San Diego, US</td>
</tr>
<tr>
<td>Heterogeneous asynchronous time integrators for structural dynamics</td>
<td>M. Brun, A. Gravouil &amp; A. Combescur, Institut National des Sciences Appliquées, Lyon, France</td>
</tr>
<tr>
<td>Model updating in hybrid simulation</td>
<td>G. Ou &amp; S. Dyke, Purdue University, US</td>
</tr>
<tr>
<td>Connection between hybrid testing and standard shaking tests</td>
<td>A. Le Maoult, Alternative Energies and Atomic Energy Commission, France</td>
</tr>
<tr>
<td>Explicit unconditional stable controllable dissipative integration algorithms for RTHS of complex structural systems</td>
<td>J. Ricles, Lehigh University, US</td>
</tr>
</tbody>
</table>
## Table 1. List of presentations at the EU-US-Asia workshop on hybrid testing (continued)

<table>
<thead>
<tr>
<th>Large-scale hybrid simulation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale real-time hybrid simulations</td>
<td>Y. Chae, Old Dominion University, US</td>
</tr>
<tr>
<td>Hybrid testing of real-scale structures at ELSA</td>
<td>P. Pegon &amp; J. Molina, Joint Research Centre, European Commission</td>
</tr>
<tr>
<td>Real-time hybrid simulation across multiple scales</td>
<td>B. Phillips, University of Maryland, US</td>
</tr>
<tr>
<td>Incremental hybrid simulation development method for large-scale application</td>
<td>X. Shao, University of Western Michigan, US</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Applications beyond earthquake engineering</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A framework to support distributed testing and service integration in earthquake engineering</td>
<td>M. Williams, University of Oxford, UK</td>
</tr>
<tr>
<td>Force-based hybrid simulation for expanding capabilities and applications to multi-hazards</td>
<td>N. Nakata, Clarkson University, US</td>
</tr>
<tr>
<td>Hybrid fire testing via the substructuring method</td>
<td>M. Korzen, BAM, Germany</td>
</tr>
<tr>
<td>Adaptive feedforward compensation for interface synchronization in realtime hybrid testing with harmonic excitation</td>
<td>A. Bartl &amp; D. Rixen, Technische Universität München, Germany</td>
</tr>
<tr>
<td>Use of RTHS in vibration testing and marine structure applications</td>
<td>R. Botelho, J. Franco &amp; R. Christenson, University of Connecticut, US</td>
</tr>
<tr>
<td>Envisioned applications, and associated challenges, of real-time hybrid testing in the field of marine technology</td>
<td>T. Sauder, Norwegian Marine Technology Research Institute, Norway</td>
</tr>
<tr>
<td>Exploring the challenge of hybrid testing in city-scale experimentation</td>
<td>C. Taylor, University of Bristol, UK</td>
</tr>
</tbody>
</table>
An application in marine engineering in the USA focused on the transmission of vibrations from a physical vibration source, i.e. a motor, to the marine support structure. The feasibility of the method was verified and real time hybrid testing was used to interface the vibration source to a numerical model of the support structure to capture the interaction mechanism, including the effect of structural response on the source. There is interest also in Europe for similar applications for testing of components and addressing issues related to scaling and limitations of the laboratories. Similar to other fields, the key questions that were identified include the design of the experimental setup, the control and accuracy of the test, the development of numerical models and the quality of results. The Norwegian independent research organisation SINTEF will facilitate the contribution from the earthquake engineering research community in a forthcoming research project.

Real time hybrid simulation is being currently applied in the USA for the study of fluid-structure interaction and particularly for the simulation of buildings and bridges under tsunami-induced loadings.

Lastly, there is interest and potential for use of the method in full- and reduced-scale wind tests. Possible applications include tall buildings and slender vertical structures, long-span bridges, flexible roofs, building appendages and structural members.

The workshop participants confirmed the advantages of hybrid simulation and the wide range of possible applications in earthquake engineering and beyond. Issues for further development that were raised and discussed by the working groups include the improvement of accuracy, the testing of real- and large-scale specimens and the application of loads along two or three main directions.

A working group discussion was devoted to actions needed to increase the awareness, acceptance and use of real time hybrid simulation by the broader testing community. The proposed actions aim to: i) involve industry for the exploitation of the results of real time hybrid tests; ii) design a clear testing process and benchmark to ease understanding of the method and attract new students and engineers; iii) consider technological developments such as robotics in construction and prefabrication and iv) broaden the scope to multiple hazards and modelling at city level.

Concerning the conclusions from the round table session, the group is keen on continuing collaboration at international level, and a similar meeting might be held again in two years’ time. Most of the attention was drawn on how to transpose hybrid testing as it used today in the field of earthquake engineering, to address multiple hazards, for instance by using cities as a living laboratory.
5. Conclusions

This report examines the current state of the collaboration of earthquake engineering research infrastructures and the outlook for future joint activities among European and international partners. Because of their particular requirements, i.e. the need to perform large-scale experiments making use of highly-specialised equipment, few facilities exist and their efficient use to the benefit of all researchers and the society at large, calls for a better coordinated framework for transnational access, sharing of data and international collaboration.

The earthquake engineering community has an impressive record of research projects that produced excellent results as regards innovation and transnational access. The European research infrastructures, in particular, manage to maintain their important role at world level despite the fact that they receive significantly less funding than their international peers. In the future it is important for the European earthquake engineering research community to establish a long-term strategy for the use of the research infrastructures with focus on wider transnational access, transfer of knowledge and innovation to industry (particularly small and medium-sized enterprises) and international collaboration. In this respect, they should exploit the possibilities offered by the European Strategy Forum for Research Infrastructures and the Horizon 2020 programme, and seek active support from the member states of the European Union. Scientific topics to be considered should aim at excellence and innovation, should be relevant to the policy priorities of the European Union, as expressed also in the JRC priority nexuses, and should contribute to the next generation of European standards for structural design.

There are ambitious programs for earthquake engineering research in the USA, South Korea and Taiwan, with funds that are up to 10 times higher than what is available in Europe. Moreover, these countries have a long-term vision for research, with a time frame of 10 or 20 years, as opposed to the European framework programmes for research that cover only four-year projects. It is evident that research infrastructures worldwide recognise the importance of addressing risk in a multi-hazard dimension (i.e. wind, tsunami, fires and earthquakes.

Hybrid cyber-physical simulation is an example of the highly-innovative achievements of earthquake engineering research facilities. While technical issues such as improving the accuracy of experiments and the testing of real- and large-scale specimens require further development, there is notable interest for the application of the method in other sectors, for instance wind, fire and marine engineering, which presents opportunities for the development of tools for the mitigation of risks due to multiple natural hazards.

Future work of the JRC regarding networking and advancement of earthquake engineering research infrastructures will focus on the opening of access to the ELSA facility and the preparation of collaborative research projects with European and international partners within Horizon 2020, ESFRI and the collaborative research agreements.
References


2. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Europe 2020 Flagship Initiative Innovation Union. COM(2010) 546 final

3. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. For a European Industrial Renaissance. COM(2014) 14 final

4. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. An integrated industrial policy for the globalisation era putting competitiveness and sustainability at centre stage. COM(2010) 614 final


11. Mandate for amending existing Eurocodes and extending the scope of structural Eurocodes, M/515 EN. European Commission, Enterprise and Industry Directorate-General, Brussels, 12 December 2012
### List of abbreviations and definitions

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRA</td>
<td>collaborative research agreement</td>
</tr>
<tr>
<td>ELSA</td>
<td>European Laboratory for Structural Assessment</td>
</tr>
<tr>
<td>ERIC</td>
<td>European Research Infrastructure Consortium</td>
</tr>
<tr>
<td>ESFRI</td>
<td>European Strategy Forum on Research Infrastructures</td>
</tr>
<tr>
<td>GSO</td>
<td>Group of Senior Officials</td>
</tr>
<tr>
<td>ILEE</td>
<td>International Joint Research Laboratory for Earthquake Engineering</td>
</tr>
<tr>
<td>KOCED CMI</td>
<td>Korea Construction Engineering Development Collaboratory Management Institute</td>
</tr>
<tr>
<td>NCREE</td>
<td>National Center for Research on Earthquake Engineering</td>
</tr>
<tr>
<td>NEES</td>
<td>George E. Brown, Jr. Network for Earthquake Engineering Simulation</td>
</tr>
</tbody>
</table>
List of tables

Table 1. Presentations at the meeting on the future collaboration of earthquake engineering research infrastructures ................................................................. 3
Table 2. Collaborative research agreements in the field of earthquake engineering ....... 7
Table 3. List of presentations at the EU-US-Asia workshop on hybrid testing............ 12
Annex – presentations at the EU-USA-Asia workshop on hybrid testing
Uncertainty Propagation and Global Sensitivity Analysis in Hybrid Simulation using Polynomial Chaos Expansion

EU-US-Asia workshop on hybrid testing
Ispra, 5-6 October 2015
G. Abbiati, S. Marelli, O.S. Bursi, B. Sudret and B. Stojadinovic

Acknowledgements

1. The speaker gratefully acknowledges the Workshop Organizing Committees for the invitation.

2. The authors gratefully acknowledge the financial supports from the European Union through the SERIES project (Grant number: 227887).

3. The authors gratefully acknowledge the financial supports of the University of Trento for Lab. activities.

Pipe Size Material Liquid/Internal Pressure
8” and 6” Schedule 40 API SL; Gr. X52
fy = 418 Mpa; fu = 554 Mpa;
Elongation = 35.77%
Water
3.2 MPa

Hybrid Simulation of a piping system response

Dimensions and specifications of the piping

Critical structural elements

Test setup for a single elbow
Hysteretic response of elbows

The experimental setup

Seismic loading

Test setup at the University of Trento (Italy)
Deterministic testing assumptions

Clamped piping ends
0.5% viscous damping

How to handle model uncertainties in hybrid simulation?

The benchmark problem

Input stochastic parameters

Output response quantities

Method development objectives

Uncertainty propagation: estimation of the variance of output response quantities given the variance of input stochastic parameters.

Global sensitivity analysis: decomposition of the variance of output response quantities into components related to a generic subset of input stochastic parameters.
The testing protocol

**The surrogate model of the system response**

\[ Y = M(X) \]

\[ Y = \{U_1, U_2, R, E\} \quad X = \{K_1, K_2, \zeta\} \]

\[ \text{OUTPUT} \quad \text{INPUT} \]

**The Polynomial Chaos Expansion (PCE)**

\[ M^{PCE}(X) = \sum_{\alpha \in \mathcal{A}^{M,p}} y_{\alpha}(X) \Psi_{\alpha}(X) \]

- \( \mathcal{A}^{M,p} = \{\alpha : |\alpha| < p\} \) is the truncated set of multi-indices
- \( \Psi_{\alpha} \) is multivariate polynomial with multi-index vector \( \alpha \)
- \( y_{\alpha} \) is coefficient of the single multivariate polynomial

**Definition of multivariate polynomial**

\[ \Psi_{\alpha}(X) \equiv \prod_{i=1}^{M} \Psi_{i}^{(\alpha_i)}(X_i) \]

\[ |\alpha| = \sum_{i=1}^{M} \alpha_i \quad \text{Degree of the univariate polynomial i-th} \]


**Definition of multivariate polynomial**

\[ \langle \psi_i(x), \psi_k(x) \rangle = \int_{\mathbb{D}_x} \psi_i(x) \psi_k(x) f_x(x) dx = \delta_{ik} \]

<table>
<thead>
<tr>
<th>Probability density function</th>
<th>Orthogonal polynomials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>Legendre</td>
</tr>
<tr>
<td>Gaussian</td>
<td>Hermite</td>
</tr>
<tr>
<td>Gamma</td>
<td>Laguerre</td>
</tr>
<tr>
<td>Beta</td>
<td>Jacobi</td>
</tr>
</tbody>
</table>


**Uncertainty Propagation**

\[ \text{E}[M^{PCE}(X)] = E \left[ \sum_{\alpha \in \mathcal{A}^{M,p}} y_{\alpha}(X) \right] = y_{\alpha} \]

\[ \text{Var}[M^{PCE}(X)] = E[(M^{PCE}(X) - y_{\alpha})^2] = \sum_{\alpha \in \mathcal{A}^{M,p}} \hat{y}_{\alpha}^2 \]

\[ \text{Var}[U_i] \]

\[ \text{Polynomial Chaos estimate} \quad \text{Reference 95% Gaussian CI} \]

\[ \text{Training set size} \]
Global sensitivity analysis: Sobol’ indices

\[ S_i = \frac{D_i}{D} \]

First order Sobol’ index = Fraction of the total output variance explained by the input parameter \( i \)-th alone

\[ S_I^T = \sum_{|\mathbf{u}|=i} \frac{D_u}{D} \]

Total Sobol’ index = Fraction of the total output variance explained by the \( i \)-th input parameter in combination with all other parameters

\[ D_u^T = \text{Var}[M_u^T(X)] = \sum_{J=1}^{d} \hat{y}_J^2 \]

\[ D_u = \text{Var}[M^u(X)] = \sum_{J=1}^{d} \hat{y}_J^2 \]

Sobol’ index

where \( u \) is a generic subset of all input parameters

Surrogate model of the entire response history

HYBRID SIMULATION 1

\[ X^{(0)} = \{ k^{(0)}(x_1), k^{(0)}(x_2), c^{(0)} \} \]

\[ Y^{(0)} = \{ u^{(0)}(t_1), u^{(0)}(t_2), \ldots, u^{(0)}(t_n) \} \]

HYBRID SIMULATION 1

\[ X^{(0)} = \{ k^{(0)}(x_1), k^{(0)}(x_2), c^{(0)} \} \]

\[ Y^{(0)} = \{ u^{(0)}(t_1), u^{(0)}(t_2), \ldots, u^{(0)}(t_n) \} \]

HYBRID SIMULATION i

\[ X^{(0)} = \{ k^{(0)}(x_1), k^{(0)}(x_2), c^{(0)} \} \]

\[ Y^{(0)} = \{ u^{(0)}(t_1), u^{(0)}(t_2), \ldots, u^{(0)}(t_n) \} \]

HYBRID SIMULATION N

\[ X^{(0)} = \{ k^{(0)}(x_1), k^{(0)}(x_2), c^{(0)} \} \]

\[ Y^{(0)} = \{ u^{(0)}(t_1), u^{(0)}(t_2), \ldots, u^{(0)}(t_n) \} \]

INSTANTANEOUS PCE? … NOT EFFECTIVE

Time warping transform 1/3

Reference signal

\[ \tau^{(1)}(t) = k^{(1)}(t) + \phi^{(1)} \]

Time warping transform

\[ \tau^{(0)}(t) = k^{(0)}(t) + \phi^{(0)} \]

Time warped signal

\[ u_1^{(0)}(t) \]
### Time warping transform 2/3

<table>
<thead>
<tr>
<th>Test</th>
<th>Sampled input parameters</th>
<th>Output response quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$k_1^{(1)}, k_2^{(1)}, \xi_1^{(1)}$</td>
<td>$k(\xi), \phi(\xi), u_i^{(1)}(\tau)$</td>
</tr>
<tr>
<td>...</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>N</td>
<td>$k_1^{(N)}, k_2^{(N)}, \xi_1^{(N)}$</td>
<td>$k(\xi), \phi(\xi), u_i^{(N)}(\tau)$</td>
</tr>
</tbody>
</table>

PCE time warping coefficients:

$$k(X), \phi(X)$$

PCE of the time warped response:

$$u_i^*(\tau, X)$$

### Time warping transform 3/3

- **Generic set of input parameter and time**
  - $t, X(0)$

- **Linear time warping**
  - $\tau = k(X(0)) t + \phi(X(0))$

  $$u_i^*(\tau, X(0)) \Leftrightarrow \hat{u}_i(t, X(0))$$

### Conclusions

- In the current practice, numerical substructure design relies on deterministic assumptions and the probabilistic character of the emulated system response is completely missed.

- Polynomial Chaos Expansion is a robust framework for accommodating uncertainty propagation and global sensitivity analysis in Hybrid Simulation.

- About 20 hybrid simulations guarantee good estimates of both statistical moments and Sobol’ indices of the response quantities for typical tested structures.

- According to the most widely used seismic performance-based design code models, such number agrees with the size of the ground motion set required to perform a reliable nonlinear dynamic analysis.

### QUESTIONS?

THANK YOU!
Verification of different approaches in implementing hybrid simulation

S. Bousias
Structures Laboratory
Univ. of Patras, GR

Hybrid Simulation
Years of development but Diffusion still difficult to achieve

Hybrid Simulation Primer & Dictionary
“While the concept of hybrid simulation is not difficult to understand, configuration and implementation are not always straight-forward for those who are new to hybrid simulation”.

...configurations of hybrid simulation are highly dependent on available and selected tools in computational and physical components, …”

Implementation issues
Two approaches have been identified:

– **Simulation Coordinator**: a central component performs the integration & communicates to all modules (e.g. UI-SimCor)
– **Master Simulation**: the FEM software itself manages communication to the lab module (e.g. OpenFresco)

Communication to controller:

– Modern controllers with networking capabilities
  – Software-based: rely on the specifications of host laboratory digital control software
  – Older controllers
    – Hardware/software-based: based on feeding target displacements to controller in analog form.

Overview of software-based scheme

Host controller software
**Laboratory network layout**

- Network Camera
- Data Collector
- Telepresence Server
- Lab. Network
- Internet
- Data Acquisition
- Control
- Virtual Network
- Test Structure

**Hardware & Software-based scheme**

- Network Interface for Controllers (NICON)
- Ethernet
- tcpip
- Coordinator software: SanCar
- Local software: Labview-Nicon
- Safety issues, offsets, ramp generation
- 2 net cards

**Application**

- Project: EXCHANGE-SSI
  European Commission, FP7

**The structure**

- A1 P1 P2 A2
- 27.00 m 45.00 m 27.00 m
- 10.00 m 5.00 m 5.00 m
- 1.50 m 0.25 m 0.25 m
- Ø47.1
- 2.00 m
- 49625
- 2.00 m
Hybrid simulations

- Hybrid simulation at Univ. of Patras - HSUPat.
- Hybrid simulation between Univ. of Patras and Aristotle Univ. - HSGR.
- Intercontinental multi-platform simulation - IMPS
- Intercontinental hybrid simulation – IHS

<table>
<thead>
<tr>
<th>Module</th>
<th>HSUPat</th>
<th>HSGR</th>
<th>IMPS</th>
<th>IHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module 1+</td>
<td>UPATRAS</td>
<td>AUTH</td>
<td>AUTH</td>
<td>AUTH</td>
</tr>
<tr>
<td>Module 2+</td>
<td>UPATRAS</td>
<td>AUTH</td>
<td>UIC</td>
<td>AUTH</td>
</tr>
<tr>
<td>Module 3+</td>
<td>UPATRAS</td>
<td>AUTH</td>
<td>AUTH</td>
<td>AUTH</td>
</tr>
<tr>
<td>Module 4+</td>
<td>UPATRAS</td>
<td>UPATRAS</td>
<td>UPATRAS</td>
<td>UPATRAS</td>
</tr>
<tr>
<td>Module 5+</td>
<td>UPATRAS</td>
<td>AUTH</td>
<td>UTORONTO</td>
<td>UTORONTO</td>
</tr>
<tr>
<td>Coordinator</td>
<td>UPATRAS</td>
<td>AUTH</td>
<td>AUTH</td>
<td>AUTH</td>
</tr>
</tbody>
</table>

IHS Hybrid simulation

- Distributed: AUTH (Coordinator & num. mod. 1–3), UPAT (physical module), Utoronto (num. mod. 5)
- Simulation full scale – scaled physical module
- Compensation for rate-effects (per Molina et al.)

Module 4 (EBR on the left) response

- Step completion time: 0.5 – 4 s (50–400 time scale expansion)
- Analog–input scheme: marginally better performance
Step duration → experimental module
- *Labview* script: multi-thread application (timing assigned when value is available in memory)
- *Matlab* script: timing determined when signal is saved
- Software-only approach: two network cards
Reliability Assessment of Real-time Hybrid Simulation in Presence of Actuator Tracking Error

Cheng Chen, Ph.D., Associate Professor
San Francisco State University

Outline of Presentation

• RTHS Background
• Probabilistic Analysis
• Implementation
  o Use of Tracking Indicator
  o Use of Frequency Domain Analysis
• Summary and Conclusion
• Acknowledgement

Outline of Presentation

• RTHS Background
• Probabilistic Analysis
• Implementation
  o Use of Tracking Indicator
  o Use of Frequency Domain Analysis
• Summary and Conclusion
• Acknowledgement

RTHS Background

Servo-Hydraulic Actuators

Critical to maintain the boundary conditions between substructures!

Courtesy of Lehigh RTMD

Servo-Hydraulic Actuators

Critical to maintain the boundary conditions between substructures!

Courtesy of Lehigh RTMD

Servo-Hydraulic Actuators

Critical to maintain the boundary conditions between substructures!

Courtesy of Lehigh RTMD

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Actuator Delay in Predefined Test

Command Maximum: 50 mm
Frequency Content: 0 ~ 5 Hz

Maximum tracking error 16.90 mm (35% of command maximum)!

Effect of Actuator Tracking Error

Comparison of structural responses for a linear SDOF Structure with 2 Hz natural frequency and 1 msec delay
Questions to be answered?

How will the tracking errors affect the accuracy of simulated structure response from RTHS?

How will researchers assess the accuracy of simulated response in replicating the true structural response when the latter is not available?

Probabilistic Analysis

Reliability Assessment

Effect of Nonlinear Behavior

Effect of Stiffness Degradation

Different Natural Frequencies

Critical delays based on 10% MAX error

Critical delay distribution for different ductility demands for an SDOF

Critical delay for same ductility demand and different stiffness degradation

Distribution of critical delay for SDOF structures with significant stiffness degradation for different natural frequencies
Effect of Strength Degradation

Critical delay for same ductility demand and different strength degradation

Probabilistic Assessment

With known delay in RTHS, probability of simulated response having MAX error larger than 10%

Implementation using TI

Tracking Indicator (Mercan and Ricles 2010)

Application of Proposed Approach

Perform real-time hybrid simulation

Implementation using TI

Test 1: IC with $\phi_{test}=15$

P.E. = 50%

Test 2: AIC with $\phi_{test}=15$

P.E. = 15%

Test 3: AIC with $\phi_{test}=30$

P.E. = 5%

Analytical Substructure Properties:
- structural mass: $m=503.4$ ton
- natural frequency: $f_n=0.172$ Hz
- viscous damping ratio: $\zeta=0.02$
- viscous damping ratio: $\zeta=0.02$
- analytical substructure modeled using Bouc-Wen model (Wen 1980)

Implementation using Freq. Anal.

- Input \( I(t) \)
- Output \( O(t) \)
- \( F\hat{I}(\omega) \)
- \( F\hat{O}(\omega) \)
- Amplitude
- Phase
- Time Delay
- Phase Diff. \( \phi \)

Integrated Time and Frequency Domain Analysis for Probabilistic Assessment

- Time Domain Analysis (LE)
- Critical Delay Distribution (LE)
- Real-Time Hybrid Simulation
- Critical Delay Distribution (NL)
- Reliability Assessment
- Freq. Domain Analysis
- Equivalent time delay

Summary and Conclusion

- Actuator tracking error could lead to error in RTHS deviating from actual structural responses under earthquakes.
- Probabilistic approach is more appropriate for reliability assessment of RTHS results due to the fact that actual response is not known before or even after the experiments.
- With proper adjustment, critical delay distribution from linear structure analysis can account for nonlinear behavior with stiffness and strength degradation.
- Probabilistic analysis could be implemented through both tracking indicator and frequency domain analysis

Acknowledgements

- National Science Foundation under the award number CMMI-1227962
- Office of Research and Sponsored Program at San Francisco State University
- Presidential Research Award from SFSU President office
- Wang Family Research Award from CSU Chancellor’s office

Thanks for your attention!

Questions?
Real-time hybrid simulation: stability, performance and execution
...our approach to planning and execution

Shirley J. Dyke & Amin Maghareh
School of Mechanical Engineering  Lyles School of Civil Engineering

October 2015
Joint Research Center, Ispra, Italy EU

Background

Primer and Dictionary (March 2014, @nees.org)
• General introduction to hybrid simulation, its components, capabilities, and the procedures by which a simulation is typically performed
• Dictionary to help users new to hybrid to understand synonyms and terminology associated with hybrid simulation.

Assessment Measures (September 2014, @nees.org)
• Summary of the various methods used to assess a hybrid simulation, through evaluation of the results
• Toolkit of matlab codes to execute the calculations
• Examples from real world experiments of the computations

Objectives

Perhaps …
• What options do I have in implementing this RTHS to allow me to achieve my goals?
• What are the main challenges in each configuration? Instabilities? Accuracy?
• How well will the results represent reality in each case?
• What adjustments may alleviate the challenges? Or improve the accuracy or fidelity of the test?

In planning an RTHS, …
• Establish clear goals and objectives
• Execute with those objectives in mind
• Make decisions and trade-offs along the way

Match the tools to the task

Match the tools to the task
From a stability perspective, are all these partitioning options identical? If not, what makes the difference? How can we quantify the differences?

From an accuracy perspective, how realistic are the responses? What makes the difference? How can we quantify the differences?

Objectives

Predictive Indicators
- Predictive stability indicator (PSI)
- Predictive performance indicator (PPI)

Purpose
- Plan and design a safe, stable, and accurate experiment
- Generate pre-experiment measures (stability and accuracy) to optimize the use of available tools and algorithms
- Advance our understanding of various sources of error and instability in RTHS

Predictive analysis

An approach is proposed to assess the sensitivity of a partitioning configuration to any phase discrepancy at the interface of the substructures.

Virtual is independent of the setup/equipment.

Multi-DOF RTHS

Using publicly available data in the NEEShub (NEES project ID: 648) for a three story prototype building, which have been studied and identified in a NEESR project on performance based design using semi-active control.
Simulated results

9M simulated RTHS configurations
(1 first order system: variation cases: 3 0.05 3 0.08 3 0.15 3 0.2 3 0.25 3 0.35 3 0.4 3 0.5 3 0.65 3 0.7 3 0.8 3 0.9 3 1.0)

PSI and simulated results

Stability results

Predictive results

Concluding remarks

A systematic approach to plan and execute a RTHS.

Advantages:
- Do not need a detailed model of the components
- Independent of the equipment or controller designs.
- Useful for distributed testing.

Predictive indicators:
- Map a configuration choice to a measure which can be associated with minimum control requirements for a successful execution.
- Identify how realistic experimental results are in the absence of a reference response.

This approach is an effective tool for planning and successful execution of more challenging experiments.

Optimal Discrete Time Feedforward Compensator

Wei Song (weisong@eng.us.edu); Seraj Haghighi
Civil, Construction and Environmental Engineering Department
The University of Alabama, Alabama, U.S.A.

\[ TF(x^{-1}) = \frac{B(x^{-1})}{A(x^{-1})} = \frac{B^*(x^{-1})}{A^*(x^{-1})} \]

\[ TF: \text{Actuator transfer function} \]
\[ B^*(x^{-1}) : \text{Stable roots} \]
\[ B^*(x^{-1}) : \text{Unstable roots} \]

\[ u_T(x^{-1}) = \frac{1}{TF(x^{-1})} \frac{A(x^{-1})}{B^*(x^{-1})} \]

\[ G_{up}: \text{Compensator} \]
\[ \frac{1}{B^*(x^{-1})} \text{is replaced by} \frac{1}{x^{-1}} \]

The compensator \( X(x^{-1}) \) is designed by using the following optimization scheme:

**Optimization**

Objective: \( \min(\text{Frequency response} - 1) \)

Constraint:
- Steady-State gain = 1
- Pass-band magnitude = 1
- Pass-band phase = 0

Experimental Results

Actuator with 110 kips capacity
Mass box (weight = 1280 lb)
Spring (k = 8000 lbf/in)

System
Hybrid Simulation in Seismic Research
A Major Challenge and Opportunity to ILEE
Tongji University

LU Wensheng
Professor
Tel: 021-65983428-108
Fax: 021-65983428
wally@tongji.edu.cn

Wang Yangling
PhD
Tel: 021-65982666
Fax: 021-65982668
wangyling@gmail.com

Ren Xiangxiang
PhD
Tel: 021-65982666
Fax: 021-65982668
lvqing06300440@163.com

LU Xilin
Professor
Tel: 021-65983430
Fax: 021-65982668
lxlst@tongji.edu.cn

CONTENT

- Background
- Zonal Hanging Glass CW of Shanghai Tower
- Isolated Conservatory on the Top of Raffles Tower
- ILEE

BACKGROUND

HS Classification

- Slow Hybrid Simulation
- Real-time Hybrid Simulation
  - Actuator Configuration
  - Shaking Table Configuration
  - Actuator + Shaking Table Configuration

HS Facilities in Tongji University

Labs with Strong Wall & Floor

- + MTS
- + IST
- + SW
- + Domestic System

Typical Projects

HS @ Tongji U

LACK OF PROJECT EXPERIENCE TECHNICIAN ILEE TJU

Challenge Opportunity
EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

ZONAL HANGING GLASS CW OF SHANGHAI TOWER

EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

Structural Model @ Shaking Table

- 1/25
- Micro-concrete
- 5 Earthquake Waves
- Numerical Simulation

EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

Curtain Wall @ Shaking Table

- Full-sized CW
- Floor Response Spectrum
- 7 Earthquake Waves
- Numerical Simulation

EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

Detail of CW hanging design

EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

Typical hanging floor: stiffness of suspension beam differ

EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

Full-sized CW Floor Response Spectrum

EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

Shanghai Tower
Schematic Diagram of Hybrid Simulation on Zonal Hanging CW System

HS Test @ UC Berkeley

Challenge and Opportunity

ISOLATED CONSERVATORY ON THE TOP OF RAFFLES TOWER

Friction pendulum bearing

Viscous damper

Complex Structure Beyond Chinese Codes

• Full-sized HS testing is under planning in ILEE Tongji University
Design & Construction of Hybrid Testing

Material: HPB300 bar + 5mm plate
Similarity: dynamic behavior, loading capacity

Mode 1:
- Material: HPB300 bar + 5mm plate
- Similarity: dynamic behavior, loading capacity
- Design & Construction of Top Conservatory

Design & Construction of Model Isolators and Dampers

Friction Pendulum Bearing

Parameter of Prototype Friction Pendulum Bearings

Parameter of Model Friction Pendulum Bearings

Viscous Dampers

Parameter of Prototype Viscous Dampers

Parameter of Model Viscous Dampers

Energy equivalent hysteresis curve

Model on the Shaking Table
EU-US-Asia Workshop on Hybrid Testing
Ispra, 5-6 October 2015

**Model Mounting and Installation**

**The Responses of Isolation Layer under Earthquakes**

**ILEE 地震工程国际合作联合实验室**
International Joint Lab in Earthquake Engineering
Minimising hybrid testing errors by optimal test rig design and control

Prof A R Plummer
Director
Centre for Power Transmission & Motion Control
University of Bath, UK

www.bath.ac.uk/ptmc

Model-in-the-Loop

Combine a
• Physical laboratory test rig
  With a
• Real-time computer simulation
To obtain
• Test data for a hybrid real-virtual specimen

F1 chassis dynamics testing
4 and 7/8 post rigs
Aerodynamic Model-in-the-Loop

Analysis of numerical/physical interaction
Linear physical and numerical models

Numerical-physical interaction with actuator dynamics
Load controlled-actuators

Actuator response

Predicted vertical response error

Measured actuator disturbance response, \( r_f(s) \) (N/mm)

Actual vertical response measured using test rig
Analysis of numerical/physical interaction
Linear physical and numerical models – quarter car model

Solution?
Compensation for actuator response

Tyre Model-in-the-Loop

Predicted vertical response error

Tyre force response to road input (N/mm), comparing actual (MiL) and ideal responses

Solution?
Compensation for actuator response

Tyre force response to road input (N/mm) BETTER!

BUT!
Sensitivity of the actuator command signal to measurement noise
Minimise the cost function:

\[
\min \left\{ \left( \frac{e}{z_0} \right)^2, \frac{e}{w_1}, \frac{z_1}{c} \right\}
\]

Conclusions

- The challenge of achieving appropriate interaction between numerical and physical parts to give a realistic emulation of the complete system is often underestimated.
- Using approximate (linear) models of whole system, with and without actuator / sensor / computation characteristics, allows performance to be assessed.
- The trade-off between emulation error and noise amplification (+ actuator saturation) can be manipulated using techniques from optimal control.
- It should be possible to calculate the actuator performance envelope required for a specified test input spectrum envelope and emulation error bound.
TOWARDS REAL-TIME HYBRID TESTING OF RC FRAMES WITH MASONRY INFILLS

António A. Correia
Alfredo Campos Costa
Paulo Candeias

Status of hybrid testing at LNEC

- Large experience with shake table tests and control
- Experienced with substructure/component testing
- Strong capabilities in numerical modelling
- But, inexperient on hybrid testing
  - Learn/cooperate with other facilities!

LNEC seismic testing facility

3D shake table:
- Max payload: 40 ton (392kN)
- Plan dimensions: 4.6m × 5.6m
- Displacements actively controlled (3 DOF)
- Rotations passively restrained
- Frequency range: from 0.1Hz up to 40Hz

Motivation

- Recent earthquakes demonstrated the inadequacy of current European masonry infill solutions
- Particularly vulnerable to out-of-plane collapses after in-plane damages
- Eurocode 8 requires the out-of-plane seismic stability for non-structural masonry infills
- Eurocode 8 addresses this issue by imposing the use of reinforced masonry infill solutions but fails to give design and detailing methodologies

Objectives

- Experimental evaluation of the seismic response of RC frames with innovative solutions for masonry infill walls
- Structures designed to the Eurocodes (possible contribution to its development)
- Assess the dynamic response characteristics and its evolution up to collapse:
  - collapse mechanisms
  - ductility and ultimate drift capacity
  - equivalent damping, etc.
- Interaction of RC frame response with masonry infill
- Provide further experience for retrofitting and strengthening
- Calibration and development of numerical models

Motivation

- For economic and test repeatability reasons, substructuring is an obvious choice, which has important requirements on the boundary conditions and on the seismic input

State-of-the-art:

- Angel (1994)
- Airbags
- Komaraneni (2009)
- Reduced scale
Idealization of the test

- Simulation representing the response of a typical frame panel from a RC building (floor response actions)

- In and out-of-plane dynamic actions:
  - Inter-storey drift (narrow bandwidth signal at low frequencies)
  - Out-of-plane absolute acceleration (narrow bandwidth signal at larger frequencies)

In-plane motion enforcing an inter-storey drift time-history:
- Dynamic inter-storey drift imposed by the shake table
- Top beam restrained by strut to reaction wall
- Prestressed top beam for push-pull action
- Prestressed columns representing the vertical load

Out-of-plane motion consisting on a rigid-body vibration of the RC frame reproducing the narrow band storey absolute accelerations perpendicular to the masonry panel:
- Shake table motion transmitted to the top beam through the rigid steel caisson
- Conical rollers at the base hinges
- RC frame moving as a rigid body with the shake table

Frequencies and mode shapes

- Longitudinal: $f = 18.4$ Hz
- Transverse: $f = 23.1$ Hz
- Torsion: $f = 25.5$ Hz
Idealization of the test
Capacity curve of the bare frame

Construction and setup

RC frames:
- Dimensions: 6.40m x 3.25m
- Beams: 0.50m x 0.30m
- Columns: 0.40m x 0.30m
- C25/30 concrete class
- S500NR steel class
- 360kN centred prestress in columns and upper beam

Masonry infill walls:
- Single leaf masonry
- Traditional brick units 30x20x22
- M5 class mortar
- Bed joint reinforcement
- (Wire mesh reinforcement)

Seismic Input Motion
- Bi-directional artificial horizontal ground motion fitted to EC8 response spectra for Lisbon
- Several stages of seismic action amplitude:

<table>
<thead>
<tr>
<th>Nível</th>
<th>Período de retorno</th>
<th>Probab. de exceedência</th>
<th>Factor de escala</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.2 anos</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>72 anos</td>
<td>50%</td>
<td>24%</td>
</tr>
<tr>
<td>3</td>
<td>224</td>
<td>20%</td>
<td>63%</td>
</tr>
<tr>
<td>4</td>
<td>475</td>
<td>10%</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>975</td>
<td>5%</td>
<td>159%</td>
</tr>
<tr>
<td>6</td>
<td>2475</td>
<td>2%</td>
<td>292%</td>
</tr>
<tr>
<td>7</td>
<td>4975</td>
<td>1%</td>
<td>464%</td>
</tr>
</tbody>
</table>
Unreinforced masonry test

- In-plane collapse mechanism formation initiated at 34% of reference input seismic motion
- Mechanism composed of horizontal cracks at 1/3 and 2/3 of infill height + diagonal ramifications towards the corners
- Posterior destruction of upper row bricks due to transverse motion
- Overall decrease of infill out-of-plane fundamental frequency from 20 Hz to 3 Hz

Reinforced masonry test

- In-plane collapse mechanism formation also initiated at 34% of reference input seismic motion
- Initial mechanism composed of two main diagonal cracks
- Posterior development of groups of diagonal cracks with rigid infill parts sustained by bed joint reinforcement only
Reinforced masonry test

Thank you for your attention!
Framework Development of Multi-axial Real-time Hybrid Simulation

Gaston Fernandois-Cornejo and Billie F. Spencer, Jr.
University of Illinois at Urbana-Champaign
fermand@illinois.edu

EU-US-Asia Workshop on Hybrid Testing @ JRC-ELSA
October 5-6, 2015

What is Hybrid Simulation?

Numerical Substructure + Physical Substructure

\[ M \ddot{x} + C \dot{x} + R(x, \dot{x}, \ddot{x}) + R^E = F^N \]

Multi-axial Boundary Conditions

Load and Boundary Condition Box (LBCB)

Types of Actuator Dynamic Coupling

Coupling through flexible continuum
(Philips and Spencer, 2013)

Coupling through rigid body kinematics
(Nakata, Spencer and Elareshi, 2010)

maRTHS Framework
**maRTHS Cyber-system Implementation**

- Host PC (Matlab/Simulink/ControlDesk)
- ISpace DS1103 Controller Board
- G1104 Connector Panel (I/O)
- Actuator LVDT
- Actuator Load Cell
- Command Actuator Displacement
- Shore Western Servo Controller
- Command Servo Valve Voltage
- LBCS (Physical Specimen)

---

**Physical Substructure Description**

- 1/5th Scale LBCS
- Strong wall
- Physical Specimen (3"x3" hard rubber column)

---

**RTHS Block Diagram**

- Excitation
- Numerical Component
- Model-based Controllers
- Physical Component
- Feedforward Compensator
- LGG Feedback Regulator

---

**Kinematics of Parallel Manipulator**

- **Inverse Kinematics Transformation (IKT)**
  \[ q = F(x, q_0) \]
  \[ f_i(x) = \| R(x)A_i + p(x) - B_i \| \]

- **Forward Kinematics Transformation (FKT)**
  \[ x = \{ \mathbb{R}^6 \mid G(x, q, q_0) = 0 \} \]
  \[ g_i(x, q_i) = \| R(x)A_i + p(x) - B_i \| - q_i = 0 \]

- **Note:** \( q_0 = \| A_1 - B_1 \| \)
**Approach 1:** Task Space Controller w/ Real-time FKT

**Approach 2:** Task Space Controller w/ Direct Sensing

**maRTHS Framework**

**Task 1: System Identification**

**Task 1: System Identification**

\[ H_m(s) = \left[ H_i(s) \right]_{\text{meas}} \]
**Task 1: System Identification**

- Experimental transfer functions are fitted using nonlinear parametric optimization tool (i.e. MFDIO)
- The identified MIMO plant was proper, i.e. number of poles was greater than number of zeros

\[ G_{\text{model}}(s) = \prod_{i=1}^{m} (s - z_{i})^{k} \]

\[ G_{\text{excitation}}(s) = \prod_{i=1}^{n} (s - p_{i}) \]

(Kim, Spencer and Yun, 2000)

**Task 2: Model-based controller**

- Model-based feedforward controller
  - Inverted transfer function using backward-difference method
    \[ u_{FF}[k] = C_{0}(z)x[k] + C_{1}(z)i[k] + C_{2}(z)i[k] \]
  - Feedback controller
    - Robust LQG regulator
      \[ u_{LQG}[k] = -K_{LQG}i[k] \]
  - Discrete systems for digital control

(Phillips and Spencer, 2013)

**Example: Compensator Analytical Simulation**

- Reference tracking performance
  - Sine wave, cartesian X disp., amplitude 5 mm, 5 Hz frequency
  - BLWN + KT filter, cartesian X disp., RMS 10 mm, 20 Hz bandwidth
  - EL Centro EQ (scaled), cartesian X disp., max rel. disp. 10 mm
- Implementation: Matlab & Simulink
  - Fixed Time Step = 0.5 ms
  - Numerical Solver = Runge Kutta 4th Order (ode4)

**Reference Tracking Performance**

Sine wave, CartX, no Compensation (approx. delay = 18 ms)
Reference Tracking Performance

- RMS tracking error (%)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Sine Wave</th>
<th>BLWN + KT</th>
<th>El Centro (scaled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Compensation</td>
<td>59.9723</td>
<td>37.4062</td>
<td>45.4360</td>
</tr>
<tr>
<td>FF only</td>
<td>0.7844</td>
<td>0.4861</td>
<td>0.7095</td>
</tr>
<tr>
<td>FF + FB</td>
<td>0.5631</td>
<td>0.3572</td>
<td>0.5928</td>
</tr>
</tbody>
</table>

Error_{\text{RMS}} = \sqrt{\frac{\sum (q_i - y_i)^2}{\sum q_i^2}}

maRTHS Framework

- Newton-Raphson method
  \[ x_{n+1} = x_n - \left( \frac{\partial g}{\partial q_n} \right)^{-1} g(x_n, q_n) \]
  - Note: rate of convergence and accuracy depends on convexity of the solution hypersurface, initial guess, etc.
  - May not yield the exact solution for real-time applications

- Other approaches
  - NR + neural networks
  - Extra sensors in task space

Task 3: Real-time FKT

- While iterator subsystem (Simulink)

<table>
<thead>
<tr>
<th>Tolerance:</th>
<th>Max number iterations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1e-3 mm (X,Y,Z)</td>
<td>100</td>
</tr>
<tr>
<td>1e-5 rad (RX,RY,RZ)</td>
<td></td>
</tr>
</tbody>
</table>

FKT Simulation

- Sine wave, cartesian X disp., amplitude 5 mm, 5 Hz frequency
Real-time FKT Solutions (Work in Progress)

- Very fast implementation (1 or 2 iterations)
- Good results for X task trajectory
- Other trajectories have slightly small errors, probably due to numerical errors caused by bad condition of Jacobian matrix

maRTHS Framework

Intermediate Step: maRTHS Analytical Simulation

maRTHS Proof of Concept (work in progress)

Pseudo-static Cyclic Test (time-lapse)

Rubber Column Hysteresis Curve

Closing Remarks

1. The framework is useful only if a detailed model of the physical component is achieved
2. Real-time FKT is difficult to implement in embedded systems
   - Issues of convergence and Jacobian matrix singularities
   - A solution is to linearize the kinematic transformations for small displacements
   - For future research, we could explore multi-metric feedback control, i.e. include external LVDT sensors to measure task trajectories directly
3. Next steps, create code for DSP embedded system (numerical integration, digital control, and DAQ).
4. Commissioning Tests will take place in the 1/5th scale LBCB with hard rubber specimens for academic purposes
Questions?
MDOF Hybrid Shake Table Testing for Bridge and Building Structures

Andreas Schellenberg, Ph.D., P.E.
Shawn You, Ph.D., P.E.
Stephen Mahin, Ph.D.

Outline of Presentation
1. Motivation
2. Hybrid Shake Table Testing
3. Stability and Accuracy Considerations
4. Test Rehearsal and Safety Precautions
5. Bridge Application
6. Building Application
7. Summary & Conclusions

Motivation
- Many structures exhibit significant rate of loading effects
- Need testing to occur at or near real time
- Large systems such as tall buildings, long-span bridges, or SFSI are difficult to test on shake tables

Hybrid Shake Table Testing
\[ M \ddot{u} + C \dot{u} + P(t, u, \dot{u}, \ddot{u}) = \mathbf{P}_0 \]

Hybrid Shake Table Configuration
- Tall Building Application
- 3 translational DOF + 3 rotational DOF
- Long-Span Bridge Application
- 1 actuator DOF + 2 table DOF
Important Analysis Parameters

- OpenSees or OpenSeesSP as comp. driver
- Using AlphaOSGeneralized ($\rho_{inf} = 0$)
- No iterations necessary
- Using MultipleSupport excitation pattern in OpenSees to get absolute response
- Gravity loads on test specimen always present → apply gravity loads to numerical portion before connecting with shake table + apply disp. commands relative to start of test

Connecting to MTS 469D + FlexTest

Improving Stability & Accuracy

- Delay compensation is essential for real-time hybrid simulations (RTHS)
- Use Adaptive Time Series (ATS) delay compensator (by Y. Chae)
- Modify ATS to use target velocities and accelerations computed by predictor-corrector algorithm instead of taking derivatives of target displacements
- Use stabilization and loop-shaping
- Sensor noise reduction by filtering fbk

Test Rehearsal

- Use FE-Adapter element method to simultaneously connect hybrid model to a numerically simulated test specimen

Safety Precautions

- At analysis side
  - Set limit on displacement command (saturation and possibly rate limit)
  - Set limit on actuator force so that once the limit is exceeded, the analysis model sends displacement commands to ramp both table and actuator to starting positions
- At controller side
  - Set both displacement and force limits so that once the limit is exceeded, the actuator pressure is switched to low, therefore, limiting the actuator force that can be applied to the specimen

Bridge Application

Four 2DOF Shake Tables
Shake Table + Structural Actuator

Hybrid Model Development

Actual Bridge Configuration
(with foundation + soil)

Simplified Hybrid OpenSees
Model of Bridge (Stage 2)

Experimental Setup

Partial-weight
bridge deck

Using table observer to get shear forces at bottom of columns
(load cells would be better)

Movie of Test

Displ. Response Comparison

Force Response Comparison

Accuracy is assessed using
- FFTs of tracking error
- Tracking Indicator (by Mercan and Ricles)
- RMS Error histories
- Comparison with purely numerical simulation
### Triple Friction Pendulum Bearings

<table>
<thead>
<tr>
<th>L1 (in.)</th>
<th>L2 (in.)</th>
<th>L3 (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.175</td>
<td>17.17</td>
<td>17.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T1 (s)</th>
<th>T2 (s)</th>
<th>T3 (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.67</td>
<td>1.41</td>
<td>1.87</td>
</tr>
</tbody>
</table>

### Analytical Substructure Parameters

#### Experimental Substructures (with TP isolation bearings)
- 15-DOF Shear Building
  - $W_{tmd} = 53$ kip
  - $W_{bldg} = 450$ kip
  - $f_{x1} = 1$ Hz
  - $f_{y1} = 1.25$ Hz
  - $f_{z1} = 9.8$ Hz

#### Analytical Substructures
- 3-DOF Equivalent Model
  - $W_{tmd} = 53$ kip
  - $W_{bldg} = 0.886 \times 450$ kip
  - $f_{x1} = 1$ Hz
  - $f_{y1} = 1.25$ Hz
  - $f_{z1} = 11$ Hz

#### Models without rotational DOF

### Delay Assessment

#### Error between Measured and Target Displacements from 5-DOF Target DOF

![Graph showing error between measured and target displacements](image)

#### Delay Assessment

![Graph showing delay assessment](image)
Delay Assessment

Tracking Indicator

Summary & Conclusions

- Ability to drive a MDOF shake table through a finite element model
- Shake table platform can thus represent a floor or the roof of a building, the motion on top of a bridge column, or the ground surface on top of a soil domain
- Performed large-scale RTHS where a shake table is combined with a dynamic structural actuator applied to a bridge
- Ability to perform parameter studies

- Use whenever the dynamics of the test specimen significantly affects the response of the supporting structure or soil and, therefore, alters the required input to the shake table as testing progresses
- ATS delay compensator worked very well
- Need to further investigate sensor noise reduction methods to improve feedback signals (look into Kalman filters)

Questions?

Thank you!

http://openfresco.berkeley.edu

EU-US-Asia workshop on hybrid testing

Ispra, 5-6 October 2015
Hybrid Tests of A Full-scale 2-story RC Frame with Buckling Restrained Braces

Keh-Chyuan Tsai
An-Chien Wu
Kung-Juin Wang

National Taiwan University (NTU)
National Center for Research on Earthquake Engineering (NCREE)

EU-US-Asia workshop on hybrid testing
Ispra, October 5-6, 2015

Retrofit of RC frame with BRB

- Post-Installed anchors

Mahrenholtz et al. (2015), Retrofit of Reinforced Concrete Frames with Buckling-Restrained Braces, EESD. pp 44:59-78

Retrofit of RC frame with BRB

- Steel Frame

Tsai et al., 2015, Seismic retrofit of reinforced concrete frames using buckling-restrained braces with bearing block load transfer mechanism, EESD, in review.

Steel Embedment for New RCF

D-region check
Full-scale BRB-RCF tests

Objectives:
- Proof of concept
- Design of Steel embedment
- D-region check
- Validate analytical model

Specimen Details

Vertical Force
Applied: 2550 kN

Column: 500x500, 12-#7
Top Beam: 400x500, 8-#5
Mid Beam: 450x500, 8-#7

A36 Material
f'c = 35 MPa
fy = 420 MPa

Steel Embedment

Shear demand:
UFM + Frame Action
Tension demand:
UFM (For conservative)

Shear stud:
take horizontal shear force
Rebar or steel plate:
take vertical tensile force

Steel Embedment Fabrications

Axial force: 590 kN
Post tension: 590 kN
Lateral support
Actuator x3
Actuator x3
Assign Mass and Damping ratio

- Select the mass: $T = 0.4$ sec
- Assume the same mass for the two floors
- Mass = 0.113 (kN·s²/m)
- $\xi_1 = \xi_2 = 2\%$
- $T_1 = 0.38$ sec, $T_2 = 0.13$ sec

PISA3D response predictions

- 5 m
- 3.28 m
- 3.13 m
- With Rigid end zones (REZ)

- **T Beam & Column:**
  - Fiber element
  - Concrete: OpenSees Con04
  - Rebar: Degrading
- **BRB:**
  - Hardening material
  - Truss element

Experimental procedures

- Free vibration test 1
- 50/50 hybrid test
- Free vibration test 2
- 10/50 hybrid test
- Free vibration test 3
- 2/50-1 hybrid test
- Free vibration test 4
- 2/50-2 hybrid test
- Free vibration test 5
- Cyclic loading test

Response Spectra

- Free vibration test 1, 2, 3, 4, 5
- Cyclic loading test
- Newmark explicit integration procedure
- Time step size = 0.005 sec
- Rayleigh damping = 2%
- 20 seconds ground motions → 60 min. test

Hybrid tests of the 2-story BRB-RCF

- Newmark explicit integration procedure
- Time step size = 0.005 sec
- Rayleigh damping = 2%
- 20 seconds ground motions → 60 min. test
Story shear vs inter-story drift

- 50/50 - FOE
- 10/50 - DBE
- 2/50 - MCE1

MCE1 vs MCE2

Response Simulations of Hybrid Test1 (FOE)

+3.5 %

MCE1 vs MCE2

Story shear vs story drift

BRB hysteresis

Response Simulations of Hybrid Test1 (FOE)
Conclusions

- The BRBs enhance the RCF stiffness, strength and ductility, comply with PBSD
- Steel embedment can be conveniently designed and installed
- D-region can be properly designed and detailed using SSST model
- The pseudo-dynamic responses can be accurately predicted

Thank you for your attention!!
HYBRID SIMULATION OF COMPLEX ISOLATED BRIDGES ENHANCED WITH PARALLEL FETI TIME INTEGRATORS AND MODEL UPDATING

G. Abbiati, Oreste S. Bursi, I. Lanese & A. Pavese

Acknowledgements

1. The speaker gratefully acknowledges the Workshop Organizing Committees for the invitation.

2. The authors gratefully acknowledge the financial supports from the European Union through the SERIES project (Grant number: 227887).

3. The authors gratefully acknowledge the financial supports from the Italian fund RELUIS.

4. The authors gratefully acknowledge the financial supports of the EUCENTRE and University of Trento for further laboratory activities.

Some issues in the hybrid simulation of non isolated\isolated bridges

1. Model order reduction strategies applied to complex Numerical Substructures (NS).

2. Model identification techniques applied to nonlinear NSs and isolators in both the Rio Torto Viaduct and EUCENTRE Case Studies.

3. Presence of isolators characterized by variable friction coefficients

4. Issues with Parallel Partitioned Time Integrators

Model identification techniques applied to nonlinear NSs

The Rio Torto Viaduct case study

Hybrid simulations was set within the RETRO' TA of the SERIES European research project.

To this end, flexible reduced nonlinear models of Numerical Substructures (NSs), i.e. piers isolators and deck, were devised allowing for:

- fast time integration of the hybrid system;
- simulation of a consistent degradation of PSs and NSs based on run-by-run SI and updating of physical and numerical piers, respectively.


Substructuring scheme of the Rio Torto Viaduct and DoFs target

Model identification techniques applied to nonlinear NSs

Guyan reduction applied to pier matrices

Plane 3-DoFs superelement obtained via Guyan reduction based on Constraint modes*

Accommodation of isolator elements

*Constraint modes: static deformation shapes owing to unit displacements applied to boundary DoFs, one by one, whilst the others retained.
Model identification techniques applied to nonlinear NSs
Nonlinear state space model for reduced piers

Each state space model was tuned with respect to OpenSEES RM for both limit states as a stand alone MIMO system by means of a robust optimization approach.
Preliminary cyclic tests/Hybrid test at PGA level i
Identification of Concrete01 parameters of OpenSEES 2D models of piers
Updating of the OpenSEES 3D model of the bridge
Time history analysis of the OpenSEES 3D model at PGA level i+1
Updating of reduced MatLAB/Cat3m models of piers (NSs)
Hybrid test at PGA level i+1

Offline model updating of NSs
Flow chart of the procedure

Synchronization of Num. and Phys. Substructures via monolithic algorithms

Time integration NS
Actuator control PS

\[
\Delta t^C \cdot SS \cdot (k-1) \quad \Delta t^C \cdot SS \cdot k \quad \Delta t^C \cdot SS \cdot (k+1)
\]

Wall clock time [s]
\[\Delta t^C = \text{controller time step}\]

More flexibility ... via the parallel partitioned PM method


Link solutions vs. continuous testing

Coupled-problem solutions

The mass fraction parameter

The displacement response of Pier #9

\[
M^N = (1 - mf^r) \cdot M^P
\]

\[
M^P = M^M + mf^r \cdot M^P
\]

\[\Delta t^C = \Delta t^P = 1 \text{ msec}\]
Starting from the GC method


A Novel Parallel Partitioned Integrator


The modified-Generalized-α algorithm

My_{x+1} + Ky_{x+1} = F_{x+1}

\Omega = \Omega / \Delta t

\rho_\infty: \text{asymptotic spectral radius}

Reference Test... Suitable for Hybrid Testing

Multi-span bridge with open-section deck and hollow RC piers

EXP. PIER
- re-bars slip/sudden failure
- brittle cracking
- ... failure mechanisms

EXP. CSB
- Wear
- Local contact pressure effects
- ...

CSB Friction Coefficient Compensation

V_{des} = a \left[ \mu_{test} N_d + \frac{N_d}{R} \right] / \eta \left[ \mu_{test} N_d + \beta \frac{N_d}{R} \right]

a = \frac{\mu_{des}}{\mu_{test}} = 1.333

\beta = 1 - a = -0.333

G. Abbiati, E. Cazzador, I. Lanese, S. Eftekhar Azam, O. S. Bursi, and A. Pavese. Recent advances on the hybrid simulation of bridges based on partitioned time integration, dynamic identification and model updating. 6th Int. Conf. on Advances in Experimental Structural Engineering, August 1-2, 2015, University of Illinois, Urbana-Champaign, USA.
**Substructuring scheme of the EUCENTRE Bridge**

**ONLINE identification of the physical pier**

\[
\begin{align*}
\dot{r} + c \cdot \dot{x} + m \cdot \ddot{x} &= p(t) \\
\dot{x} &= \left( A - (\beta \cdot sgn(\dot{x}) + \gamma) \right) r
\end{align*}
\]

**Model Updating of NSs**

Model updating online adopted during EUCENTRE PsD tests

Gray box identification: a joint state and parameter estimation approach

\[
\begin{align*}
\dot{r}_j &= \left( A - (\beta \cdot sgn(\dot{x}_j) + \gamma) \right) r_{ij}^m \\
&= \text{state process noise} \\
\dot{\theta}_k &= \theta_{k-1} + v_{\theta_k}^m \\
&= \text{parameter process noise} \\
\end{align*}
\]

**Numerical validation of the ONLINE model updating**

Identification of the linear tangent stiffness
Conclusions

✓ A methodological approach was proposed to handle PSs characterized by complex geometries with a reduced number of actuators. Model reduction strategies were applied to achieve this goal.

✓ Nonlinear state space models were proposed as NSs suitable for fast updating sessions aimed at reproducing the damage experienced by PSs.

✓ Partitioned time integration allows for flexibility as well as synchronization of both numerical and physical time integration processes.

✓ The magnitude of the physical link solution, which determines the smoothness of the actuator trajectory, can be easily reduced by moving mass from the NS to the PS.

✓ Lagrange multipliers can be calculated explicitly for a better SI.
Heterogeneous Asynchronous Time Integrators for structural dynamics

M. Brun, A. Gravouil, A. Combescure

INSA-Lyon, LGCIE, Civil engineering laboratory
INSA-Lyon, LaMCoS, Contact and structural mechanics laboratory

Presentation content

- Interests for subdomain coupling
- Use of the Energy method for building HATI (coupling Newmark and α-schemes: BGC-macro)
- Split oscillator and convergence analysis
- Applications
- Conclusion

Partitioning methods: Split a complex problem into several partitions
- Compute each partition in the most effective way and solve an interface problem

Fields of application:
- Multi-physics problem: fluid/structure interaction
- Structural dynamics:
  - Localised crash area with fine mesh, best time-integrator (explicit) and fine time step coupled with another time-integrator
  - No constraint on the time step and the time-integrator for the main part
- Hybrid testing: making interact experimental and numerical partitions

Pseudo-energy balance for one subdomain (Hughes):
\[
\frac{1}{2} \Delta \varepsilon^T \text{A} \Delta \varepsilon - \frac{1}{2} \Delta \varepsilon^T \text{K} \Delta \varepsilon = \Delta \varepsilon^T \left( \text{L}_{\text{ext}} \Delta \varepsilon - \text{L}_{\text{int}} \right) - \left( \gamma - \frac{1}{2} \right) \left( \Delta \varepsilon^T \text{A} \Delta \varepsilon \right)
\]

\[
\text{L} = \text{M} \left( \beta = \frac{1}{2} \right) \text{K}
\]

Pseudo-energy balance for two subdomains (macro and micro time steps):
\[
\Delta \text{E}_{\text{inst}} = \Delta \text{E}_{\text{int}} + \sum_{j=1}^{N_{\text{sub}}} \left[ \Delta \text{E}_{\text{in}},j + \Delta \text{E}_{\text{oom}},j \right] + \sum_{j=1}^{N_{\text{sub}}} \Delta \text{E}_{\text{out},j} + \Delta \text{E}_{\text{interface}}
\]

Interface pseudo-energy:
\[
\Delta \text{E}_{\text{interface}} = \left( \frac{1}{B} \sum \Delta \varepsilon^T \text{L}_{\text{ext}} \Delta \varepsilon \right) + \left( \frac{1}{B} \sum \Delta \varepsilon^T \text{L}_{\text{int}} \Delta \varepsilon \right) \left( \lambda_{\text{inst}} - \lambda_{\text{int}} \right)
\]

Goal: building HATI by cancelling the interface pseudo-energy
- stability and second order of accuracy

Assumption about the Lagrange multipliers:

\[
\lambda_{\text{inst}} - \lambda_{\text{int}} = \frac{\lambda_{\text{inst}} - \lambda_{\text{int}}}{B}
\]

leading to the interface pseudo-energy:
\[
\Delta \text{E}_{\text{interface}} = \left( \frac{1}{B} \sum \Delta \varepsilon^T \text{L}_{\text{ext}} \Delta \varepsilon \right) + \left( \frac{1}{B} \sum \Delta \varepsilon^T \text{L}_{\text{int}} \Delta \varepsilon \right) \left( \lambda_{\text{inst}} - \lambda_{\text{int}} \right)
\]
Employing both the multiplier Lagrange assumption and the kinematic condition ensures stable, second-order convergent HATI.

Proof: convergence analysis on the split oscillator through the spectral analysis of the amplification matrix

Application to Newmark and $\alpha$-schemes (HHT, WBZ, CH-\(\alpha\))

Equation of motion in $\alpha$-schemes: weak equilibrium in time by averaging the terms by $\delta \alpha$ and \(\delta f\) parameters

Match the CH-\(\alpha\) scheme with:

\[ \sigma_\alpha = \frac{2f_\alpha}{1 + \alpha} \quad \sigma_f = \frac{2f}{1 + \alpha} \]

and $\beta$ Newmark parameters derived from $\sigma_m$ and $\sigma_f$ parameters

Applying both the multiplier Lagrange assumption and the kinematic condition (zero interface pseudo-energy)

Interface equation:

\[ H \lambda_m = b_m \]
HATI for structural dynamics

Local truncation error:

Local truncation error: 

\[ \tau_n = AX(t_n) - X(t_{n+1}) \]

Accurate order for any time step ratio \( ss \):

- One order more than the GC (and PM, Bonelli et al. IJNME 2008) method for \( ss > 1 \)
- Lax theorem: stability + second order consistency = second order convergent

Damping ratio and period elongation error for CH-\( k \) schemes for \( ss \) from \( 1 \) to \( 10 \)

Order of the damping ratio:

\[ \frac{\tau}{\tau_0} = \alpha \cdot \Omega^2 \]

Order of the period elongation:

\[ \frac{T - T_0}{T_0} = \alpha \cdot \Omega^2 \]

Same order as CH-\( k \) schemes

HATI for structural dynamics

Explicit/implicit multi time step co-simulation using a coupling software (GC algorithm): SPEAR mock-up

Full-explicit

Full-explicit

GC co-simulation

GC co-simulation

PML

Design of efficient absorbing layers based on the Rayleigh damping and PML:

Explicit/implicit multi time step computations using the GC algorithm

HATI for structural dynamics

Coupling \( k \)-schemes with their own time step

Interface pseudo-energy from the generalization of the Energy method for dual subdomain coupling (Lagrangian multipliers DAE)

Canceling the interface pseudo-energy provides dual stable HATI

BGC macro: Spectral analysis of the amplification matrix confirms stability and second order of accuracy

BGC micro: Stable but only one order of accuracy

Perspective: extension to the same level of accuracy.
Thank you for your attention!

Presentation content:
- Interests and overview of coupling approaches
- GC algorithm and setup of the coupling software
- PH algorithm and setup of the coupling software
- Features of the coupling schemes for academic cases
- Application on a RC structure under blast loading

Energy balance (classical energy norm):

One subdomain:

\[ \Delta W_{\text{int}} + \Delta W_{\text{comp}} = \Delta W_{\text{ext}} + \Delta W_{\text{diff}} \]

m subdomains:

\[ \Delta W_{\text{int}} + \sum_{j=1}^{m} \Delta W_{\text{ext},j} + \sum_{j=1}^{m} \Delta W_{\text{comp},j} = \Delta W_{\text{ext}} + \Delta W_{\text{diff}} \]

- Interface energy plotted to evaluate the coupling method accuracy

PH method: built from the GC method with the interface problem at the large time scale

\[ H \Lambda_m = b_m \]

\[ b_m = (L^m v^a_{\text{out},m} + L^m v^b_{\text{out},m}) \]

\( H \) operator computed for the fine subdomain by time-marching:

- Much more time consuming

Advantages:
- Best control of the Lagrange multipliers at the interface
- Ensure the zero interface energy in the sense of the energy method (Hughes, 1987)
Global error analysis for the split oscillator: displacement and velocity

- BGC-macro second order convergent for any $\tau$-schemes and any time step ratios $\delta$

Global error analysis for the split oscillator in acceleration: need of a numerical post-treatment to obtain the second order convergence (Erlicher et al., CM)

$$(1 - \alpha_1) \ddot{u}(t+1) + \alpha_1 \ddot{u}(t) = O(h^2)$$
Connection between hybrid testing & standard shaking table tests – Hybrid testing Workshop - 10/2015

Connection between hybrid testing and standard shaking tests

Alain Le Maoult, CEA (alternative energies and atomic energy commission), France

Connection between hybrid testing & standard shaking table tests – Hybrid testing Workshop - 10/2015

TAMARIS shaking table facility is performing tests for the last 25 years

Hybrid testing is a secondary research field

Hybrid testing has to demonstrate ability

Brief history of hybrid testing in CEA

2005: first work on hybrid testing (HT) with UNIKA
- design of a simple linear 3 DOF mock up
- Tests on a standard 1D shaking table (ST)

2006-2008:
Design of a hybrid bench: a little hydraulic shaking table

Selection of the testing configuration

Configuration selection

Advantages:
1/ no additional actuator
2/ a familiar quality criteria

Accuracy assessment in CEA hybrid tests

Spectral criteria of accuracy in standard tests, accepted by testing community:

specified earthquake and realized earthquake

\[ \Delta \alpha = \alpha_{\text{ref, soil}} + \Delta \delta \]

Try to have a similar criteria for hybrid testing:

specified earthquake vs realized equivalent earthquakes

\[ \alpha_{\text{realized, soil}} = \alpha_{\text{ref, soil}} + \Delta \delta \]

Brief history of hybrid testing in CEA

Numerical errors & noise errors

Errors of control

Video of a HT:
Sinus sweep 0-10 Hz
Linear 1 DOF Numerical substructure

< 3 Hz: OK
> 3 Hz: errors come from control

- No sub stepping & the time step is 1 ms
- Most efforts as been done on the reduction of control errors
Brief history of hybrid testing in CEA

2008-2011:
- Model of the setup to understand and perform virtual hybrid tests:
  - NL analytic model of the hybrid bench
  - Validation of the model: comparison between the real and the virtual HT bench
  - Evaluation/prediction of the control errors with the virtual bench:
    - Amplitude & delay = function (frequency & force)

2011-2014:
- Creation & evaluation of a specific control method for HT
- Hybrid upgrade of a larger mono axial ST

2015:
- Multi DDL control development

CEA feedback on HT field

→ for the time being:
- NO useful hybrid test performed for seismic research in CEA

BUT with hybrid testing field, we can:
- Catch the attention of PhD students on experimental field
- Make people from "the numerical world" more interested in experimental things
- Collect financial resources: an attractive subject, easy to understand
- Increase experimental collaborations, workshops, national and international projects
- Ask manufacturers for new features and a more opened hardware
- Improve skills
- Improve control of standard shaking table tests

Accuracy assessment: equivalent earthquake

\[
\begin{align*}
\tilde{u}_{\text{realized soil}} &= \tilde{u}_{\text{ref soil}} + \tilde{u}_{x} + \Delta \tilde{u} \\
\tilde{u}_{\text{realized eq}} &= \tilde{u}_{\text{realized soil}} + \Delta \tilde{u}
\end{align*}
\]

\[\tilde{u}_{\text{realized soil}}: \text{ table acceleration measurement} \]
\[\tilde{u}_{\text{ref soil}}: \text{ reference earthquake} \]
\[\tilde{u}_{x}: \text{ numerical estimation with } \tilde{u}_{x} \text{ measurement} \]
\[\Delta \tilde{u}: \text{ errors of control, A to D conversions, measure...} \]
\[\tilde{u}_{\text{realized eq}}: \text{ equivalent earthquake} \]

The earthquake we should have sent to the complete structure to obtain the relative acceleration at the first stage during the HT
Integration algorithms for hybrid simulation of structural response through collapse

EU-US-Asia Workshop on Hybrid Testing, Oct 5-6, 2015

Gilberto Mosqueda
Associate Professor
Dept. of Structural Engineering
University of California, San Diego

Performance Characteristics in Current 1-DOF Configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>±0.75m</td>
</tr>
<tr>
<td>Plateau/Sec</td>
<td>62 ft x 29 ft (12.2 m x 7.6 m)</td>
</tr>
<tr>
<td>Peak Velocity</td>
<td>5.8 m/s</td>
</tr>
<tr>
<td>Peak Acceleration (bare table condition)</td>
<td>4.7g</td>
</tr>
<tr>
<td>Frequency Bandwidth</td>
<td>1-53 Hz</td>
</tr>
<tr>
<td>Horizontal Actuator Force Capacity</td>
<td>6.8 MN (1680 tons)</td>
</tr>
<tr>
<td>Vertical Payload Capacity</td>
<td>20 MN (2,000 tons)</td>
</tr>
<tr>
<td>Overturning Moment Capacity</td>
<td>50 MN-m (5,000 ton-m)</td>
</tr>
</tbody>
</table>

Overview of Hybrid Testing to Collapse

- Experimental simulation of framed structures to collapse
- Previous shake table tests
- Description of structural models
- Numerical modeling
- Substructuring techniques
- Challenges in hybrid simulation to collapse
- Use of complex numerical models
- Stability issues
- Comparison of hybrid and shake table tests
- Validation
- Large scale application of hybrid simulation for structural performance assessment

REAL-TIME HYBRID SHAKE TABLE TESTING

Basic hardware and software in place for real-time hybrid shake-table testing:
- Multi-channel MTS FlexTest controller
- SCRAMNet ring for real-time communication and synchronization of data flow
- Easy integration of OpenSees/OpenFresco open-source software framework
- 50-ton dynamic actuator
- Portable hydraulic power system

Shake table test to collapse of moment frame

Full scale four story steel moment resisting frame tested to collapse at E-Defense Shake Table, Sept. 2007

Shake table test to collapse of moment frame

- 1:8 scale moment frame structure was subjected to 5 ground motion intensities of the Northridge 1994 Canoga Park station
- Captures response range from linear elastic to collapse
- Frame has replaceable fuse type elements for repeated testing
- Provides baseline data for validation of hybrid simulation to reproduce collapse – improve acceptance of test method

NHERI@UC San Diego LHPOST

NEES Project on collapse assessment using shake table testing (Özsen, Kravárnik and Whittaker 2011)
Shake table test to collapse of moment frame

- Loading sequence for shake table tests – Canoga Park Record
  - Same loading sequence used in hybrid simulations

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Name</th>
<th>Seismic Hazard Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>SLE</td>
<td>Service Level EQ, Level</td>
</tr>
<tr>
<td>100%</td>
<td>DBE</td>
<td>Design Basis EQ, Level</td>
</tr>
<tr>
<td>150%</td>
<td>MCE</td>
<td>Maximum Considered EQ, Level</td>
</tr>
<tr>
<td>190%</td>
<td>CLE</td>
<td>Collapse Level EQ, Level</td>
</tr>
<tr>
<td>220%</td>
<td>CLEF</td>
<td>Final Collapse Level EQ, Level</td>
</tr>
</tbody>
</table>

Improved Substructuring Techniques

- Substructuring Technique with Overlapping Domain using force feedback at top of first story columns
- Define New Experimental Setup Class in OpenFresco

Numerical Verification

- Substructuring Technique with Overlapping Domain
- Finite Element Coupling Simulation

Issues with Numerical Instability

- Model with 2.5 story experimental substructure
- Pretest numerical simulations provided good results with integration parameters selected
  - Newmark Method with fixed number of iterations
  - $\Delta t=0.0039$ with 4 iterations for MCE
**Issues with Numerical Instability**

- Response traced until MCE record (24.9 sec)

**Experimental Verification**

- Model with 1.5 story experimental substructure

**Assessment of Numerical Errors**

- Integration parameters were revised especially for MCE and above, and stiff elements were relaxed
  - Newmark Method with fixed number of iterations
  - \( \Delta t = 0.00156 \) with 8 iterations for MCE

**Large-scale Application**

- Two ½-scale subassemblies of a moment and gravity frames were tested via hybrid simulation
- 4-Story Moment Frame Prototype Structure

**Experimental Program**

- Hybrid Model #1 (Moment Frame)

- Subjected to 25%, 100%, 160% & 200% Loma Prieta (LGPC)
Physical Sub-Structures

- Physical Sub-Structures
  (1/2-Scale Subassembly of Moment Frame)
  - Composite Floor Slab

Test Setup

- Test Setup
  - Substructuring Technique
    - Substructuring Technique with Overlapping Domain and Simplified Boundary DOFs

Integration Method

- Similar to previous test, used Newmark Method with Fixed number of iterations
- Conducted numerical studies to examine modeling approaches, time step and iterations

Substructuring Algorithm

- Hybrid Sim. #1
  - Substructuring Algorithm
    - Numerical Model
      | Numerical Model | Stiffness Factor | Integration Method |
      |----------------|-----------------|-------------------|
      | M1             | Corotational 10 | INM-HS            |
      | M4             | Corotational 1   | HHT-HS            |
      | M5             | P-Delta 1        | HHT-HS            |
      | M6             | P-Delta 1        | INM-HS            |

INM: Implicit Newmark Method
HHT: Hilber, Hughes and Taylor
"n" is used to distribute rotational elastic stiffness between the elastic beam and rotational springs (plastic hinge elements) in a concentrated plasticity model (Barrs and Krawinkler 2005)
Test Results: Hybrid Simulation #1

- Roof Drift Ratio

![Roof Drift Ratio](image1)

Test Results: Hybrid Simulation #1

- Base Shear: Hybrid Model #1

![Base Shear](image2)

Test Results: Hybrid Simulation #1

- East Column Plastic-Hinge Region

![East Column Plastic-Hinge Region](image3)

Concluding Remarks

- Application of hybrid simulation to realistic and complex structural models to collapse was validated
  - Application to small scale moment frame compared well to previous results from shake table test
  - Use of complex models presents challenges in numerical integration – monitoring of unbalance force errors seems to be indicator of stability
  - Use of substructuring techniques simplified experimental setup
- Application of hybrid simulation to large-scale structures provides insight into system level structural response
  - Test provided insight into response of columns, beams with composite slab, panel zones, and interaction between these components
  - Damage to each component is clearly documented after each level of loading
Acknowledgements

• Former PhD students
  • M. Javad Hashemi, Swinburne Institute of Technology
  • Maikol Del Carpio, KPFF Consulting Engineers, Los Angeles

• This work was primarily supported by the National Science Foundation (NSF) under grant CMMI-0936633 and CMMI-0748111. Any opinions, findings, and conclusion or recommendation expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

• Part of this work resulted from a collaborative project with Eduardo Miranda (PI), Ricardo Medina (Co-PI), Dimitrios Lignos and Helmut Krawinkler.

• NEES equipment at the University at Buffalo
Model Updating in RTHS with Highly Nonlinear Devices: Experimental Study

EU-US-Asia Workshop on Real-Time Hybrid Simulation  
JRC, Ispra, Italy

Ge (Gaby) Ou  
Shirley Dyke  
10.05.2015

Hybrid Simulation (HS) and Real Time Hybrid Simulation (RTHS)

Reference System:
\[ Mx + Cx + Kx + R(x, x, \theta, \omega) = -M\dot{\gamma}_x \]

Conventional (RT)HS:
\[ M\ddot{x} + C\dot{x} + Kx + R(x, \dot{x}) = f \]

HS with Structural component (HSMU)

• Component design repeatedly used
• Difficult to choose the critical component.
• Single component as experimental substructure affect the fidelity of RTHS.

Numerical Substructure  
Experimental Substructure

Online Model Updating
**HS with Structural component (HSMU)**

- Component design repeatedly used
- Difficult to choose the critical component
- Single component as experimental substructure affect the fidelity of RTHS

**In additional to boundary condition information exchange, model level information exchange is considered.**

**HSMU**

**Outline**

- Motivation
- Feasibility of RTHSMU
  - Experimental Case Study
  - Model Updating Performance
- The Enabling Role of RTHSMU
  - Local response
  - Global response
- Conclusion and Remarks
- Acknowledgement

**Experimental Case Study**

Story Mass M: 208.44 slug 3040 kg/floor
\(k_1: 31.49 \text{ kips/in (5511.8 kN/m)}\)
\(k_2: 19.7 \text{ kips/in (3447.5 kN/m)}\)
Damping: 2%

\[
egin{bmatrix}
0 & 17.37 \\
0 & 17.37
\end{bmatrix}
\begin{bmatrix}
f_x \\
f_y
\end{bmatrix}
\]

\[
egin{bmatrix}
17.27 & -11.5 \\
-11.5 & 27.27
\end{bmatrix}
\begin{bmatrix}
f_x \\
f_y
\end{bmatrix}
\]

\[
egin{bmatrix}
31496 & -19685 \\
-19685 & 19685
\end{bmatrix}
\begin{bmatrix}
f_x \\
f_y
\end{bmatrix}
\]

Natural frequency at 2.7 Hz and 8.2 Hz

Input:
- E1 El-Centro Earthquake (intensity: 0.4)
- E2 Gebeze Earthquake (intensity: 0.5)
- E3 Mexico Earthquake (intensity: 1)

**4 Stage Approach**

1. Numerical Submodel
2. MR Damper Model
3. MR Damper Model
4. Para

Stage 1: Simulation Stage
4 Stage Approach

Stage 2: RTHS Stage

Stage 3: RTHSMU

Stage 4: RTHSMU Validation

Experimental Setup and Nonlinear Model

Model Updating Performance (Stage 3)

Time Domain Updating Performance (El-Centro Case)

Model Updating Performance (Stage 3)

Model Updating Performance (first 4 sec)

Model Updating Performance (after 4 sec)
Model Updating Performance (Stage 3)

Updating Convergence

Parameter Convergence

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial</th>
<th>Final (E1)</th>
<th>Final (E2)</th>
<th>Final (E3)</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ (1/(\text{m}^2))</td>
<td>300</td>
<td>388.9</td>
<td>391.6</td>
<td>358.8</td>
<td>18.1</td>
</tr>
<tr>
<td>$\gamma$ (1/(\text{m}^2))</td>
<td>300</td>
<td>417.1</td>
<td>419.4</td>
<td>465.8</td>
<td>27.5</td>
</tr>
<tr>
<td>$\eta$</td>
<td>1.21</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.0007</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>300</td>
<td>195.46</td>
<td>156.3</td>
<td>175.64</td>
<td>19.58</td>
</tr>
<tr>
<td>$a_0$ (bf/ft)</td>
<td>150</td>
<td>121.69</td>
<td>105.44</td>
<td>124.22</td>
<td>10.19</td>
</tr>
<tr>
<td>$a_0$ (bf/ft \cdot ft)</td>
<td>5</td>
<td>0.14</td>
<td>0.23</td>
<td>0.30</td>
<td>0.08</td>
</tr>
<tr>
<td>$c_{oa}$ (bf \cdot ft/s/(\text{m}^2))</td>
<td>50</td>
<td>46.29</td>
<td>42.19</td>
<td>42.18</td>
<td>2.36</td>
</tr>
<tr>
<td>$c_{ob}$ (bf \cdot ft/s/(\text{m}^2))</td>
<td>5</td>
<td>2.5</td>
<td>2.05</td>
<td>2.94</td>
<td>0.44</td>
</tr>
</tbody>
</table>

4 Stage Approach

Local Performance

Hysteresis Behavior on First Floor Damper

Hysteresis Behavior on Second Floor Damper

Global Performance

Global Response, Displacement (El-Centro Case)
Global Performance

Nodal Displacement (El-Centro Case)

Simulation (s1)  RTHS (s2)  RTHSMU (s3)

El-Centro Case  Gebeze Case  Mexico Case

Conclusion and Remarks

- Feasibility of RTHSMU is demonstrated through a simple experimental case study.
- Results indicate the updated model can capture the MR behavior both on training and validation data.
- With MU, fidelity of RTHS is expected to be improved when multiple nonlinear components are utilized.
- The parameter sets may not be unique due to different initial condition and updating constraints.
- Model includes physical parameter (FEM) is the further research focus.

Acknowledgement

- National Science Foundation under Grant No. CMMI 0927178 and CNS 1136075.
- Purdue University Bilsland Fellowship

Thank You!
Explicit Unconditionally Stable Dissipative Integration Algorithms for Real-time Hybrid Simulations of Complex Structural Systems

James M. Ricke, Bruce G. Johnston Professor
Christopher Kolay, Ph.D. Research Fellow
Richard Sause, Joseph T. Stuart Professor
Thomas M. Marullo, Research Scientist III & RTMD IT Manager
NSF NHERI Experimental Facility
Lehigh University
Bethlehem, PA 18015, USA
EU-US-Asia Workshop on Hybrid Simulation
JRG, Lehigh
October 5-6, 2015
EU-US-Asia Workshop on Hybrid Simulation
JRG, Lehigh
October 5-6, 2015

Inherent and Numerical Damping

- In RTHS using explicit algorithms, generally the mass and initial stiffness proportional damping (PD) models are used to model inherent damping in the system:
  \[ C = \omega_0 M + \omega_1 K \]
- Known to produce unrealistically large damping forces and inaccurate results when structure undergoes inelastic deformations.
- Alternatively nonproportional damping (NPD) can be used:
  \[ C = \omega_0 M + \omega_1 R^2 \]
- Produces accurate results in nonlinear dynamic analysis using implicit algorithms.
- Produces erroneous results in nonlinear dynamic analysis using explicit algorithms (e.g., CR) with realistic time step size.
- Member forces become contaminated with participation of spurious higher modes.
- The problem becomes worse by experimental error in RTHS, including the effects of actuator delay compensation algorithms which amplify high frequency signals.
- Numerical damping can be used to circumvent the above problem.

Explicit KR-\(\alpha\) Method

- Unconditional stability, 2nd order accuracy, controllable numerical energy dissipation
- Velocity update: \[ \dot{X}_{k+1} = \dot{X}_k + \Delta t \dot{\alpha}_k \dot{X}_k \]
- Displacement update: \[ X_{k+1} = X_k + \Delta t \dot{X}_k + \Delta t^2 \alpha_k \dot{X}_k \]
- Weighted equations of motion:
  \[ M \ddot{X}_{k+1} + C_k \dot{X}_{k+1} + R_{k+1} \dot{X}_{k+1} = F_{k+1} \]
  where,
  \[ \dot{X}_{k+1} = (1 - \alpha_k) X_{k+1} + \alpha_k \dot{X}_k \]
  \[ X_{k+1} = (1 - \alpha_k) X_{k+1} + \alpha_k \dot{X}_k \]
  \[ F_{k+1} = (1 - \alpha_k) F_{k+1} + \alpha_k F_k \]
- Initial acceleration:
  \[ M \dot{X}_0 = [F_0 - C_0 \dot{X}_0] \]


Integration Parameters

- Parameter controlling numerical energy dissipation
  \[ \rho_{\alpha} = \text{spectral radius when } \Omega = \omega_0 \Delta t \rightarrow 0 \]
- \( \rho_{\alpha} = 1 \): No numerical energy dissipation
- \( \rho_{\alpha} = 0 \): Asymptotic amplification
- \( \alpha_1, \alpha_2, \text{ and } \alpha_3 \) are determined using \( \rho_{\alpha} \)
- Scalar: \( \rho_{\alpha} \)
- Matrix: \( \rho_{\alpha} = \frac{\sqrt{\Omega^2 + 4 \Delta t^2}}{2 \Delta t} \)

KR-\(\alpha\): One parameter (\(\alpha_1\)) family of algorithms

Numerical Characteristics

- Spectral radius: \( \rho_{\alpha} \)
- Mode of interest: \( \Omega \)
- Higher mode: \( \Omega \)

Prototype and Test Structure

- MRFs designed to satisfy ASCE7 code strength requirement
- Story drift controlled by nonlinear elastomeric dampers installed in DBFs
- DBFs designed to remain elastic under design basis earthquake (DBE) ground motion
- Test structures derived by scaling down the prototype by a factor of 0.6


Analytical Substructure

- FE model developed in HybridFEM (Karavasilis et al., 2012)
- Columns and beams
  - displacement-based nonlinear beam-column fiber elements and elastic beam-column elements
- MRF panel zone
  - nonlinear panel-zone elements
- Nonproportional damping (NPD) model
- Gravity system
  - lean-on-column using elastic elements with second order $P – \Delta$ effects
- 247 DOFs and 74 elements


RTHS: Ground motion and time step

- Ground motion
  - B-WSM180 component of the 1987 Superstition Hills, California earthquake recorded at the Westmoreland Fire Station
  - Scaled to two hazard levels
    - Design basis earthquake (DBE)*: Scale factor = 1.51
    - Maximum considered earthquake (MCE)**: Scale factor = 2.26
- Time step
  - $\Delta = \frac{\Delta}{1024}$ sec, the smallest time step within which the numerical computation can be finished in real-time

*Note: DBE has 475 year return period (10% probability of exceedance in 50 years)  
MCE has 2475 year return period (2% probability of exceedance in 50 years)
**Compensator coefficients:**

Initial values for coefficients are based on mean values from low level BLWN response.

![Graph](image1.png)

**Large-scale RTHS on Structure with Nonlinear Viscous Dampers: Procedure**

- **Compensator coefficients:**
  - Initial values for coefficients are based on mean values from low level BLWN response.

![Graph](image2.png)

**Actuator control: Typical MCE level test & $\rho_{\infty} = 0.75$**

- **Error indices**
  - Floor-1: 0.27, 0.46, 0.93
  - Floor-2: 0.04, 0.50, 0.58
  - Floor-3: 0.29, 0.14, 0.13

![Graph](image3.png)

**High frequency oscillations in member forces**

- Under nonlinear structural behavior, pulses are introduced in the acceleration at the Nyquist frequency ($\frac{1}{2T}$) when the state of the structure changes occur within the time step.
- These pulses excite spurious higher modes present in the system which primarily contribute to the member forces.
- The problem becomes worst by the noise introduced through the measured restoring forces and the actuator delay compensation which can amplify high frequency noise.
- How can we remove them?
  - Reduce the time step: Not always possible due to the computation time required for each time step.
  - Introduce controllable numerical damping.

![Graph](image4.png)
Summary and Conclusions

- Reviewed formulation and numerical characteristics of the explicit unconditionally stable parametrically dissipative KR-\( \alpha \) method
- Proposed an efficient implementation for real-time hybrid simulation using the KR-\( \alpha \) method
- Experimentally demonstrated the significance of numerical energy dissipation in eliminating participation of spurious higher modes through large scale real-time hybrid simulations
- Controllable numerical energy dissipation in the KR-\( \alpha \) method is shown to be effective for conducting RTHS

Acknowledgements

- Financial support provided by the P.C. Rossin College of Engineering and Applied Science (RCEAS) fellowship through the CEE Department, Lehigh University.
- Grants from the Pennsylvania Department of Community and Economic Development through the Pennsylvania Infrastructure Technology Alliance.
- National Science Foundation, Award Nos. CMS-0936610, 0830173 in the George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) program, and Award No. CMS-0402490 NEES Consortium Operation.
- The compressed elastomeric dampers were manufactured and donated to the project by Corry Rubber Company.

Lehigh NHERI Experimental Facility

- Sponsored by NSF as part of the Natural Hazards Engineering Research Infrastructure (NHERI) initiative
- 5-Year grant, commencing on Jan. 1, 2016
- Replaces NEEs
- Shared-use experimental facility with large-scale multi-directional hybrid simulation testing capabilities for multi-hazards:
  - Earthquake, Wind
  - Soil-structure interaction Effects
  - Advanced instrumentation

More information:

- http://www.nees.lehigh.edu/
- https://www.youtube.com/watch?v=YWYaOE-Cfik

Contact:

Dr. Chad Kusko - chk205@Lehigh.EDU

Lehigh NHERI Researchers’ Workshop

- 1-day workshop at Lehigh on Nov. 9, 2015
- Agenda
  - NHERI@Lehigh Equipment Facility capabilities
  - Basics of RTHS through lectures and hands-on demonstrations
  - How NHERI@Lehigh Equipment Facility capabilities can enhance your research
  - Information for preparing research proposals which utilize the NHERI@Lehigh Experimental Facility
- Visit www.atlss.lehigh.edu for information postings
Thank you
Large-Scale Real-Time Hybrid Simulations

Yunbyeong Chae, Ph.D.
Assistant Professor
Department of Civil and Environmental Engineering
Old Dominion University

Large-Scale Real-Time Hybrid Simulation for A 3-Story Steel Frame with MR Dampers

Prototype Building Structure

Analytical Substructure

MRF & Gravity Frames (Lean-on column)
- Structural modeling using HybridFEM (Karavasilis and Ricles 2009)
- Nonlinear displacement based beam-column fiber element for columns and beams
- Nonlinear panel zone element for beam-column joints
- Lean-on column representing gravity columns (with geometric nonlinearity) to consider P-Delta effect

- Number of DOFs=148
- Number of NL elements=41

Experimental Substructure

DBF with Two MR Dampers

Adaptive Time Series (ATS) Compensator

Adaptive coefficients are optimally updated to minimize the error between the target and measured actuator displacement using the least squares method.
Adaptive Time Series (ATS) Compensator

Unique features of ATS compensator
- No user-defined adaptive gains → applicable for large-scale structures susceptible to damage (i.e., concrete structures)
- Negates both variable time delay and variable amplitude response
- Time delay and amplitude response factor can be easily estimated from the identified coefficients

Amplitude response: $A = \frac{1}{\alpha_{s0}}$
Time delay: $r = \frac{a_{s1}}{\alpha_{s0}}$

RTHS: 1994 Northridge EQ (80% DBE), LQR Control

RTHS: Maximum Story Drift

RTHS: 3rd Floor Spectral Acceleration

- for Nonstructural Component -
9-Story ASCE Benchmark Structure

Deployment of MR dampers after Simplified Design Procedure
- 10 dampers
- 5 dampers
- 2 dampers
- 1 damper

Schematic of Real-Time Hybrid Simulation
- Analytical substructure modeled using HybridFEM (236 dofs, 152 NL elements)
- Experimental substructure

Multi-Grid Real-Time Hybrid Simulation
- xPC1: Intel Core 2 Duo (2.66GHz CPU), 2GB RAM; runs at 512Hz (1/512sec)
- xPC2: Intel Pentium 4 (2.4GHz CPU), 1GB RAM; runs at 102.4Hz (5/512sec)

Comparison of Normalized TET
- Task Execution Time (TET): the amount of time needed to complete a single step during real-time hybrid simulation

<table>
<thead>
<tr>
<th></th>
<th>With Two xPCs</th>
<th>xPC1 only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum TET (TET_{max}, sec)</td>
<td>0.0009</td>
<td>0.0048</td>
</tr>
<tr>
<td>Running time step (∆t, sec)</td>
<td>1/512 (=0.0019)</td>
<td>5/512 (=0.0098)</td>
</tr>
</tbody>
</table>
Slow and Real-Time Hybrid Simulations for Concrete Bridge Piers

- Test conducted in the Hybrid Structural Testing Center (HYSTEC) at Myongji University, Yongin, South Korea
- Collaborative research with Prof. Chul-Young Kim

Prototype Bridge Structure

- Typical two-span bridge with prestressed concrete girders
- T-shape reinforced concrete pier in the middle (experimental substructure)
- Remaining structural systems are modeled analytically (analytical substructure)
- Mass of the bridge is determined to have a natural period of $T=0.8$ sec

Reinforced Concrete Pier

Experimental Test Setup

Predefined Displacement Tests

- Apply the same displacement pattern for slow and fast tests
- Maximum velocity for slow test = 2.1 mm/sec
- Maximum velocity for fast test = 220 mm/sec
- ATS compensator used

Slow Vs Real-Time Hybrid Simulations

Comparison of Bridge deck displacement under the 1940 El Centro EQ

Force-displacement relationship of pier
Concluding Remarks

Current status of real-time hybrid simulation
- Mainly focused on developing actuator control algorithms, time integration methods, and stability issues
- Mostly conducted for small scale and simple structures – not for large-scale structures

Future of real-time hybrid simulation
- Use of multiple actuators for large-scale structures
- Simulation of force boundary conditions (e.g., P-Delta effect)
- Will be widely used for effectively evaluating the performance of various structural systems under earthquake or wind loadings

Thank you!
Joint Research Centre
the European Commission’s in-house science service

Serving society
Stimulating innovation
Supporting legislation

Hybrid Testing of Real-Scale Structures at ELSA

F. Javier Molina & Pierre Pegon
ELSA Laboratory, IPSC
Ispra, 5th-6th of October 2015

Content

- PREC8 Bridge 1995/1996 (New design)
  Prenormative Research Program in support of EuroCode 8
- VAB Bridge 2000-2001 (Assessment)
  Advanced Methods for Assessing the Seismic Vulnerability of Existing Motorway Bridges
- SERIES/RETRO Bridge 2013 (Retrofitting)
  Seismic Engineering Research Infrastructures for European Synergies
- Lessons learnt

PREC8 Bridge: overview

General Characteristics of the Bridges
(dimensions of the 1:1 scale) - Models 1:2.5 scale

- Regular and irregular bridge configurations
- Non-synchronous earthquake input motions (multi-support)
- Isolated bridges

PREC8 Bridge: implementation

- Classical PSD
- ω-OS Implicit Scheme
- Elastic Deck
- Parallel implementation (staggered)
- "Constant" vertical forces

Numerical part
(Deck & Abutments)

Controllers

Data Acquisition

PREC8 Bridge: results

SYNCHRONOUS MOTION: Action 1.0 & 1.2

ASYNCHRONOUS MOTION: Action 1.0 & 1.2

PREC8 Bridge: results with further substructuring

SYNCHRONOUS MOTION: Action 1.2

ASYNCHRONOUS MOTION: Action 1.2
VAB Bridge: overview

- Irregular bridge configurations
- Non-Synchronous earthquake input motions
- Preliminary cyclic tests for model identification

The Talübergang Warth bridge (Austria, 1980)

VAB Bridge: implementation

- Classical PSD
- α-OS Implicit scheme
- Elastic Deck + non-linear piers
- Parallel implementation (staggered)
- Controlled vertical forces

(Rio Torto highways bridge (Italia, 1960)

VAB Bridge: results

Analytical piers

Maximum relative displacement

Experimental piers

Ductility demand

RETRO Bridge: overview

- Irregular bridge configurations
- Synchronous earthquake input motions
- Tests with or without isolation devices

RETRO Bridge: implementation

- Continuous PSD
- Explicit/implicit schemes
- Elastic Deck + non-linear piers + model update
- Parallel implementation (inter-field)
- Controlled vertical forces
- Complex coupling between 18 actuators (!)
**Lessons learnt: long preparation**

- Simplify as much as possible the tested geometry and the interface interactions
  - ... and no "C matrix" for the laboratory structure
- Simplify as much as possible the modelling used during the test
  - Limit NL nodes (OS methods work better); Use as many elastic nodes as needed
  - Easy to document and reproduce in numerical simulation
  - (Too complex model might be useless)
- Use model updating (for NL parts) when increasing the level of load
  - Use results of detailed modelling to identify coarse/global modelling (criteria!)
  - Various levels of modelling

**Lessons learnt: rely on low level "linear" tests**

- Always have a good estimation of the linear stiffness of the experimental structure (in particular with each new configurations)
  - Allow to choose the time step for accuracy
  - Check stability
  - Do rehearsal with the control system at zero pressure
  - Make "linear" predictions and check them at the beginning of the tests
  - **Substructuring is VERY flexible -> easy to make errors!!!**
    (Stop the test in case of doubt)
- Perform low amplitude "linear tests"
  - They are the most difficult (low dissipation of the experimental structure)
  - Choose the parameter of the control & speed of the test vs control error

**Lessons learnt: use best numerical schemes...**

- Continuous method based on Central Difference for the tested structure
  - No hold period
  - Optimum signal/noise ratio (avoid the noise of the load cells)
  - Low level of error propagation
  - Naturally adapt to change of stiffness
  - No degradation when increasing substepping
- Implicit Newmark (OS) for the numerical structure
  - Unconditionally stable (allow to keep as many elastic nodes as needed)
- Adequate coupling
  - Stability=stability of each sub parts
  - Different time steps (most convenient modelling, "normal" hardware)
  - Limited or no dissipation at the interface
Lessons learnt: ... and check the results

- During the test
  - Control of the control error energy (in particular in tracking mode)

- After the test
  - Identified modal difference between expected and effective displacements

During the test

Identified modal difference between expected and effective displacements

Lessons learnt: real time?

- Is it a "tour de force"?
  - Difference between 1 and >1 dof tested structures
  - Difference between small and large actuators (⇒ 0.5 and 1MN)
  - Problem of the physical inertia

- Start with dilated time and move towards real time?

Lessons learnt: additional check

- Reproducibility? Difference between monolithic and partitioned scheme?

Start with dilated time and move towards real time?

Joint Research Centre
the European Commission’s in-house science service

Thanks for your attention!!!

ECOLEADER (TASCB 2003-2004)
Testing of Algorithms for Semi-Active Control of Bridges

1. What is your process for planning and preparing to conduct a hybrid simulation test?
2. How (what measures) and when (before, during, after) is stability of a test assessed?
3. How (what measures) and when (before, during, after) is accuracy of a test assessed and how are the resulting errors dealt with?
4. What are the current limits of model complexity and how are you addressing these?
5. What efforts have you undertaken (or plan/hope to begin) to improve the acceptance of hybrid simulation in the overall testing community?
JRC Role
Facts & Figures

- In-house science service of the European Commission
- Independent, evidence-based scientific and technical support for many EU policies
- Established 1957
- 7 institutes in 6 locations
- Around 3000 staff, including PhDs and visiting scientists
- 1370 publications in 2014

Stay in touch

JRC Science Hub: www.ec.europa.eu/jrc
Twitter: @EU_ScienceHub
LinkedIn: european-commission-joint-research-centre
YouTube: JRC Audiovisuals
Vimeo: Science@EC
Real-Time Hybrid Simulation across Multiple Scales

Brian M. Phillips
Assistant Professor
University of Maryland

Joint work at Tohoku University

Simplified Structure of Interest for Small Scale Testing

Substructured Real-Time Hybrid Simulation Loop

Shake Table Control

Shake Table Controller
Identification of Shake Table

- 0-10 Hz BLWN

---

Structural Identification

- Specimen natural frequency
  - 1st mode: 3.2 Hz
  - 2nd mode: 8.4 Hz
- Specimen damping ratio
  - 1st mode: 4.3%
  - 2nd mode: 3.9%
- Structure natural frequency
  - 1st mode: 2.3 Hz
  - 2nd mode: 6.5 Hz
  - 3rd mode: 9.2 Hz
- Structure damping ratio
  - 1st mode: 2.6%
  - 2nd mode: 3.5%
  - 3rd mode: 9.4%

---

Test Setup

- Test specimen: 1-story base-isolated frame
- Tohoku University

- Mass: 5 tons
- Stiffness: 12.3 kN/m
- Natural frequency: 0.25 Hz

---

Acceleration Tracking

- Online acceleration tracking of the interface DOF under 30% El Centro with FF+FB controller
- Desired accel. of 1st story
- Measured accel. of 1st story

---

RTHS of 10-Story Building with Mid-story Isolation

- Target Structure
- Structure in RTHS

- Natural frequency (Prototype)
  - 0.24 Hz, 0.83 Hz, 2.32 Hz, 3.88 Hz, 5.49 Hz
- Natural frequency (Target Structure)
  - 0.29 Hz, 1.04 Hz, 2.93 Hz, 4.89 Hz, 6.89 Hz
System Identification

Acceleration Tracking

RTHS Performance

Demonstration of benefits of mid-story isolation through RTHS

Conclusions

- A simple shake table setup becomes much more versatile through RTHS
- RTHS algorithms for the small scale translate well to the large scale
- RTHS stability and performance is more closely tied to experimental and numerical component relationships than the size of the experimental specimen alone

Acknowledgements: We would like to acknowledge the support of the National Science Foundation under awards 1011534 and 1444160.

Thank you for your attention
A framework to support distributed testing and service integration in earthquake engineering

Martin Williams and Ignacio Lamata
University of Oxford, UK

Contents

• Introduction
• Distributed hybrid testing
• Celestina – computing tools to promote collaboration
• Celestina-Sim framework for distributed hybrid testing
• Proof-of-concept tests between Oxford and Kassel
• Conclusions

Introduction

• Presentation relates to distributed hybrid testing but elements of it may be relevant to single-lab hybrid testing too
• Need for systematic approach, and a common language, to promote international collaboration, taking account of differing hardware, software, protocols in different labs
• Work performed by Ignacio Lamata at Oxford under the SERIES project, and during his later collaborative work with Shirley Dyke’s group at Purdue University
• Proof-of-concept tests conducted between Oxford and Kassel, with input of Uwe Dorka and Ferran Obon-Santacana

Distributed hybrid testing

• An extension of hybrid testing in which physical or numerical substructures are located in geographically remote labs
• Performed at extended timescales between Oxford-Bristol-Cambridge, and fast between Oxford-Bristol

Issues with distributed testing

• Increased complexity compared to single-laboratory testing
• Need to to interface between different software, hardware, and operational procedures
• Difficulty of error-tracing
• Need for intensive human interaction prior to testing*
• Researchers engaged in tedious tasks that could be automated

* see, e.g., de la Flor G., et al (2010)
Phil. Trans. Royal Soc. A
doi: 10.1098/rsta.2010.0140

Fast hybrid tests between Oxford-Bristol

Earthquake Engng Struct. Dyn.
doi: 10.1002/jqs.2380
Celestina

A suite of applications aimed at improving international collaboration through data-sharing and joint testing

Celestina-Sim*

- Divide activities into:
  - high level: managing and planning a test
  - low-level: running the test
- A specification to support high-level activities such as:
  - identification and location of participants
  - experimental planning
  - results collection

Celestina-Sim services overview

Networking services

- Peer-to-peer (P2P) network operated above the Internet infrastructure
- Any machine can access any other without intermediaries
- High-level Sky nodes – managers in charge of controlling the experimental plan
- Low-level Ground nodes – in charge of simulation execution

Definition services

- To verify that a test is feasible
- Verifications commanded by a sky node and executed by a ground node
- Main items are:
  - Network link – verification that the appropriate links can be established between participants
  - Data compatibility – check that each participant can correctly read and understand the others’ data and commands
  - Simulation plan agreement – agree participants, data to be exchanged, simulation workflow, speed of test execution etc.

Testing services

- Sky node manages test by setting state of all other nodes
  - Initially Available
  - Move to Not Ready while preliminary testing tasks are performed, then to Ready
  - Return to Not Ready when main simulation phase starts
  - At the end of the test, Sky node sends abort commands, returning all nodes to Available

doi: 10.1061/(ASCE)CP.1943-5487.0000403*
Implementation example

- A purely numerical simulation of an earlier, local hybrid test
- 4DOF model of third-stage separation of Arianne IV rocket launch
- Linked simulations at Oxford and Kassel

Execution of the simulation

Conclusions

- Celestina-Sim provides a framework for distributed simulation, enabling heterogeneous systems to collaborate in a systematic way
- It is a specification rather than a specific piece of software. However, the easiest way to implement it is to re-use or adapt the Java implementation developed by Lamata
- Steps will be taken to publish the Celestina framework under an open-source license that allows institutions to use and adapt the framework

Sample results

<table>
<thead>
<tr>
<th></th>
<th>Celestina (Fast network, TCP)</th>
<th>Direct communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum ms/step</td>
<td>25.99</td>
<td>25.67</td>
</tr>
<tr>
<td>Average ms/step</td>
<td>28.82</td>
<td>28.06</td>
</tr>
</tbody>
</table>

Arrangement of sky and ground nodes for the test
Exploring the challenge of hybrid testing in city-scale experimentation

What new value might ‘City-in-the-loop’ experimentation deliver?

Prof Colin Taylor
Future Cities and Communities Theme Leader, Cabot Institute, University of Bristol
(colin.taylor@bristol.ac.uk)

EU-US-ASIA Workshop on Hybrid Testing, JRC Ispra, 5-6 October 2015

Contents

• Economic context & infrastructure investment challenge
• The purpose of infrastructure
  — Servicing societal outcomes by enabling resource flows
• Infrastructure business models for identifying needs and opportunities for infrastructure performance improvement
• Justifying innovation in experimental methods
• £138m UK research lab investment
• Emerging ‘city-as-a-laboratory’ innovations
• Towards an HT development route map

Economic scale & investment risks

• UK Infrastructure Pipeline £466bn+
• Global US$57 trillion (EY, 2013)
• Can we reduce cost and increase value?
• Reducing epistemic uncertainty is the key
  — What we don’t know increases risks, drives over-conservatism, increases costs, inhibits innovation, blocks access to increased value
• We need to learn more to drive down uncertainty
  — How does infrastructure actually work?
  — Can we improve how we learn what works and what doesn’t?
  — 1% cost reduction = £4.66bn = can we afford NOT to invest in learning how to do things better?
• This scale of investment surely must target societal outcomes such as poverty reduction, equality, health and well-being etc? But how?

Infrastructure investment challenge

• £466bn (UK), $57 trillion (globally)
• Taxpayer can’t/won’t pay
• Private investment essential
• Procurement and long term operational risks deter investors

• Solution
  — Drive down epistemic uncertainty and hence risk
  — Need better understanding and control of how real infrastructure systems work
  — Then increase certainty of them working as we want

A typical Grand Challenge
4Cs for Future Rail

By 2038

• Double CAPACITY
• Halve unit COST of running the railway
• Shift CUSTOMER satisfaction from 90% to 99%
• Halve CARBON impact of the railway at point of use

Transport Advisory Group, 31 March 2010

What role might HT have in achieving these outcomes?

Loss of community resource flows and processes
Infrastructure enables energy/resource flows

Energy systems diagram of Rome

Infrastructures/g3enable/g3energy/resource/g3flows/that/lead/to/service.

Business model capital flows

Capital = Resource

Infrastructures/g3enable/g3resource/g3flows/that/lead/to/service.

Converging capabilities = scope for major innovation & performance improvement

- Sensors
- Big Data
- High performance computing
- Internet of Things
- Control and actuation
- Smart materials
- Engineering systems
- Environmental and ecological systems
- Social systems and behaviours
- Cognitive neuroscience and learning
- etc

Linking infrastructure service to high level outcomes (i.e. value)

Infrastructure service enables consumer to achieve outcome

Outcome is of value to the consumer and society

Ensuring adequate Return on Investment

- Improve certainty of long term performance of system and its components
- Improved system and component performances over whole life
  - Improves service quality, which increases willingness to pay and, hence, revenues
  - Reduces whole life costs
  - Increases RoI (Revenue – cost)

UKCRIC

UK Collaboratorium for Research in Infrastructure and Cities

£138m capital investment
2016-2021

Initiative of 14 UK universities but open to all

Strand A: World-class laboratory facilities

Strand B: Urban Infrastructure Observatories (collaboratories)

Strand C: Modelling, simulation & visualization

Strand D: Generalist node integrating robotics & industry collaboration

Experiment purpose and design

Progressive innovation & performance & properties
UKCRIC
UK Collaboratorium for Research in Infrastructure and Cities

- Infrastructure innovation and investment risks are constrained by epistemic uncertainty
- Only very large or prototype scale experiments can resolve our lack of knowledge and understanding of: 
  how infrastructure systems actually work
Towards a hybrid testing development route map?

- We have demonstrated HT viability as a test technology
  - But still scope for performance improvement
  - Can we classify and prioritise improvements?
- Now need to increase focus on HT applications for infrastructure performance improvement
- What does HT enable us to do, which we couldn’t?
  - Why is it valuable to do it?
  - What specific HT performance improvements are needed to do it?
- Target low hanging fruit, build HT ‘market’ and demand, strengthen justification of further R&D, continue to build human capability in HT
1. Substructuring Method - Motivation

- Classical Fire Resistance Tests (EN 1361, ISO 834):
  Building Elements as Stand Alone Elements
- Real Behaviour in Case of Fire
  - International Trend for Change in Design Procedure:
    From Descriptive Methods to Performance Based Design
  - Need for Special Furnaces

Extract from EN 1993-1-2 (EC 3):

4.3 Advanced calculation models

... 4.3.3 Mechanical response

(1) ...

(2) The effects of thermally induced strains and stresses both due to temperature rise and due to temperature differentials, shall be considered.
2. Basic Idea

- Basic Idea:
  - Nonlinear Part under Test
  - Linear Part by Simulation
  - Earthquake Engineering (Japan, USA, EU JRC Ispra)
  - Pseudodynamic Test Method (PSD) →
    - University of Braunschweig (80ies)

2. Basic Idea

Replace Ground Acceleration through Fire

- Finite Element Method (FEM) - Substructuring Method
- Experimental Substructuring Method
- Basic Idea:
  - Nonlinear Part under Test
  - Linear Part by Simulation
  - Earthquake Engineering (USA, Japan, EU JRC Ispra)
  - Pseudodynamic Test Method (PSD)
  - University of Braunschweig (80ies)

3. Application to Fire Engineering

4. Experimental Set-Up

Mechanical and Thermal Subsystems
4. Experimental Set-Up
Mechanical Subsystem I

- 10 actuator test rig
- 4 columns frame with furnace
- 1 compression actuator: 6300 kN
- 1 side alignment actuator: 160 kN
- 8 x 400 kN on 2 compression plates, top and bottom, to introduce moments to the specimen
- Modal control technique to control moment modes Mx, My with 8 actuators

4. Experimental Set-Up
Mechanical Subsystem II

4. Experimental Set-Up
Mechanical Subsystem III

4. Experimental Set-Up
Hardware Architecture (JRC – ELSA Lab)

5. Substructuring Method
One Control Channel
5. Substructuring Method
One Control Channel – Surrounding Stiffness
Comparison Target (black) and Process (red)

5. Substructuring Method
One Control Channel – Hybrid Method vs Real Restraining Frame (U Coimbra, ISISE)

5. Substructuring Method
One Control Channel – Hybrid Method vs Real Restraining Frame (U Coimbra, ISISE)

5. Substructuring Method
One Control Channel – Hybrid Method vs Real Restraining Frame (U Coimbra, ISISE)

6. Concluding Remarks
- Successful Portation of Substructuring Method from Earthquake Engineering to Fire Engineering
- Establishment of a Powerful Experimental Tool for Analysis of Structural Elements Subjected to Fire
- Next Step: Connection to FE Program for Simulation of Surrounding Structure
- Problems:
  - Nonlinear Characteristic of Moment Cylinders
  - Force Measurement via Pressure Transducers

Acknowledgements

JRC – ELSA Lab
Georges Magonette
Philippe Buchet
Pierre Pegon

BAM – Fire Engineering
Kai-Uwe Ziener
Sven Riemer

U Coimbra – ISISE
Joao Paulo Rodrigues
Antonio Correia
DAAD/GRICES
Real Time Hybrid Testing

Adaptive Feedforward Compensation for Realtime Hybrid Testing with Harmonic Excitation

October 6th 2015

Andreas Bartl (andreas.bartl@tum.de)
The coupling problem

\[ y_V - y_E = 0 \quad \text{and} \quad G_E f_E = G_V f_V = \lambda \quad (1) \]

Harmonic Excitations & Steady State

\[ y_V = h_V \lambda + h_{V,\omega} f_{V,\omega} \quad \text{influence interface forces} \]
\[ y_E = h_E \lambda + h_{E,\omega} f_{E,\omega} \quad \text{influence interface forces} \]

If we assume Harmonic Excitations & Steady State behavior

\[ \lambda = \sum_{i=1}^{m} W_i(t) \theta_i \]

Ansatz function matrix \( W_i(t) = [I_{mn} \cos(\omega_i t) \ I_{mn} \sin(\omega_i t)] \)

Control Structure

Rewrite \( y_V \) and \( y_E \)

\[ y_V = \sum_{j=1}^{m} W_j(t) P_{V,j} \theta_j + W_j(t) \pi_{V,j} \]
\[ y_E = \sum_{j=1}^{m} W_j(t) P_{E,j} \theta_j + W_j(t) \pi_{E,j} \]

Phase and Gain Matrices \( P_{V,j} \) and \( P_{E,j} \)

\[ P_{V,j} = \begin{bmatrix} \text{Re}(H_{V,j} \omega_j) & \text{Im}(H_{V,j} \omega_j) \\ -\text{Im}(H_{V,j} \omega_j) & \text{Re}(H_{V,j} \omega_j) \end{bmatrix} = \begin{bmatrix} P_{R,V,j} & P_{I,V,j} \\ -P_{I,V,j} & P_{R,V,j} \end{bmatrix} \]
\[ P_{E,j} = \begin{bmatrix} \text{Re}(H_{E,j} \omega_j) & \text{Im}(H_{E,j} \omega_j) \\ -\text{Im}(H_{E,j} \omega_j) & \text{Re}(H_{E,j} \omega_j) \end{bmatrix} = \begin{bmatrix} P_{R,E,j} & P_{I,E,j} \\ -P_{I,E,j} & P_{R,E,j} \end{bmatrix} \]

Harmonic Compensation with Gradient Algorithm

Choose parameter vector \( \theta \) such that the gap is closed:

\[ y_V - y_E = 0 \]
\[ W(t) (P_E - P_V) P \theta + (W(t) \pi_E - W(t) \pi_V) = 0 \]
\[ \theta = P^{-1} (\pi_E - \pi_V) \]

\[ J = \frac{1}{2} e^T e \quad \text{with} \quad e = y_E - y_V = W (P \theta + \pi_E - \pi_V) \]
\[ \dot{\theta} = -\Gamma \nabla J = -\Gamma P^T W^T (y_E - y_V) \]
Control Structure

Experimental Setup

Experimental Results
Conclusion

- formulation of Real Time Hybrid Testing problem for adaptive feedforward filters
- application of adaptive feedforward filter with harmonic regressor
- investigation of stability behavior of Real Time Hybrid Test
- validation of technique on a simple test rig

Results:
- system dynamics in adapted state not changed compared to dynamics of the subcomponents
- satisfactory convergence time on the test rig (test case < 1 s)

References

Real-time hybrid testing: Envisioned applications (and challenges) in marine technology

Thomas Sauder1,2

1Norwegian Marine Technology Research Institute - MARINTEK
2Centre for Autonomous Marine Operations and Systems – NTNU
Trondheim, Norway

EU-US-Asia workshop on hybrid testing
Ispra, Italy – 5-6 October 2015

The Marine Technology Centre in Trondheim

- Function
  - Education: 140 MSc / year
  - Fundamental research: 20 prof. / 110 PhD cand.
  - Applied research (MARINTEK):
    - Private, non-for-profit
    - 200 employees
    - Incomes: 30 M€/y
    - 90%+ through competition on the open market
  - ISO9001 certified

- Core competence: marine technology
  - Theoretical and experimental hydrodynamics
  - Marine structures
  - Marine control systems
  - Marine machinery
  - Maritime logistics

- Objects of study

Our research methods
Applications of hybrid testing in marine technology

1. Perform component testing
2. Solve some scaling issues
3. Cope with laboratory limitations

Key-questions regarding hybrid testing

- Design of the experimental setup
- Control strategies, and accuracy for extremes
- Numerical models
- Quality and traceability of the results.

Way forward...

- Starting point:
  - collaboration MARINTEK-NTNU-AMOS
  - 3 PhD on the topic
- Next step: establish a larger project with funding from the NRC
  - Investigate fundamental limitations of hybrid testing,
  - Pilot projects on three marine applications
- Contributions from the earthquake engineering/research community
  - facilitated within this proposed project

Thank you!

Contact:

thomas.sauder@ntnu.no
thomas.sauder@marintek.sintef.no

For more info:

www.marintek.sintef.no
www.ntnu.edu/imt
www.ntnu.edu/amos
Use of Real-Time Hybrid Simulation in Vibration Testing and Marine Structure Applications

Rui Botelho, PhD Candidate
Joseph Franco, PhD Candidate
Richard Christenson, Associate Professor
Department of Civil and Environmental Engineering

Motivation

- Characterizing vibration transmission of marine systems is important to operational performance
- The marine system of interest here consists of a vibration source and a fluid loaded support structure.
  - The vibration source is often very complex and challenging to model.
  - The support structure has dynamics that feedback on the response of the vibration source.

- RTHS is used to interface a physical vibration source to a numerical model of the support structure to capture this inherent interaction mechanism.

Overview of RTHS

RTHS for Structural Acoustics

- Physical mass-spring system coupled to a fluid-loaded piston provides example to extend RTHS for structural acoustics.

Additional Structural Acoustic Cases

RTHS Test Setup

- Analytical Substructure
- Actuator Dynamics Compensation
- Time Histories
- Frequency Response Functions
### RTHS of Physical Mass-Spring Coupled to Fluid-Loaded Piston

- Numerical Substructure
  - Fluid-Loaded Piston
  - Acoustic Pressure
  - Structural Admittance
  - Fluid Impedance

- Physical Substructure
  - Rigid Piston

#### Actuator Dynamics
- Measured frequency responses of servo-hydraulic actuator show inherent time delay of 20 ms.
- This time delay can lead to unwanted instability during closed-loop RTHS testing.

#### Compensated Actuator Dynamics
- Feedforward-feedback control framework with minimum-phase inverse compensation (MPIC) was developed
- Minimum-phase frequency response for the actuator dynamics is determined (Oppenheim and Schafer, 1975)
- The feedforward MPIC is obtained by inverting the minimum-phase actuator model
- MPIC reduces apparent actuator delay from 20 to ~1 msec; feedback gain to 0.1 provides balance of magnitude and phase.

#### Fluid-Loaded Piston
- $M_n=125$ lb, $K_n=560$ lb/in with 5% damping, which was needed for stable closed-loop testing
- 12" radius piston in water

#### Fluid-Loaded Piston
- Transfer function of the numerical mass-spring system without fluid-loading is
  \[ N_s(s) = \frac{1}{s^2 M_n + s C_n + K_n} \]
- Combined transfer function of numerical substructure with fluid-loading is
  \[ x(s) = N_s(s)(f_f - f_f) \]
  \[ f_f = Z_f(s)x(s) \]
  \[ N_s(s) = \frac{x(s)}{f_f} = \frac{N_s(s)}{1 + N_s(s)Z_f(s)} \]
  where $Z_f$ is the frequency-dependent fluid impedance
**Analytical Fluid Impedance**

- Fluid impedance of a baffled piston (Kinsler et. al., 2000)
  \[ Z_f(\omega) = \rho_A \left[ R_f(2kA) + iX_f(2kA) \right] \]
  \[ R_f(x) = 1 + \frac{2J_1(x)}{x} \]
  \[ X_f(x) = \frac{2H_1(x)}{x} \]

  where \( \rho_A \) is fluid mass density, \( c_A \) is fluid speed of sound, \( A \) is the cross-sectional area of the piston, \( a \) is the radius of the piston, \( k = \omega/c_A \) is the acoustic wavenumber, and \( J_1 \) and \( H_1 \) are respectively first order Bessel and Struve functions.

  \[ Z_f(\omega) = C_f(\omega) + i\alpha M_f(\omega) \]

  Where \( C_f \) represents the radiation damping of the fluid and \( M_f \) represents the fluid added mass.


**Response Transfer Function for Fluid-Loaded Piston**

- Transfer functions are combined and resulting continuous transfer function for fluid-loaded piston is
  \[ N(s) = \frac{s^2 A(s)}{f_A(s)} \]
  \[ = \frac{N_f(s)}{1 + N_f(s)Z_f(s)} \]
  \[ = \frac{N_f(s)}{1 + N_f(s)M_f(s)} \]

**Acoustic Pressure Transfer Function for Fluid-Loaded Piston**

- Acoustic pressure of a baffled piston (Kinsler et. al., 2000)
  \[ p_f(r, \theta, \omega) = \frac{i\rho f_1 f_{kA}}{\sin \theta} N_f(\omega) x_1_c i^{-\omega} \]

  \( \theta \) is the angle of the particular point in the fluid, and \( x_1_c \) is the frequency response of the piston velocity.

  The resulting continuous transfer function for acoustic pressure is
  \[ R(s) = \frac{P_f}{V_{nA}} = \frac{P_f}{x_{nA}} \]

**RTHS of Physical Mass-Spring Coupled to Fluid-Loaded Piston**

**Robust Stability and Performance**

- **Robust Stability**
  \[ \Delta(s) = \tilde{\Delta}(s) - I \]

- **Robust Performance**
  \[ T(s) = [I + P(s)N(s)]^{-1} P(s)N(s) \]

- **Robust Stability and Performance**
  \[ \left\| P_s(s) \Delta(s) \right\| < 1 \]
  \[ \left\| P_s(s) \Delta(s) \right\|_{\infty} < 1 \]
Conclusions

- Using same test setup, RTHS was used to interface a physical mass-spring system to several fluid-loaded analytical substructures (a fluid-loaded piston presented here).
- Results demonstrate that RTHS captures low frequency behavior of fluid-loaded system and can provide physical insight into the dynamic coupling with physical specimen.
  - RTHS results for canonical structural acoustic cases compare well to analytical solutions.
- These results demonstrate that RTHS testing of structural acoustic systems is possible in a laboratory setting.

Funding for this work provided by:
DOD/NAVY/ONR Award No. N00014-11-1-0260
ONR Program Director: Deborah Nalchajian, Code 331

Funding for travel to this workshop provided by:
NSF Award No. CMMI 14-46234
Program Director: Joy Pauschke
Force-Based Hybrid Simulation for Expanding Capabilities and Applications to Multi-Hazards

Narutoshi Nakata, Ph.D.
Associate Professor
Dept. of Civil and Env. Engineering
Clarkson University

October 5-6, 2015, Ispra
EU-US-Asia Workshop on Hybrid Testing

Organization of the Presentation

- Introduction of Force-Based Hybrid Simulation (FBHS)
- Force Control in Structural Testing
- Force-Based Numerical Integration Algorithms
- Applications of the FBHS
- Summary

Conventional Approaches in HS

Equations of Motion (EOM)
\[ \dot{\mathbf{M}}(t) + \mathbf{C}(t) + \mathbf{R}(\mathbf{x}) = \mathbf{F}(t) \]

Conventional Approaches:
- Displacement-Based: Impose strict kinematic constraints by
  i. Solving the EOM in terms of displacement
  ii. Imposing that displacement
  iii. Updating the responses with the measured force
- Unavoidable Unbalanced Forces: Force equilibrium is not always satisfied unless iterative approaches are used.
- Work fine for structural kinematics-free loading/simulation:
  Excitation is not dependent on the kinematics of the structure (does not depend on \( \dot{x}, \ddot{x}, \mathbf{x}, \mathbf{u} \), Earthquake)

Needs and Possible Approaches for the Expansion of HS Applications

What if the loading depends on the structural kinematics?
\[ F = F(\dot{x}, \dot{x}, t) : \text{Motion-Induced Loads} \]

Example: EOM of Low-rise buildings under wind loads:
\[ R(\mathbf{x}) = \ddot{\mathbf{a}} + f(t) + C_{\text{w}} \dot{\mathbf{x}}(t) + K_{\text{w}} \mathbf{x}(t) \]
\[ = 0.5 C_{\text{w}} \rho A (\ddot{\mathbf{u}} + \mathbf{u}(t)) \]

- The conventional displacement-based hybrid simulation may not be suitable for the motion-induced loads.
- One of the possible approaches to expand simulation capabilities to multi-hazards (tsunami, hurricane, etc.) is force-based approach.

Introduction to Force-Based Hybrid Simulation (FBHS)

Approaches:
- Force-Based: Impose strict force equilibrium conditions by
  i. Solving the EOM in terms of force
  ii. Imposing that force in the experiment
  iii. Updating the responses with the measured displacement

Requirements for the FBHS

1. Dynamic Force Control in Structural Testing
2. Force-based Numerical Integration Algorithms
Dynamic Force Control in Structural Testing

1. SDOF Linear Elastic System

2. SDOF Nonlinear Inelastic System

3. 3D Steel Frame Structure

4. MDOF Linear & Nonlinear Structures

5. Mixed Force and Displacement Control for Isolation

Explicit Force-based Numerical Integration Algorithm for HS

\[ m\ddot{x} + c\dot{x} + (1-\alpha)R_n + \alpha \ddot{R}_n = (1-\alpha)f_{n+1} + \alpha f_n \]

Step i) Solve for \( R_{n+1} \):
\[ R_{n+1} = f_{n+1} + \alpha \frac{\ddot{R}_n}{1-\alpha} - \frac{1}{1-\alpha} (m\dddot{x} + c\ddot{x} + \alpha \dddot{R}_n) \]

Step ii) Impose \( R_{n+1} \) in the experiment.

Step iii) Update responses based on the measured displacement:
\[ \dddot{x}_{n+1} = x_{n+1} - \frac{\dot{x}_n}{\Delta t^2} - \frac{\dot{x}_n}{\Delta t^2} \left(1 - \frac{1}{2\beta}\right) \]
\[ \ddot{x}_{n+1} = \ddot{x}_n + \Delta t \left(1 - \frac{1}{\gamma} \right) \dddot{x}_{n+1} + \gamma \dddot{x}_{n+1} \]

Force-based Hybrid Simulation for Hydrodynamic Loads

\[ M\ddot{x}(t) + C\dot{x}(t) + R(x) = F(x, t) \]

(i) Hydrodynamic Impact on Structures

Fluid-Structure Interaction Study

Structural damage by the 2011 Tohoku Earthquake and Tsunami.
Photo Credit: Ian Robertson

Water-Structure Interaction Study

Investigation through force-based hybrid simulation

(ii) Tsunami-Induced Uplifting Force on Bridges

Failure Investigation of Support Bearings

High-fidelity simulation of structures under tsunami- induced loadings:
Failure of Shinkita kami-Bridge by the 2013 Tohoku Earthquake

Tsunami simulation with CFD
Structural FEM

Structural FEM
Summary

- A concept of force-based hybrid simulation was presented.
- Two required simulation capabilities for the force-based hybrid simulation are
  1) Force control in structural testing
  2) Force-based numerical integration algorithms
- A proof-of-concept for the force-based hybrid simulation is currently underway.
- Possible applications of force-based hybrid simulation were presented.
- The proposed force-based hybrid simulation is applicable for multi-hazards (tsunami, wind, snow, etc.)

Acknowledgements

National Science Foundation
HT → Wind Engineering: Early Considerations

Forrest J. Masters, Ph.D., P.E.
Associate Dean for Research and Facilities, Herbert Wertheim College of Engineering
Associate Professor of Civil and Coastal Eng., School of Sustainable Infrastructure & Env.
University of Florida, USA

EARTHQUAKE ENGINEERS COASTAL ENGINEERS
HAVE THE SHAKE TABLE HAVE THE WAVE TANK
BLAST & IMPACT ENGINEERS WIND ENGINEERS
HAVE THE SHOCK TUBE HAVE...

… two types of full-scale simulators

• Wind Field
  – FIU Wall of Wind
  – IBHS Research Center
  – UF Hurricane Simulator

• Dynamic Pressure
  – BRERWULF
  – UWO Three Little Pigs
  – UF HAPLA, SPLA & MAWLS

 … two types of full-scale simulators

• Wind Field
  – FIU Wall of Wind
  – IBHS Research Center
  – UF Hurricane Simulator

• Dynamic Pressure
  – BRERWULF
  – UWO Three Little Pigs
  – UF HAPLA, SPLA & MAWLS

1952: Storm Protection Laboratory

• Developed by Polovkos and Thompson in the UF Dept. of Aeronautical Engineering
• 1300 hp airplane engine with hydraulically controlled throttle
• Utilized “rain grid” that produces 1.5 in/hr at 60 mph

Institute for Business & Home Safety

• 30 MW Wind Tunnel
• Test Two Story Home in Cat 3 Hurricane
• Chester County, SC
“Full-Scale” Simulators

• Wind Field
  – FIU Wall of Wind
  – IBHS Research Center
  – UF Hurricane Simulator

• Dynamic Pressure
  – BRERWULF
  – UWO Three Little Pigs
  – UF HAPLA, UF “Judge”

Pressure Loading Actuators

BRE Real-Time Wind Uniform Load Follower


g3PLA / g3(SPLA)

High Airflow PLA (HAPLA)

Spatiotemporal PLA (SPLA)
Specifications

- 1.3 MW @ 1800 RPM
- Wind pressure simulation
  - ≤ 23 kPa @ 2850 m³/min
  - ≤ 3 Hz waveform
- Combined with uplift (54000 kg) or shear (27000 kg)
- Wind velocity simulation
  - ≤ 103 m/s
  - ≤ 2 Hz waveform
- SSHWS Cat 5 or EF5

Tornadic Wind Effects

Specifications

- 1.3 MW @ 1800 RPM
- Wind pressure simulation
  - ≤ 23 kPa @ 2850 m³/min
  - ≤ 3 Hz waveform
- Combined with uplift (54000 kg) or shear (27000 kg)
- Wind velocity simulation
  - ≤ 103 m/s
  - ≤ 2 Hz waveform
- SSHWS Cat 5 or EF5

Operating Principle

- Volume Expansion Caused by Loading
- Leakage
- Ideal Gas Adiabatic
- Wind Tunnel Data (p = pressure)
- SERVO
  - Max dp/dt = Req. RPM
  - Max dp/dt/A² = Req. Torque
- FAN
  - Max p = Req. CFM

Helmholtz Resonator Model

- that considers leakage and a flexible air volume
- Valve
- Servo
- Airflow
- Air Mover

Experimental considerations

- Many similarities with seismic applications, e.g.,
  - Nonlinear material and geometric behavior
  - Multi-axis control (out-of-plane + uplift in plane)
  - etc..
- Some new challenges
  - Wind structure interaction (aeroelasticity)
  - Leakage and volumetric changes
  - Wind-driven rain effects
  - and instabilities…

Instabilities, e.g., Helmholtz Resonance

- Air Slug
- Ideal Gas Law: \( pV = nRT \)
- Adiabatic: \( \frac{P_a}{P_w} = \text{constant} \)
- The differential equation for the motion of a slug of air moving in and out of the volume:

\[
\frac{\rho_a}{\rho_w} A \frac{d}{dt} x + \frac{\rho_a A}{2} \frac{d^2}{dt^2} x + \frac{T \rho_a A^2}{P_w} x = A \Delta P, (\ell)
\]

- Inertial Term
- Loss Term
- “Stiffness” Forcing Term
- \( x = \text{distance air slug moves in and out of volume} \)

- But why stop at full-scale?

- The principle tool of the wind engineering community is the boundary layer wind tunnel

- We can conduct aeroelastic tests using flexible models… introduce controls to modulate stiffness and damping
Aeroelastic Models

- Tall buildings and slender vertical structures
- Long span bridges
- Flexible roofs
- Small structures, building appendages and structural members

Tall Buildings and Slender Vertical Structures

- Scales: 1:200 – 1:600
- Typical focus = lowest three modes (lowest sway mode in two directions and lowest torsional mode)
- Use lumped mass model between three and seven heights
- Slender vertical structures
  - Chimneys may require corrections for Re # effects
  - Guyed structures may require Fr. # similarity
Long Span Bridges

- Establish the basic aerodynamic stability
- Types of testing
  - Full aeroelastic model with or without topography
  - Sectional model. Scales = 1:10 to 1:100
Another interesting aspect: time scaling

- The reduced frequency relationship is given by
  \[
  \left[ \frac{f_L}{U} \right]_{\text{model}} = \left[ \frac{f_L}{U} \right]_{\text{full-scale}}
  \]
- Strouhal No. at model scale = Strouhal No. at full-scale
- The model-to-full-scale frequency ratio is given by
  \[
  \frac{f_{\text{model}}}{f_{\text{full-scale}}} = \left( \frac{L_{\text{full-scale}}}{L_{\text{model}}} \right) \left( \frac{U_{\text{model}}}{U_{\text{full-scale}}} \right)
  \]

Typical ratios of \( L = 50 - 400 \) (real building : model)
Typical ratios of \( U = 40 \text{ m/s} / 10 \text{ m/s} = 0.25 \)

\[
\frac{f_{\text{model}}}{f_{\text{full-scale}}} = \left( \frac{L_{\text{full-scale}}}{L_{\text{model}}} \right) \left( \frac{U_{\text{model}}}{U_{\text{full-scale}}} \right) \\
= 50 \cdot 0.25 = 12.5 \\
= 400 \cdot 0.25 = 100
\]  
Model frequencies are 10-100 times faster than full scale

Therefore WT test last a few minutes to capture an equivalent full-scale one hour dataset
Begs the question.. How far can we push RTHS?

Another interesting aspect: time scaling

Many opening moves

- Adapt control strategies to wind engineering test apparatuses (most use simple PID controls)
- Study building envelope (C&C) performance at full-scale
- Develop multi-objective limit states for wind engineering
- Implement RTHS at model-scale to optimize shape, stiffness, damping, mass… (at much faster instruction rates)
- NSF NHERI will open the door for collaborating across earthquake and wind engineering
How to obtain EU publications

Our publications are available from EU Bookshop (http://bookshop.europa.eu), where you can place an order with the sales agent of your choice.

The Publications Office has a worldwide network of sales agents. You can obtain their contact details by sending a fax to (352) 29 29-42758.
JRC Mission

As the Commission’s in-house science service, the Joint Research Centre’s mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

Serving society
Stimulating innovation
Supporting legislation