JRC Scientific and Technical Reports

1st year EFAST annual report

EFAST project (Design Study of a European Facility for Advanced Seismic Testing)

Alain Le Maoult, Ioannis Politopoulos
Commissariat à l'Énergie Atomique, Bâtiment 603, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France

Gabriela Maria Atanasiu
Technical University "Gheorghe Asachi" of Iasi, Faculty of Civil Engineering, 700050, Iasi, Romania

Chiara Casarotti, Alberto Pavese
European Centre for Training and Research in Earthquake Engineering (Eucentre), via Ferrata 1, 27100 Pavia, Italy

Uwe Dorka, Van Thuan Nguyen
University of Kassel, Moenchebergstrasse 19, 34125 Kassel, Germany

Francesco Marazzi, Francisco Javier Molina, Pierre Pegon
European Commission, Joint Research Centre, IPSC, ELSA, via E. Fermi 2749, TP 480, I-21027 Ispra (VA), Italy

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Contact information
Address: Francesco Marazzi
E-mail: francesco.marazzi@jrc.it
Tel.: +39 0332 783510
Fax: +39 0332 789049

http://ipsc.jrc.ec.europa.eu/
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PREFACE

Earthquakes remain a serious threat in many parts of the European Union (EU) and its regions, and have continued to cause major loss of life and destruction in recent years. Earthquake risk has consequences beyond national borders, and the European Commission (EC) has acknowledged its concern to reduce future earthquake risks in many ways, for example through its support for the EUROCODES, for the coordination and promotion of Civil Protection, and for related research programs. However, figures that have been collected by the United Nations suggest that the risk of death because of an earthquake in Europe today is considerably higher than in Japan or the United States. This may be connected with the fact that the investment in earthquake engineering research and development in the U.S. and Japan in recent years have also been much higher – in the order of 10 times greater than in Europe. In order to create a safer Europe it will be necessary to undertake even more considerable effort towards an efficient earthquake mitigation.

In this regard, it is widely recognized, by the Earthquake Engineering community, that high performance experimental facilities are necessary to meet the objectives of earthquake risk mitigation and to make progress in methods for the design and assessment of buildings and infrastructures. Such facilities enable testing of a large variety of structures and systems, and contribute to the validation of the numerical models as well as of analysis and design methods. A look at the international landscape reveals that seismic testing facilities in EU countries cannot be classified in the top high performance facilities in the world (except the reaction wall of the Joint Research Center in Ispra). In fact, in extra-European countries several high capacity experimental facilities are either already operating (e.g. University of California San Diego (US), E-Defense (Japan)) or under construction (several projects in Korea, China, Japan). In parallel, there is an emergence of new experimental techniques that will improve drastically, in the future, the performance and the accuracy of seismic testing. Real-time substructuring, advanced controlled methods and distributed testing are the three main fields of research activity on experimental techniques.

Therefore, in order to be positioned within the avant-garde of earthquake research it is important for Europe to build a new high performance experimental facility. For that reason, the EC supports, as a part of the 7th framework project, a design study of a new generation seismic testing facility. This is the EFAST (European Facility for Advanced Seismic Testing) project. Five European partners with a large experience in seismic and dynamic testing are involved in EFAST:
Commissariat à l'Energie Atomique (coordinator, France), the Gheorghe Asachi Technical University of Iasi (Romania), Eucentre (Italy), the University of Kassel (Germany) and the Joint Research Centre (European Commission).
The main objectives of EFAST are:

- Define the features of a new high performance testing facility answering the needs of modularity, flexibility, operating ease and complementary to existing research infrastructures in Europe.

- Make progress in advanced test methods (multiple shaking table control, real time sub-structuring techniques, hybrid testing coupling numerical and physical substructures).

- Address issues related to access as well as high-speed networking with other European laboratories that would enable the carrying out of real time geographically distributed tests in the future.

- Address and answer the key questions concerning the assessment of the technical and financial feasibility of this facility, leading to a "conceptual design report" allowing policy makers to make relevant strategic decisions.

During the first year of the project, most of the effort has been devoted to the first two objectives. This report presents a part of the work done in order to determine a) the necessary performance requirements for the new facility and b) future directions in advanced seismic testing. The first chapter presents the results of an inquiry addressed to seismic testing laboratories and possible users (industry, construction companies etc.) of the future facility. The statistical processing of the answers to the questionnaire provides useful information on the needs and therefore on the performance criteria. Chapter 2 presents the summary and the conclusions of an international workshop on "Challenges, Needs and Open Questions in Seismic Testing" held in Ispra (Italy) in March 2009.

About fifty experts from all around the world shared their experience with the team of the project and made valuable presentations and comments. Chapter 3 presents the state of the art of current experimental techniques as well as of more advanced techniques that will be used in the future. The design principles of the web portal which is a key issue for efficient access of researchers and dissemination of advanced seismic testing is presented in chapter 4.

As the coordinator of the EFAST project, I hope that this report will be useful to those who are interested in the evolution of seismic testing technology and techniques and in earthquake risk mitigation in general.

Ioannis Politopoulos
(project coordinator)

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1. INQUIRIES WITHIN EFAST PROJECT

1.1 INQUIRY ON THE NEEDS FOR SEISMIC TESTING (JRC)

1.1.1 Summary

EFAST project grant agreement Annex I (Description of Work) specifies this task as follows:

Task 2.2 – an inquiry will be addressed to different entities, including researchers, industry and administrations, asking for their views on issues such as:

- the kind and the size of the required experiments in the recent past and in the next 20 years in Europe,
- possible architecture and size of testing facilities,
- possible location for an new facility,
- integration with the existing infrastructures: communication architecture to be developed, upgrading strategy.

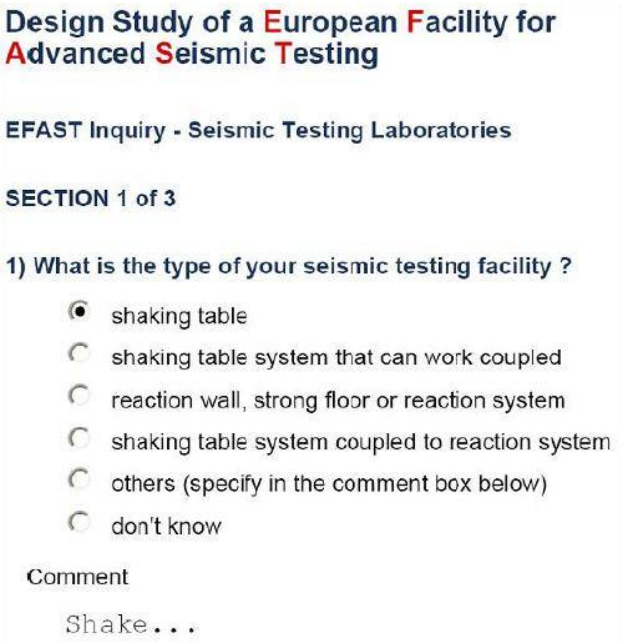
The partners agreed to prepare three different sets of questions with special focus to three different target groups: seismic testing laboratories, nuclear energy and chemical industries and construction companies. JRC prepared the first questionnaire and list of targets, CEA the second and EUCENTRE the third, then the questions were shared among all partners in order to have consistent questionnaires. Some questions were more generic and equal for everybody, some other were more focused to the specific target group. The three sets of questions were implemented in a web page accessible with a dedicated link. The web server and services of EUCENTRE were used to this purpose.

1.1.2 Structure of the inquiry

Each contacted target received an e-mail with a brief presentation of the EFAST project, a description of the main purposes of the inquiry and a reserved link to access to the inquiry. By clicking on this link, a form opened. The form contained mainly multiple choice questions (check boxes, option buttons) and some text boxes. Each question was followed by a free field for comments. This makes the form easy to be filled on the web. The user can interrupt his compilation in any time and the system saves the data. By pressing the "submit" button the results are definitively stored in a database. The following figure gives an example of the first question of the seismic testing laboratories inquiry.

1.1.3 Inquiry for seismic testing laboratories

This set of questions is divided into 12 parts. The detailed results for each question are



Design Study of a European Facility for Advanced Seismic Testing

EFAST Inquiry - Seismic Testing Laboratories

SECTION 1 of 3

1) What is the type of your seismic testing facility ?

- (•) shaking table
- ( ) shaking table system that can work coupled
- ( ) reaction wall, strong floor or reaction system
- ( ) shaking table system coupled to reaction system
- ( ) others (specify in the comment box below)
- ( ) don't know

Comment

Shake...

Figure 1.1 Example of one question of the inquiry

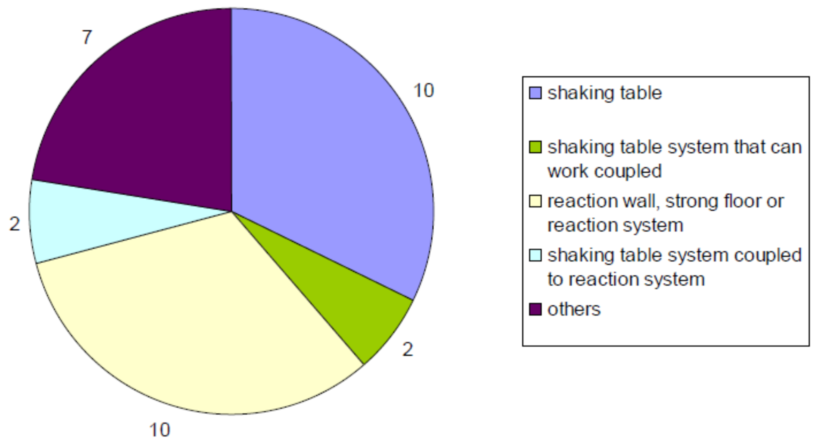
reported hereafter. The inquiry was sent to 108 large laboratories around the word. Presently, we have received back 31 compiled inquiries, so the percentage of success is 30%. This means that the statistical analysis of the obtained results must be viewed just as indicative since the sample may be not fully representative of the whole stock.

Question 1

What is the type of your seismic testing facility?

Results

Number of facilities for each type:



Comment

All types of seismic testing facilities are well represented.

Question 2

What is the capacity of your facility for a seismic test?

Results

The graph shows the number of facilities for each interval.

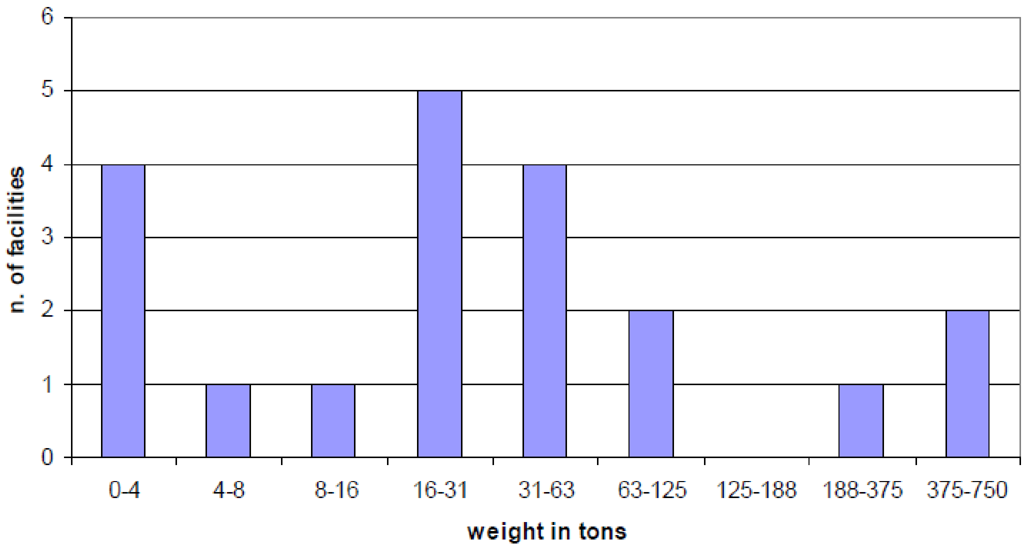


Figure 1.2 Maximum weight of the specimen in ton

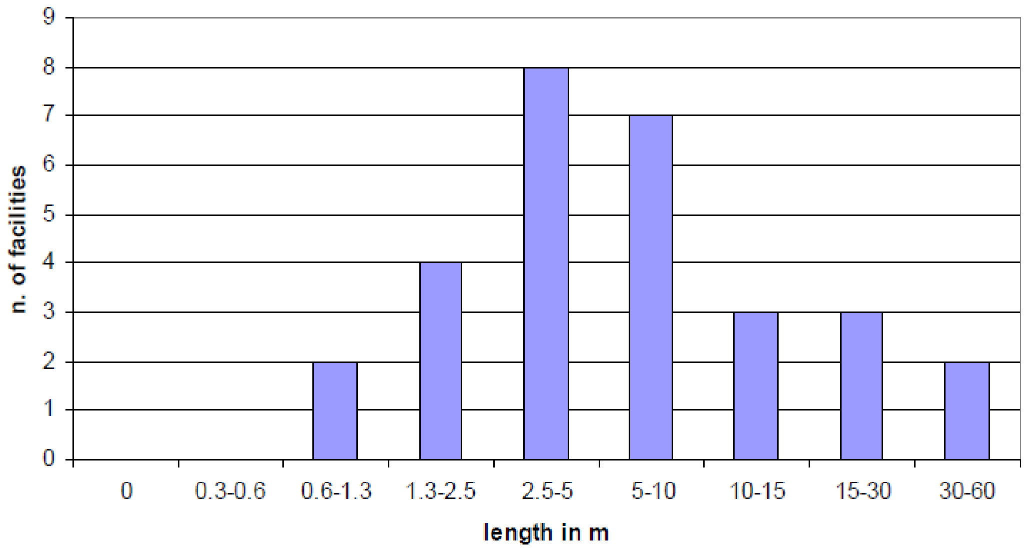


Figure 1.4 Maximum length in m

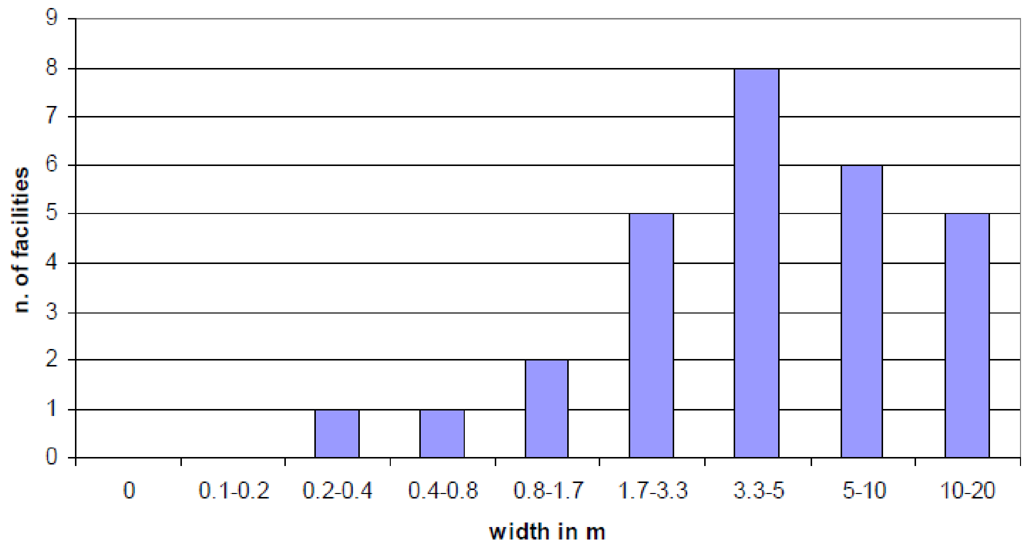


Figure 1.3 Maximum width in m

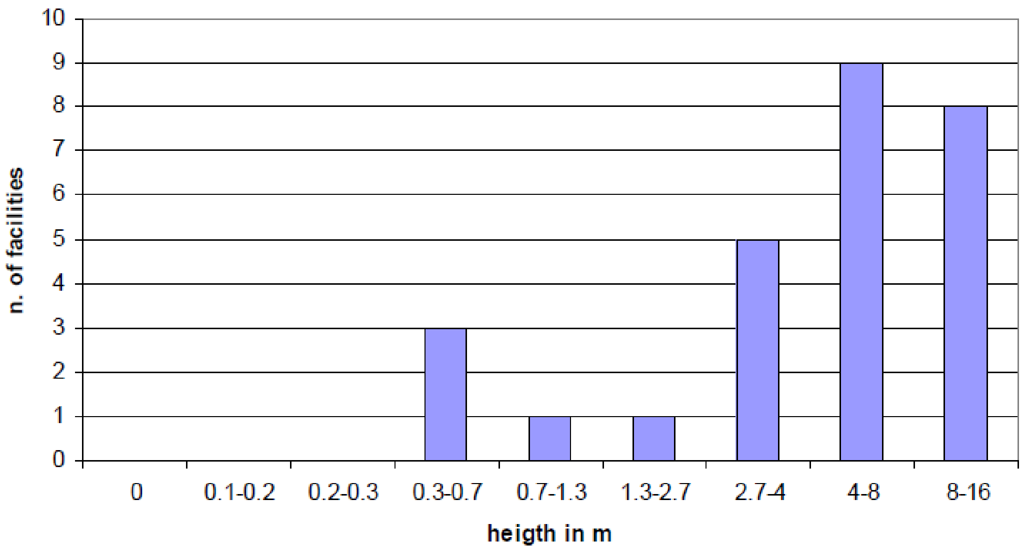


Figure 1.6 Maximum height in m

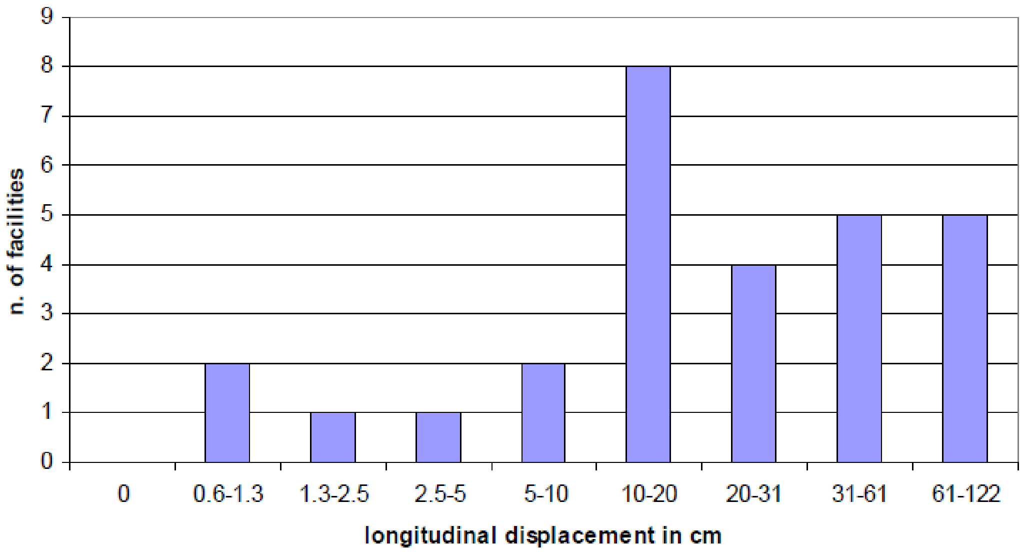


Figure 1.5 Maximum longitudinal displacement in cm

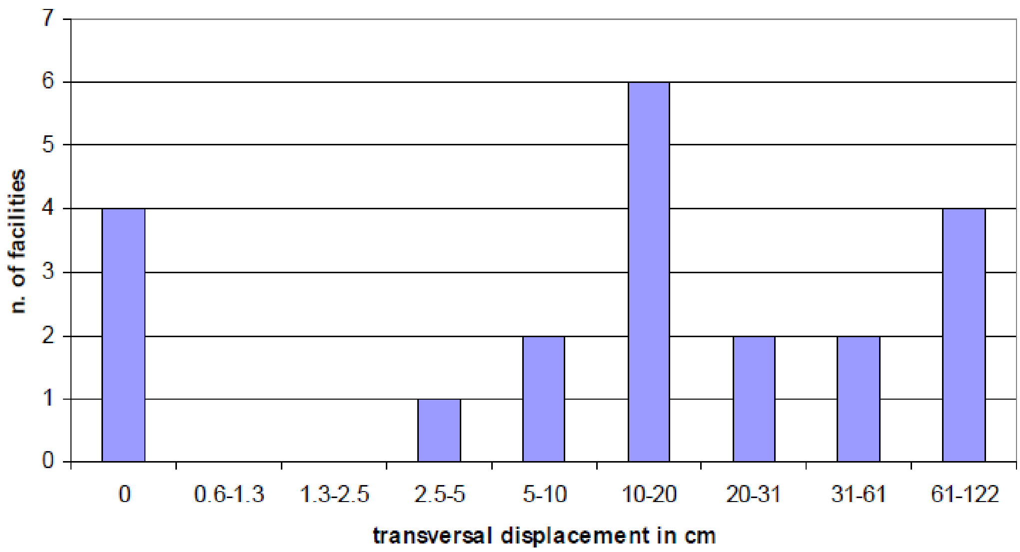


Figure 1.8 Maximum traversal displacement in cm

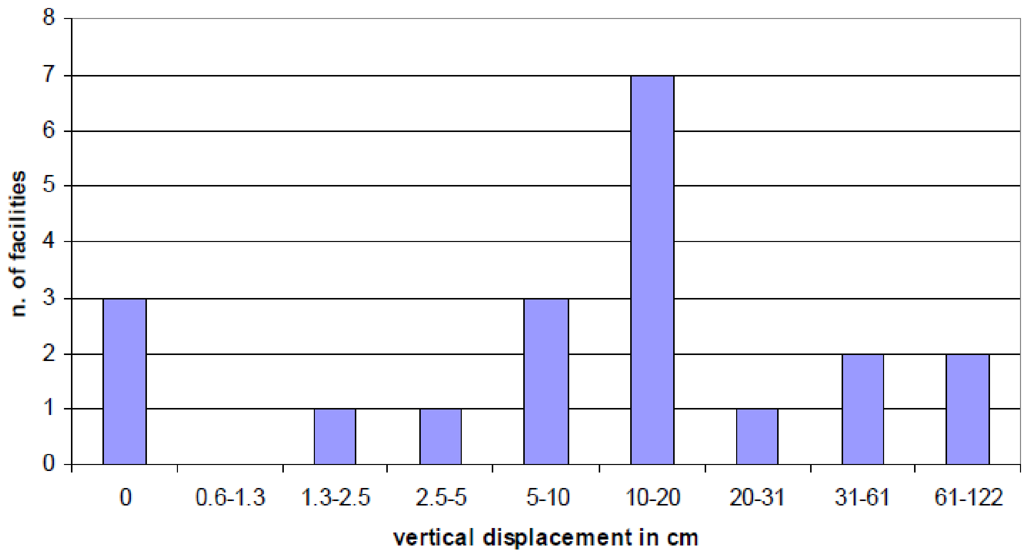


Figure 1.7 Maximum vertical displacement in cm

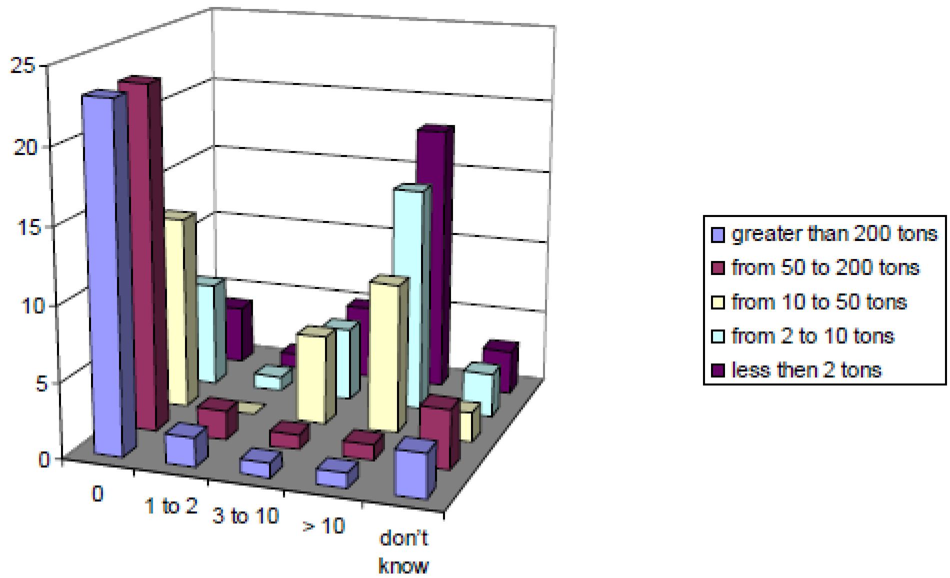
Comment

Regarding the maximum weight, length, width and height, often the upper values are for Reaction Walls (RW) facilities, the lower values for Shaking Tables (ST) facilities. Regarding the maximum displacement that the testing facility can realize, it is interesting to notice that some facilities cannot perform tests in the transversal and the vertical direction.

Question 3

Approximately, how many specimens have been seismically tested in your facility for each one of the following ranges of weight?

Results



Comment

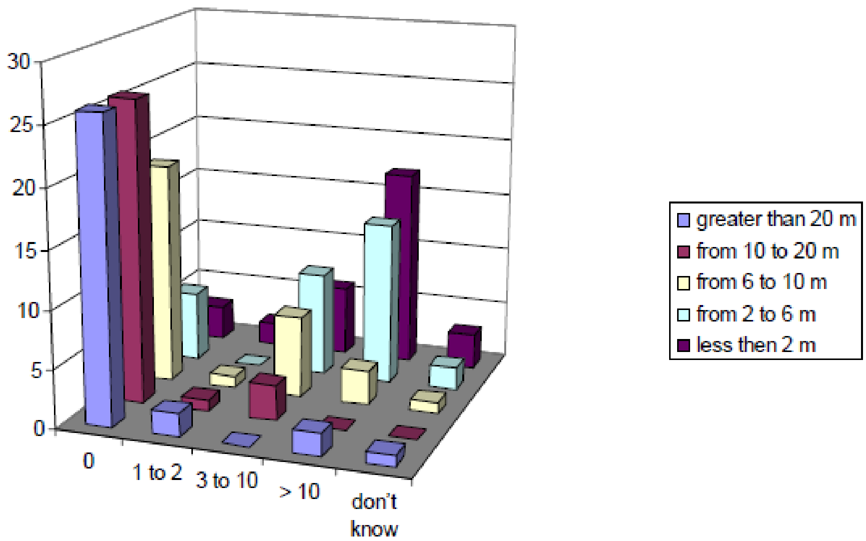
The diagram must be read as follows: for each class of weight there is a histogram representing how many laboratory has answer for each class of number of performed tests. For example: for specimens with a weight higher than 200 tons (blue histograms) there where 23 laboratories who answered they didn't perform any test, 2 laboratories answered they have performed 1 or 2 tests, 1 has answered he has performed from 3 to 10 tests, 1 has answered he has performed more than 10 tests and 3 laboratories answered they don't know.

The figure clearly shows that have been tested many light specimens but very few heavy specimens.

Question 4

Approximately, how many specimens have been seismically tested in your facility for each one of the following ranges of length?

Results



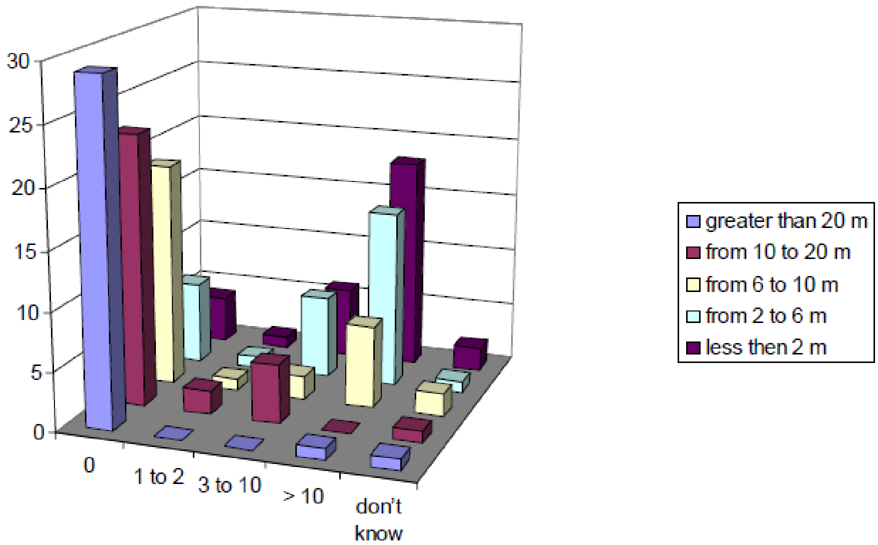
Comment

Many structures were tested with small length, very few with large length.

Question 5

Approximately, how many specimens have been seismically tested in your facility for each one of the following ranges of height?

Results



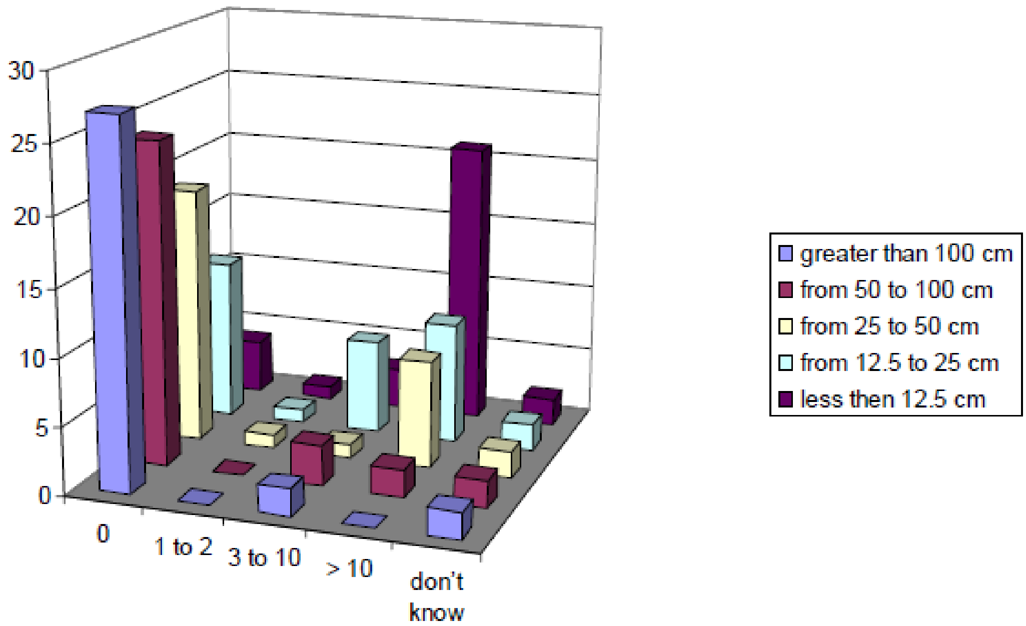
Comment

Many structures were tested with small height, very few with large height.

Question 6

Approximately, how many specimens have been seismically tested in your facility for each one of the following ranges of peak-to-peak longitudinal displacement?

Results

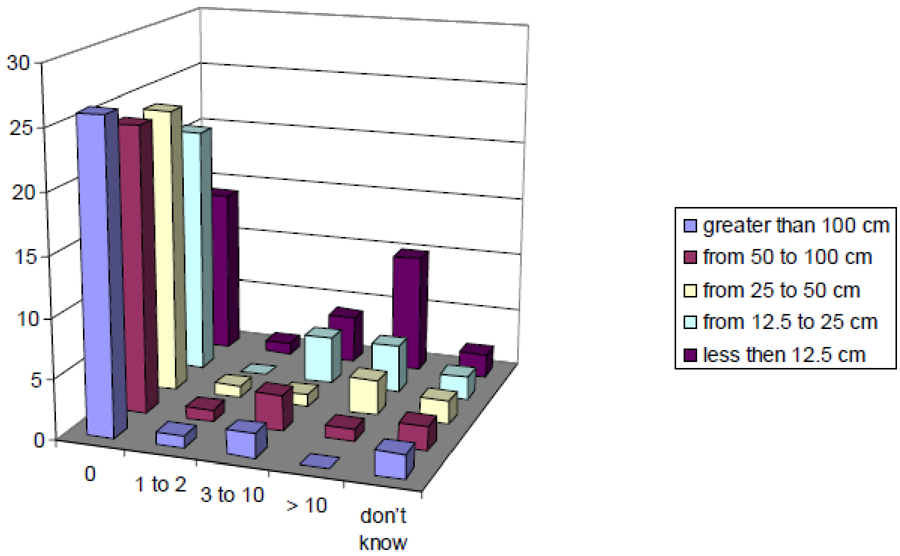


Comment

Many structures were tested with small displacements, very few with large displacements.

Question 7

Approximately, how many specimens have been seismically tested in your facility for each one of the following ranges of peak-to-peak transversal displacement?



Results

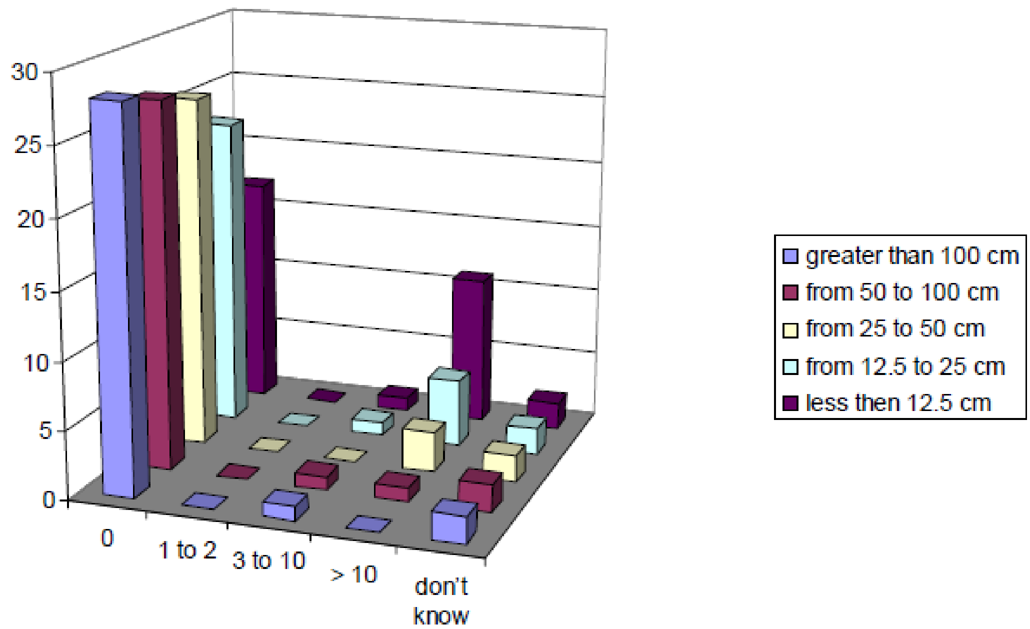
Comment

Very few specimens were tested in transversal direction independently from the value of displacement.

Question 8

Approximately, how many specimens have been/will be seismically tested in your facility for each one of the following ranges of peak-to-peak vertical displacement?

Results



Comment

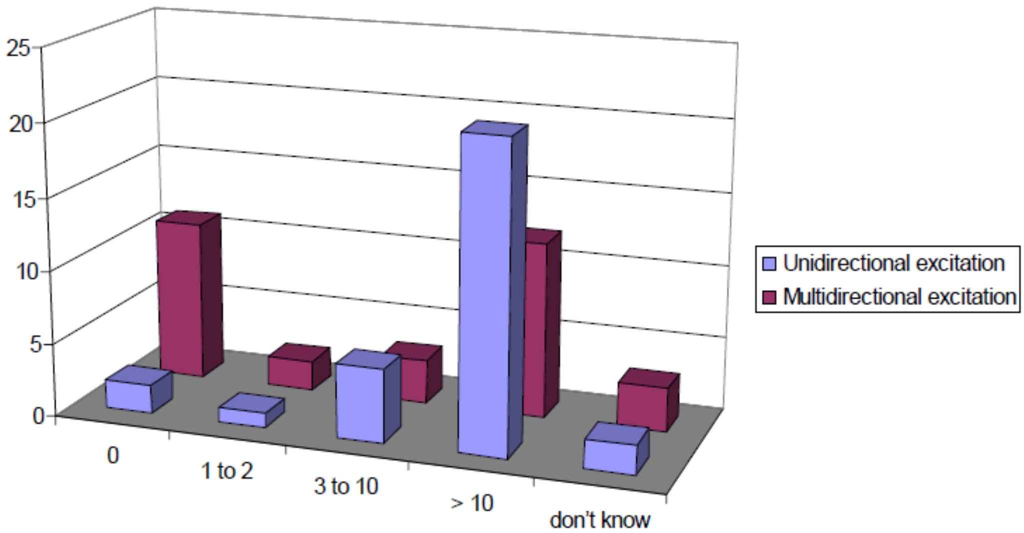
Very few specimens were tested in vertical direction independently from the value of displacement.

Question 9

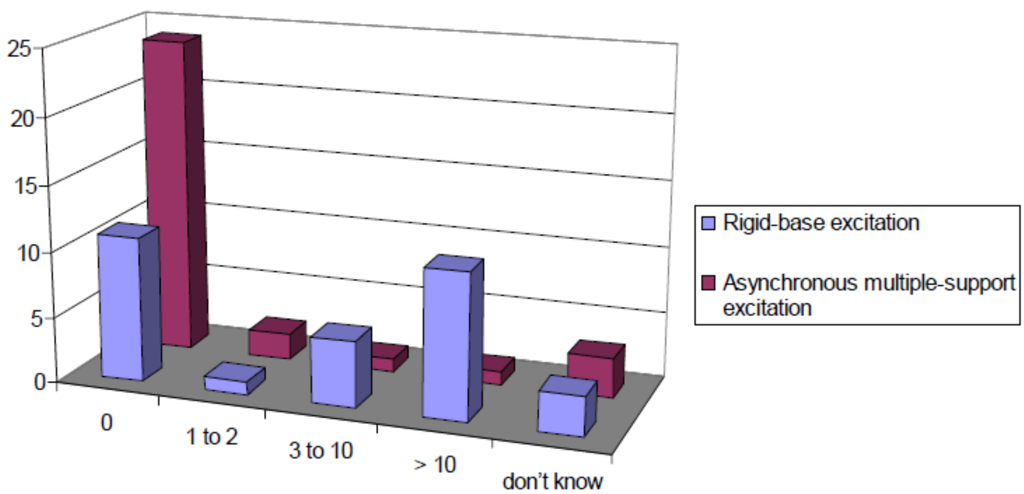
Approximately, how many specimens have been seismically tested in your facility with each one of the following specific techniques?

Results

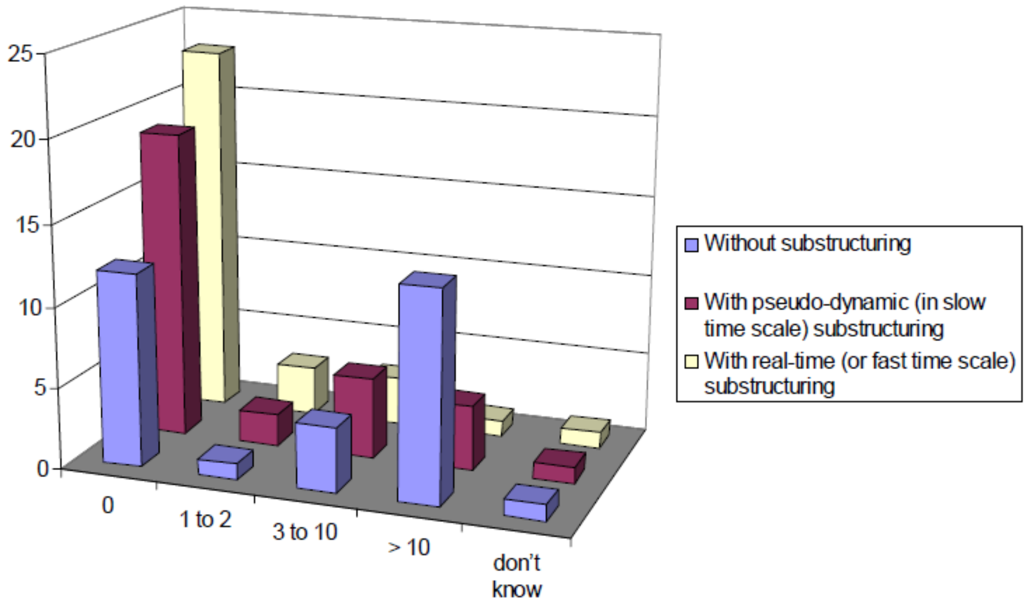
Unidirectional and multidirectional excitation:



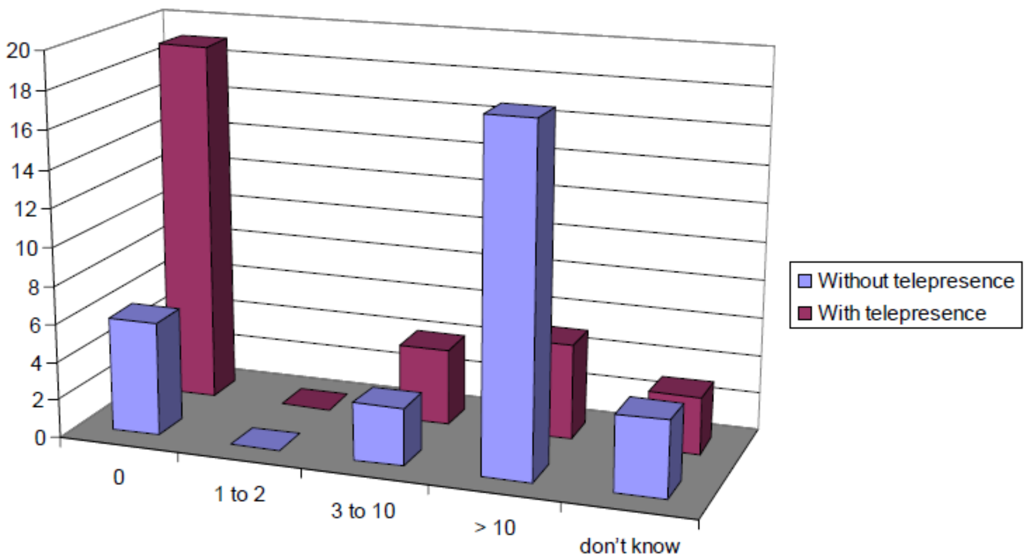
Rigid-base excitation and asynchronous multiple-support excitation:



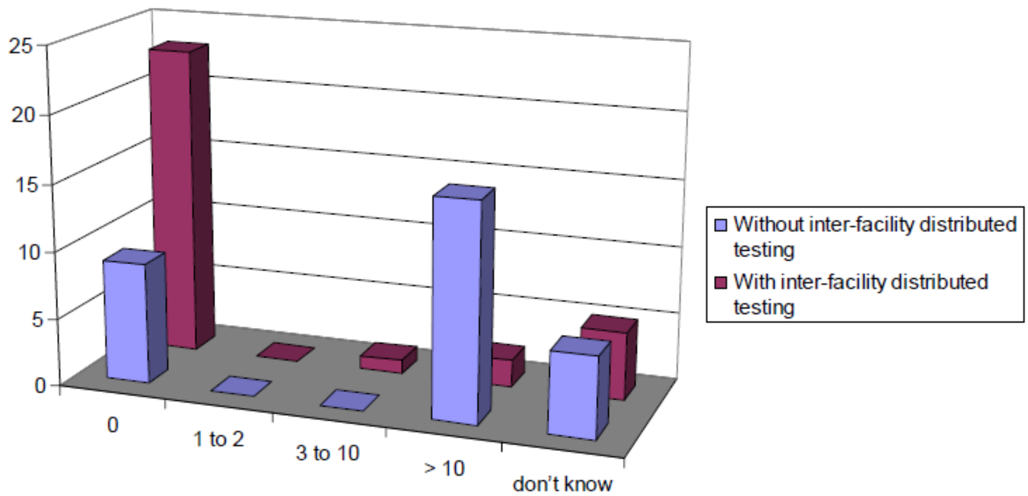
Without sub structuring, with pseudo-dynamic (in slow time scale) sub structuring and with real-time (or fast time scale) sub structuring:



With and without telepresence:



With and without inter-facility distributed testing:



Comment

Presently, there is a prevalence of unidirectional excitation tests even if several multidirectional excitation tests are also performed.

Rigid-base excitation is strongly the most common choice while asynchronous multiple-support excitation tests are very rare.

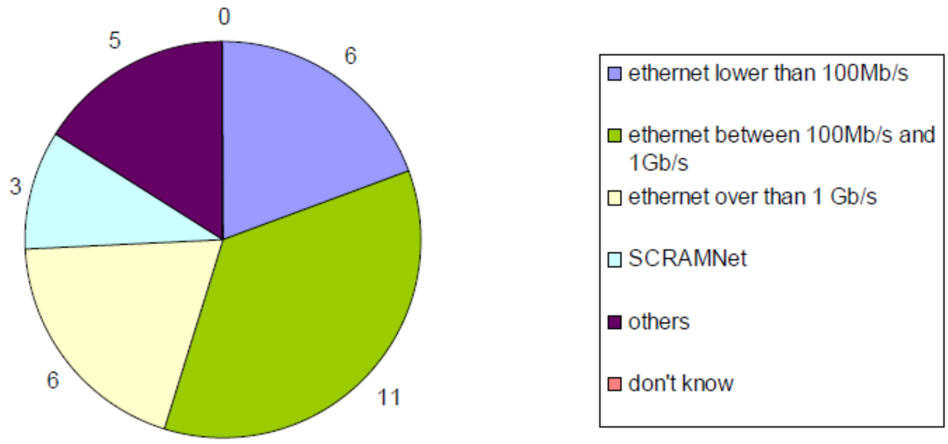
Tests are usually performed without sub structuring, sometimes with pseudo-dynamic (in slow time scale) sub structuring and only in very few cases with real-time (or fast time scale) substructuring.

Telepresence is sometimes used, but the majority of the conducted tests were without telepresence. Tests with inter-facility distributed testing are very rare, the almost totality of the performed tests being without inter-facility distributed characteristics.

Question 10

What is the type of the informatics network internal to your laboratory?

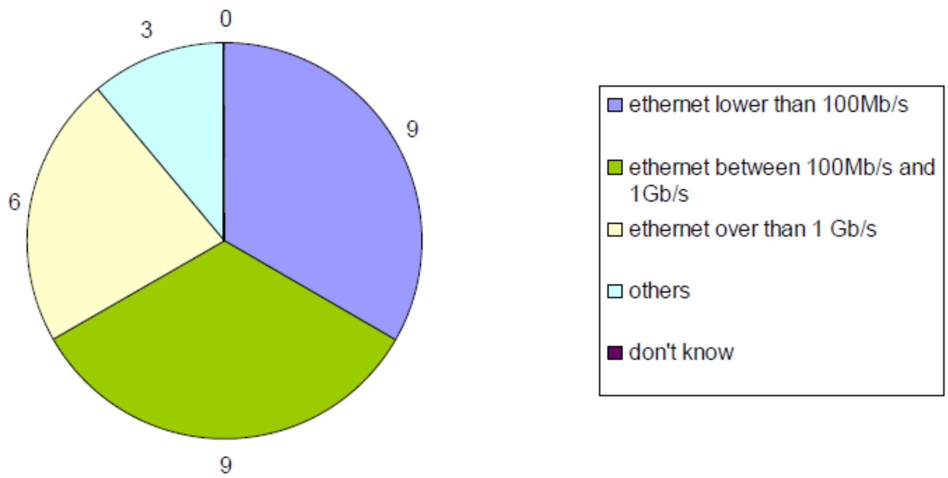
Results



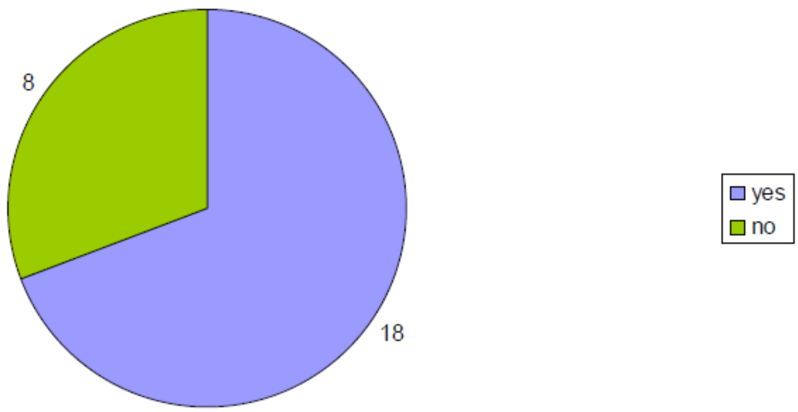
Questions 11

What is the type of the informatics network connecting your laboratory with the other laboratories?

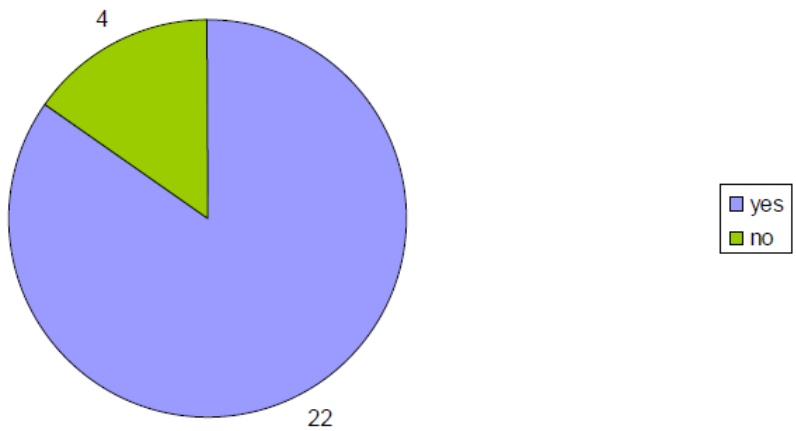
Results



Do you use an authentication system?



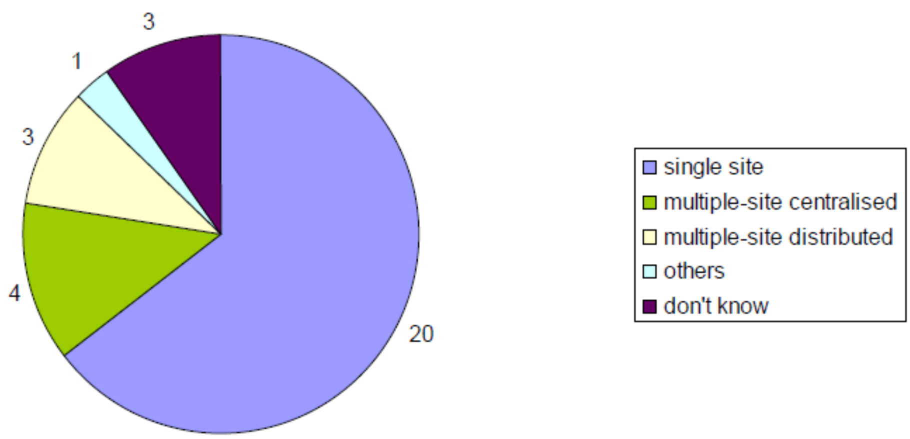
Do you have a corporate firewall?



Question 12

What is the type of database of test results?

Results



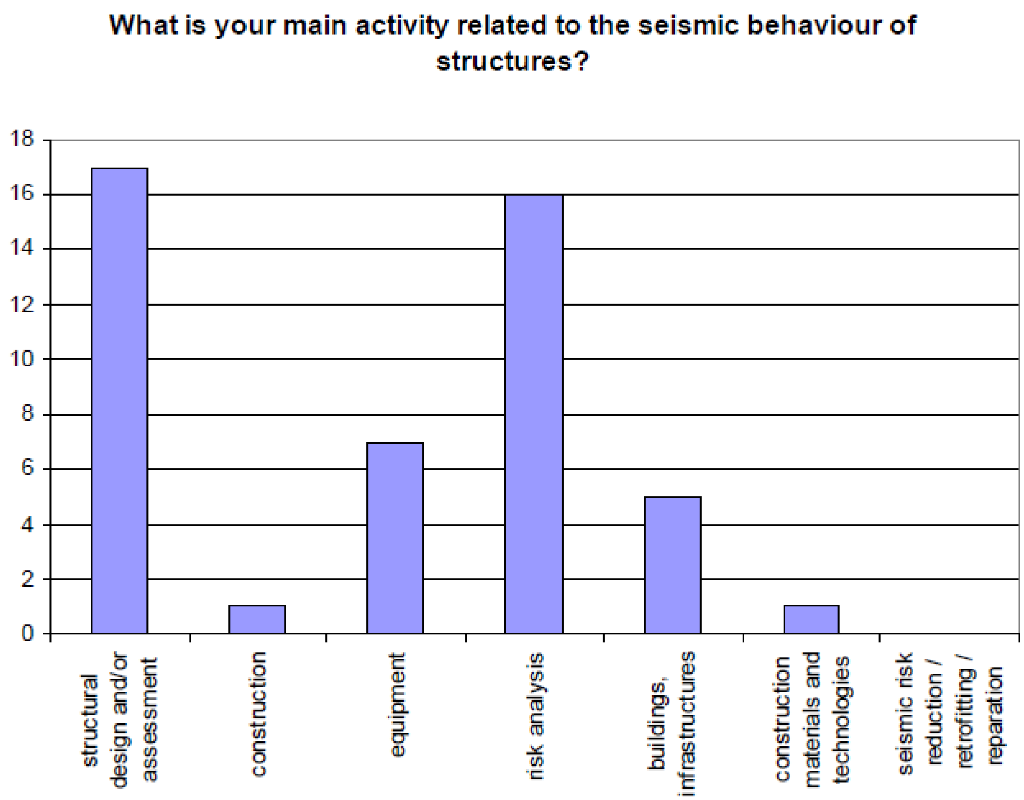
1.1.4 Inquiry for nuclear energy and chemical industry activities

This set of questions is divided into 15 parts. The detailed results for each question are reported hereafter. The inquiry was sent to 100 nuclear energy and chemical industries around the word. Presently, we received back 22 compiled inquiries, so the percentage of success is 22%. As in the previous set of questions, this means that the statistical analysis of the obtained results must be viewed just as indicative since the sample may be not fully representative of the whole stock.

Question 1

What is your main activity related to the seismic behaviour of structures (you may choose more than one activity)?

Results



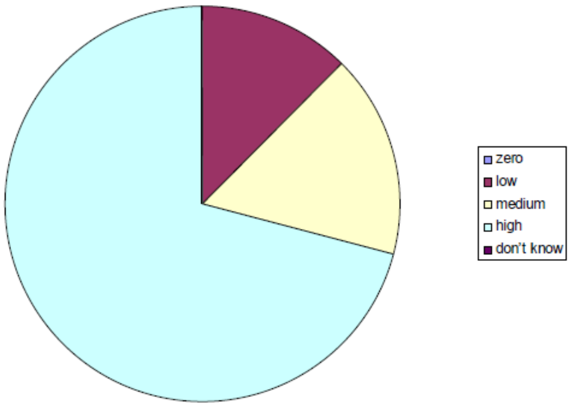
Comment

The respondents cover a wide spectrum of activities.

Question 2

How important is seismic risk in your main activity?

Results



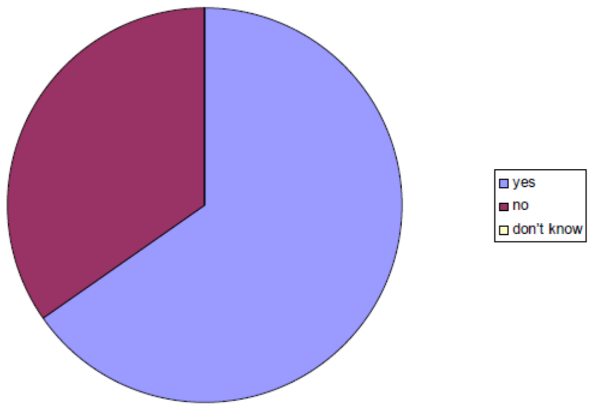
Comment

Seismic risk is very important for most of the respondents.

Question 3

Is your company directly involved in seismic design or construction of structures, components or equipments?

Results



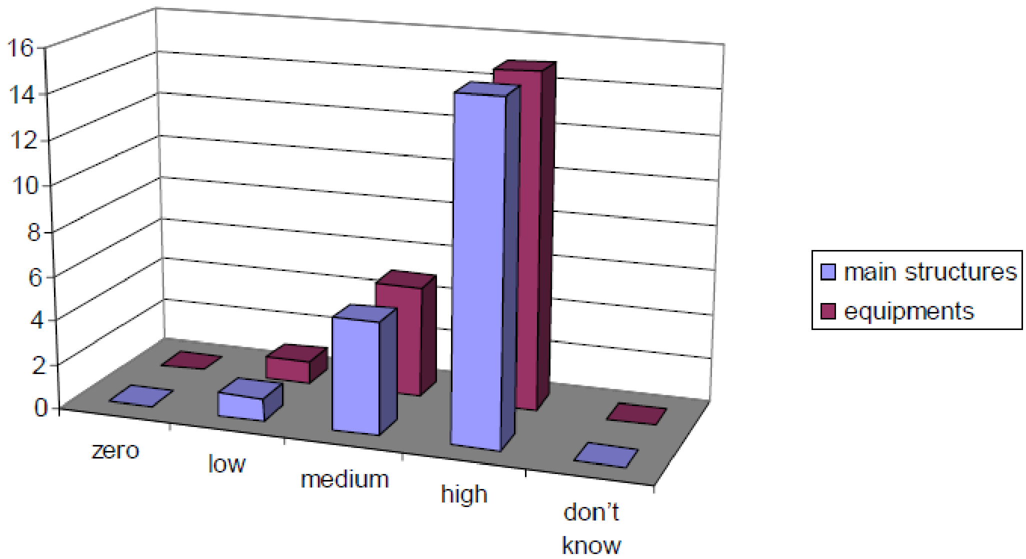
Comment

Most of the interviewed are directly involved in seismic activities.

Question 4

What is the impact on your institution's activities of the earthquake response of main structures and equipment respectively?

Results



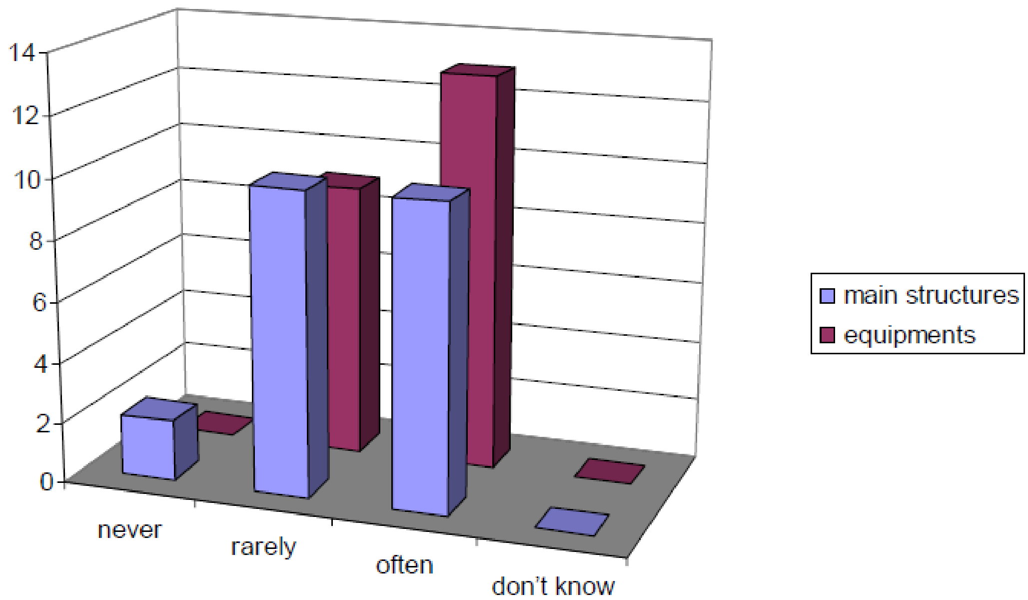
Comment

For most of the companies there is a high interest both in main structures and equipment studies.

Question 5

How often does your company make reference to results of experimental tests (even if your own institution was not involved in these tests), or to works based on these results?

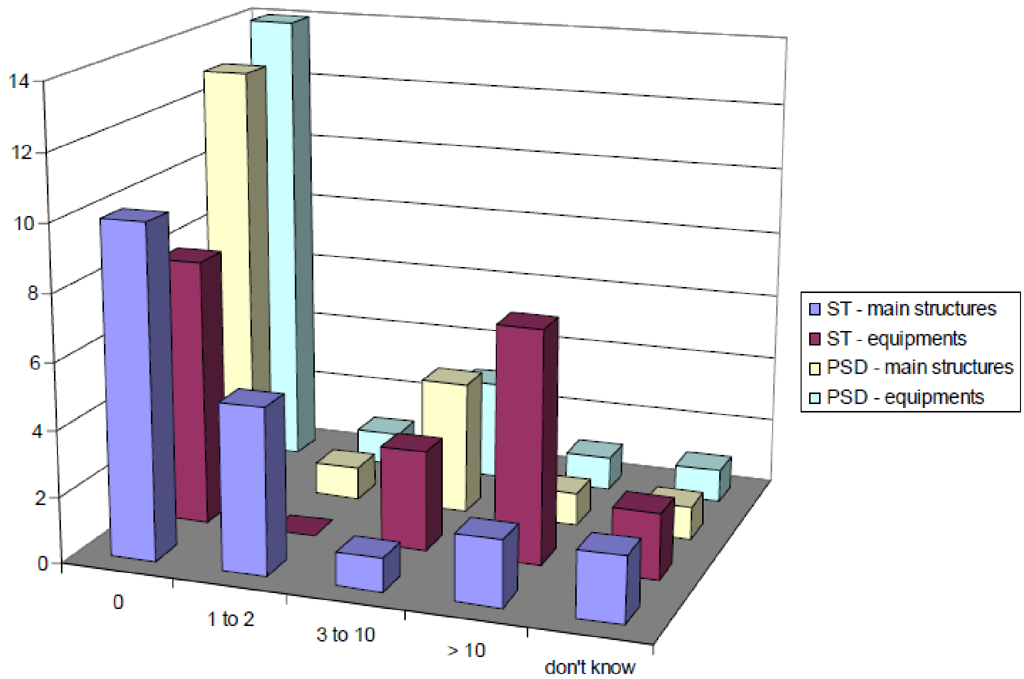
Results



Question 6

How many seismic tests did your company carry out by itself or fund during the last 15 years?

Results



Legend

ST = Shaking Tables tests

PSD = PseudoDynamic tests

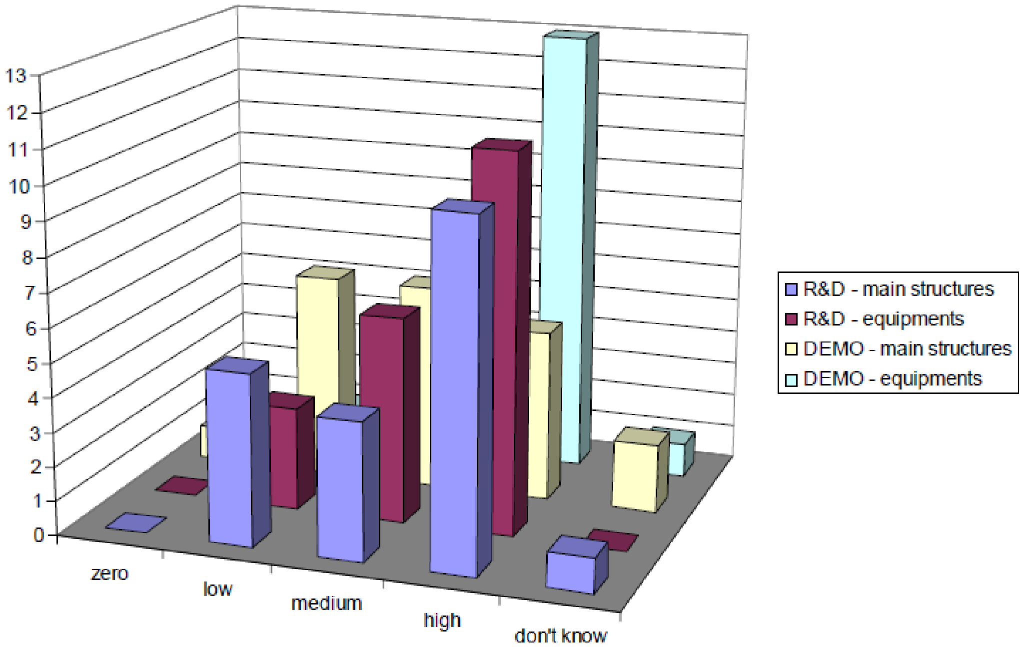
Comment

Very few tests were performed. ST is more used for equipments than for main structures. PSD is more used for main structures than for equipments.

Question 7

According to your company's experience and policy what is the benefit from seismic testing results that are used for research and development (R&D) or demonstration and qualification purposes for structures and equipment?

Results



Legend

R&D = Research and Development

DEMO = Demonstrative projects

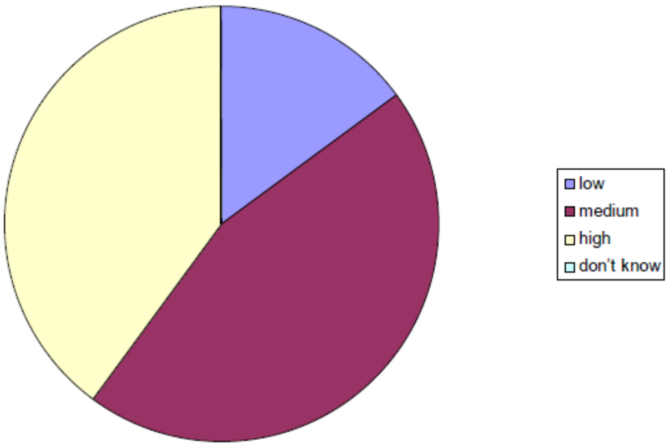
Comment

There is a very high interest for testing.

Question 8

What could be the benefit to your company from an experimental facility that would enable large-scale seismic testing?

Results



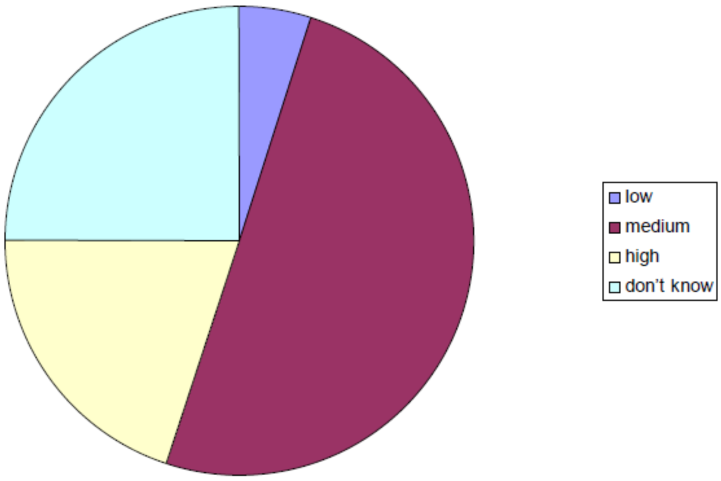
Comment

There is a very high interest for large-scale tests.

Question 9

What could be the added value for your institution of an experimental facility having a multiple point earthquake input capability?

Results

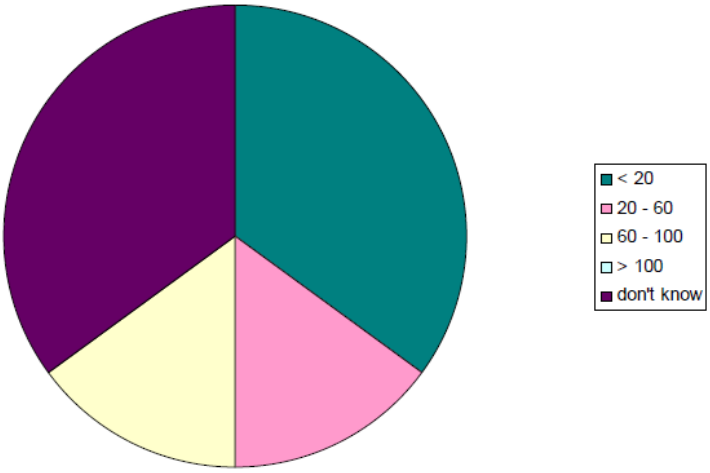


Question 10

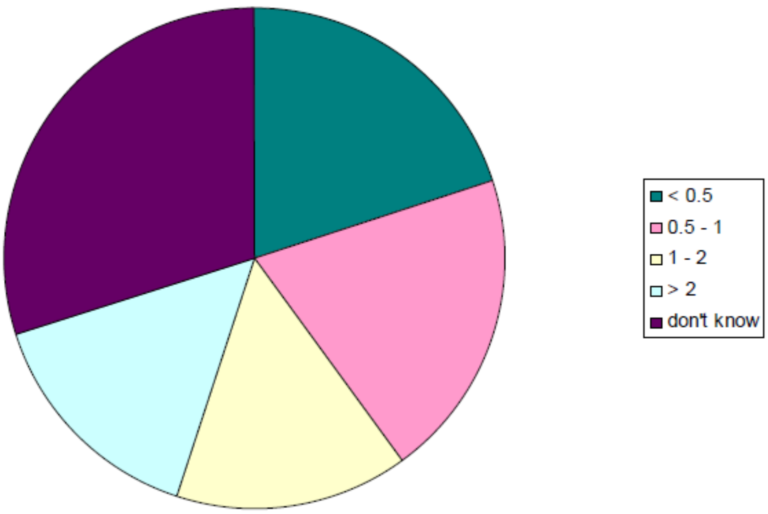
What are the characteristics of the most demanding test your institution has been involved in, in the past 15 years?

Results

Mass of specimen (tons):



Peak acceleration (g):



Comment

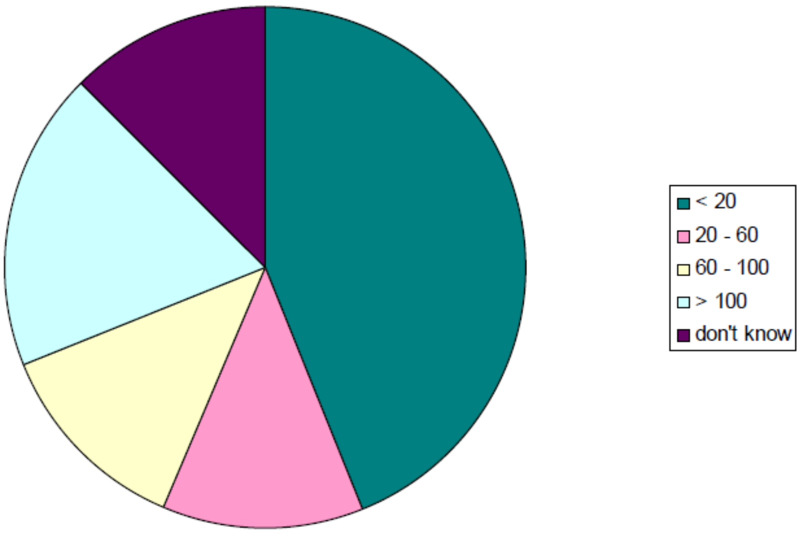
There is a large variety both in what are specimen masses and in the maximum acceleration.

Question 11

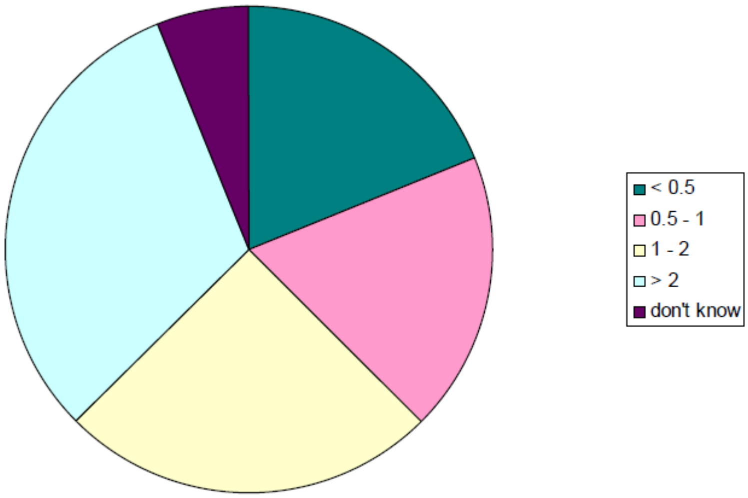
What are the characteristics of the most demanding test in which your institution could be interested?

Results

Mass of specimen (tons):



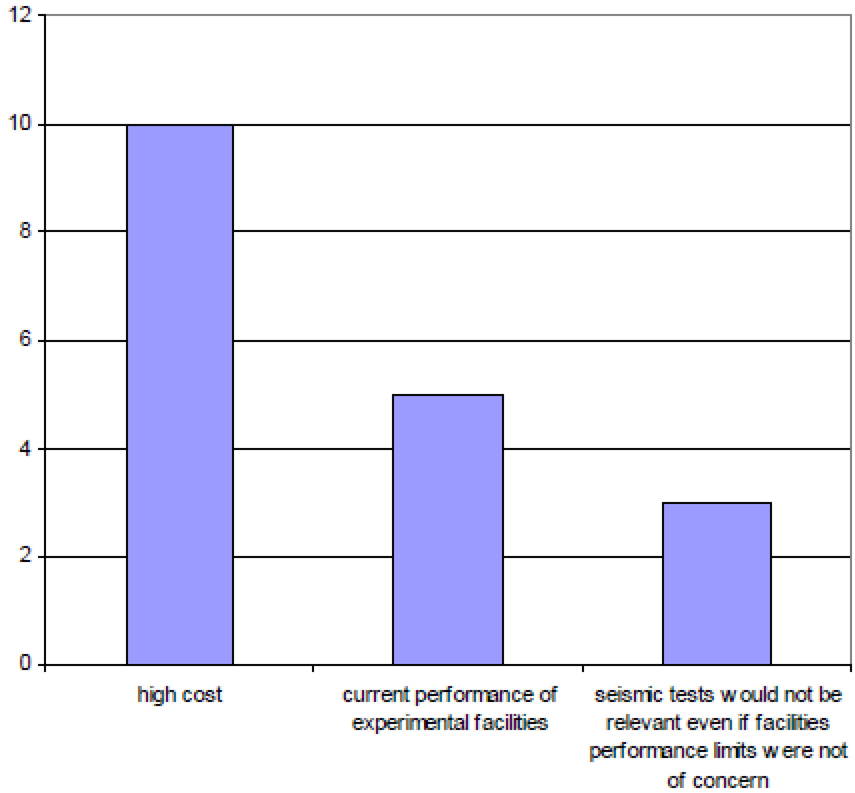
Peak acceleration (g):



Question 12

What is the main reason your institution does not use seismic testing facilities more often?

Results



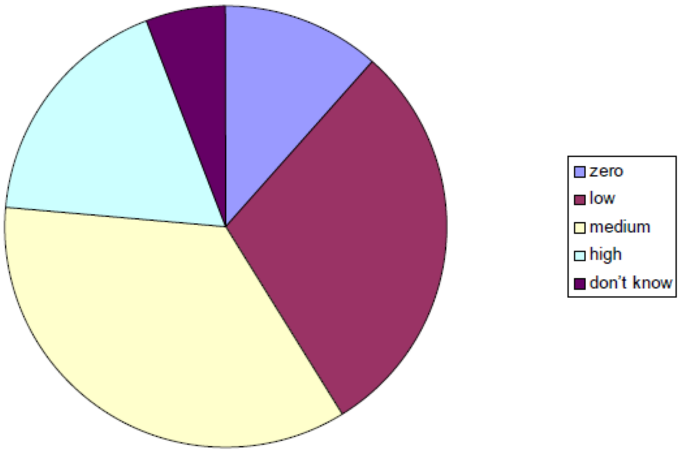
Comment

The main problem is cost, but also the lack in the current capability of the testing facilities is a reason why seismic testing is not used more often.

Question 13

What is the probability of needing, in the next 15 years, seismic testing taking into account frequency excitation content lower than 1Hz?

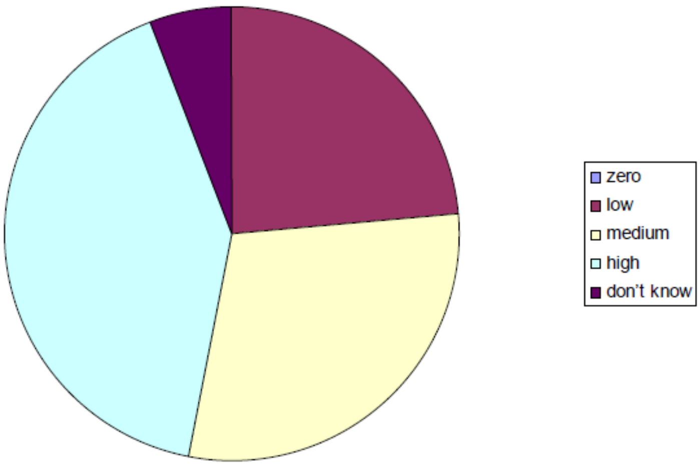
Results



Question 14

What is the probability of needing, in the next 15 years, seismic testing taking into account vertical earthquake excitation?

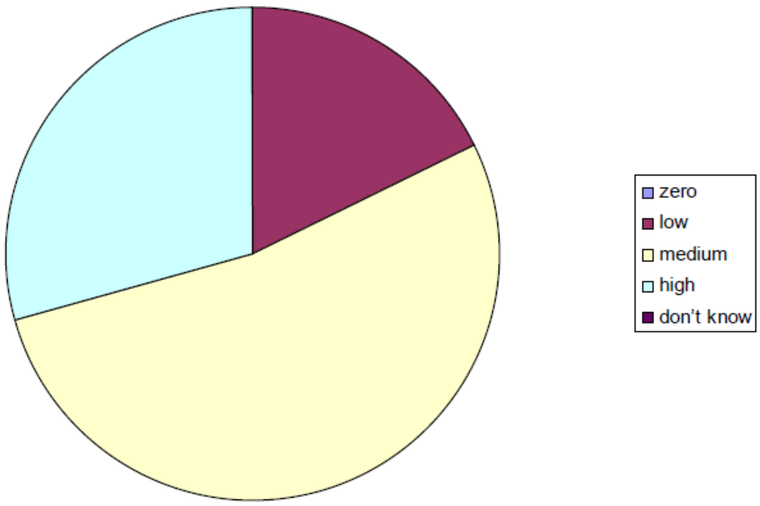
Results



Question 15

What is the probability of needing, in the next 15 years, seismic testing taking into account excitation intensity up to (or near) collapse?

Results



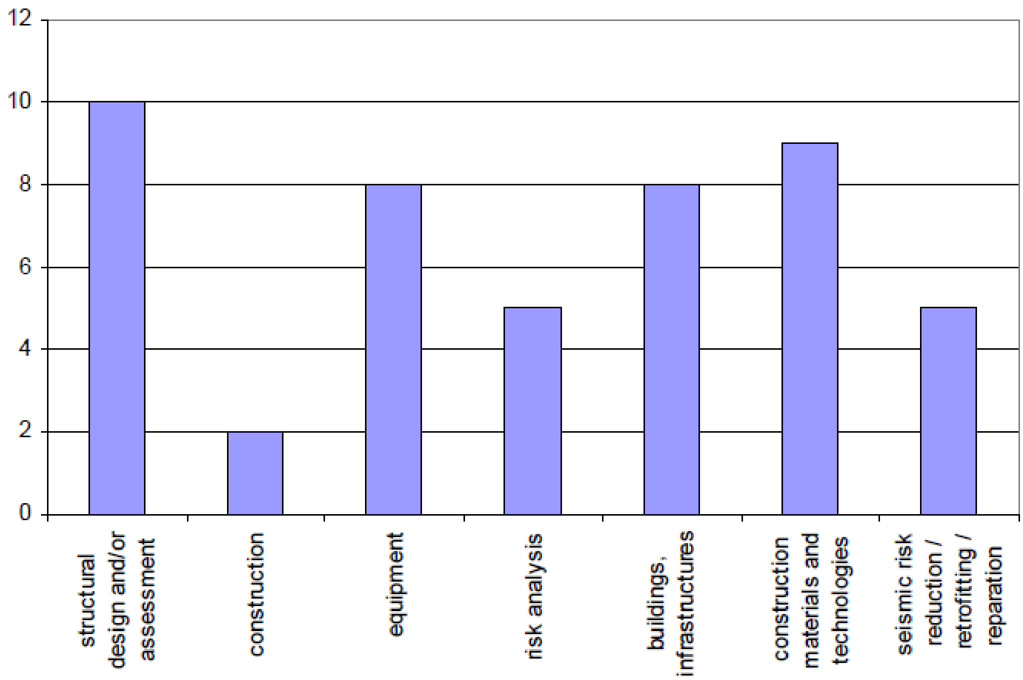
1.1.5 Inquiry for construction companies

This set of questions is divided into 17 parts. The detailed results for each question are reported hereafter. The inquiry was sent to 117 construction companies around the word. Presently, we received back only 10 compiled inquiries, so the percentage of success is around 8%. This means that the statistical analysis of the obtained results must be seen as merely indicative because they cannot be representative of the whole stock.

Question 1

What is your main activity related to the seismic behavior of structures?

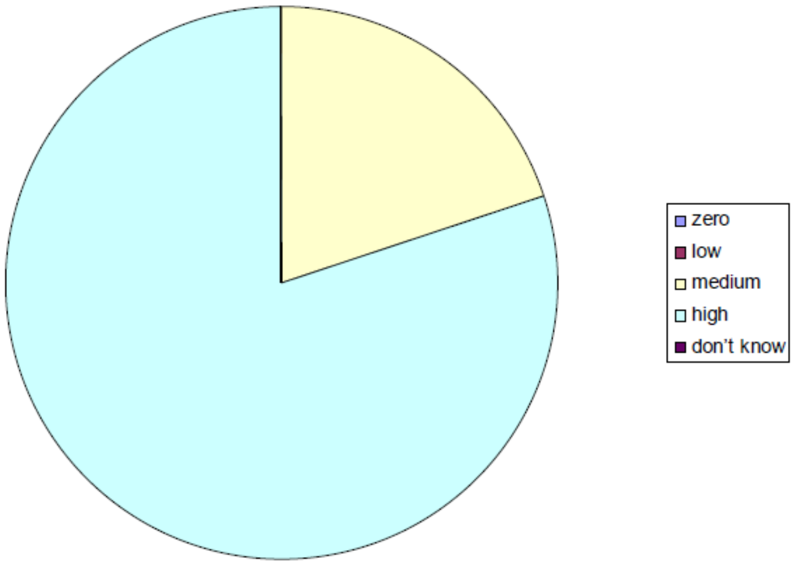
Results



Question 2

How important is seismic risk in your activity?

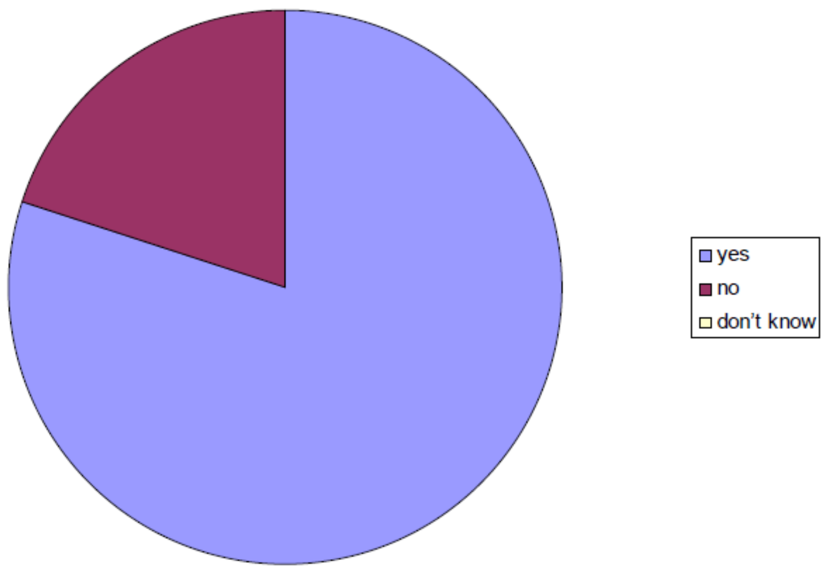
Results



Question 3

Is your company directly involved in seismic design of structures, components or equipments?

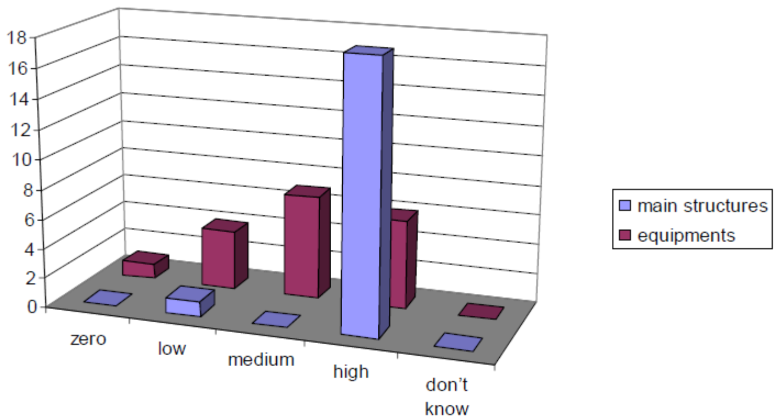
Results



Question 4

What is your company interest on analysing thoroughly the earthquake response of structures and equipments respectively?

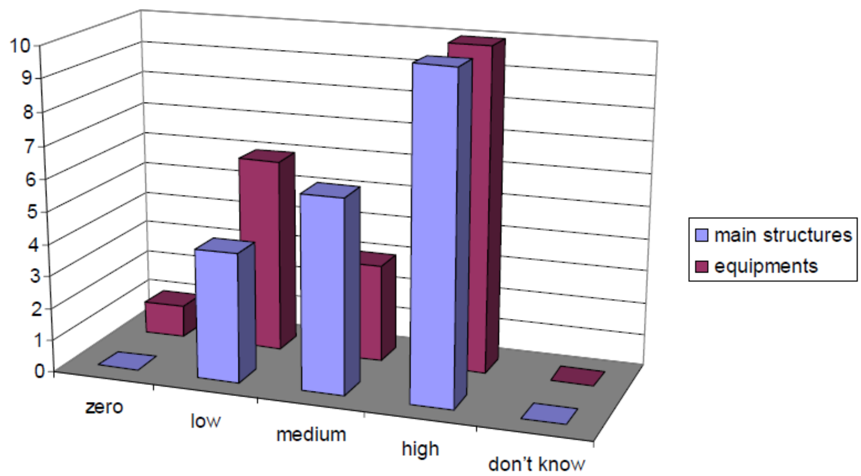
Results



Question 5

What is your company interest on performing seismic tests on structures and equipments respectively?

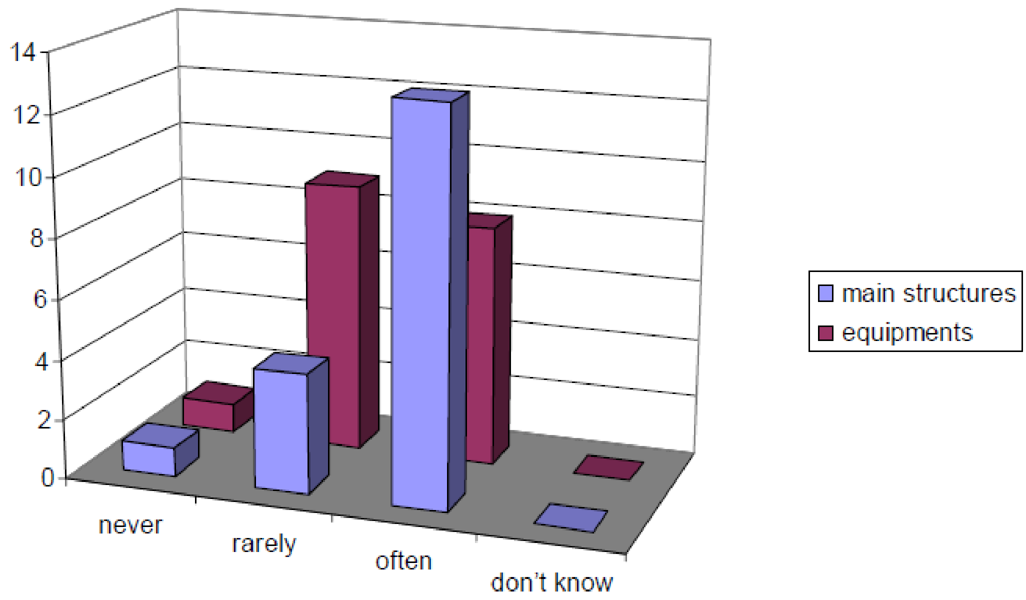
Results



Question 6

How often does your company make reference to results of experimental test?

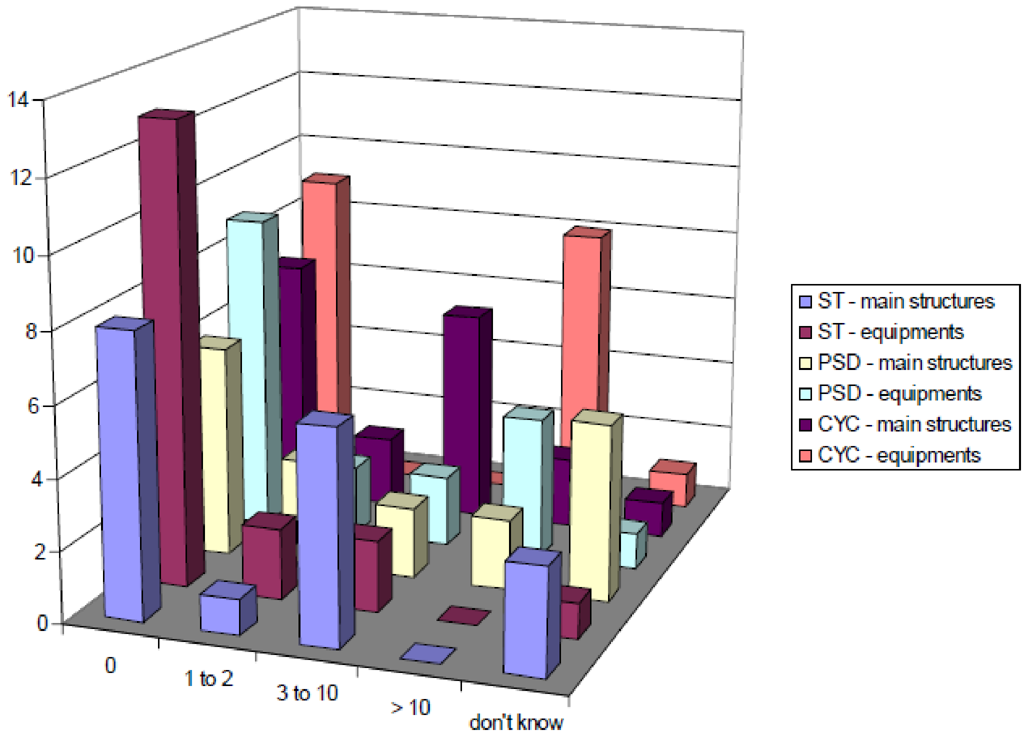
Results



Question 7

How many test campaigns did your company perform by itself or fund in the last 15 years?

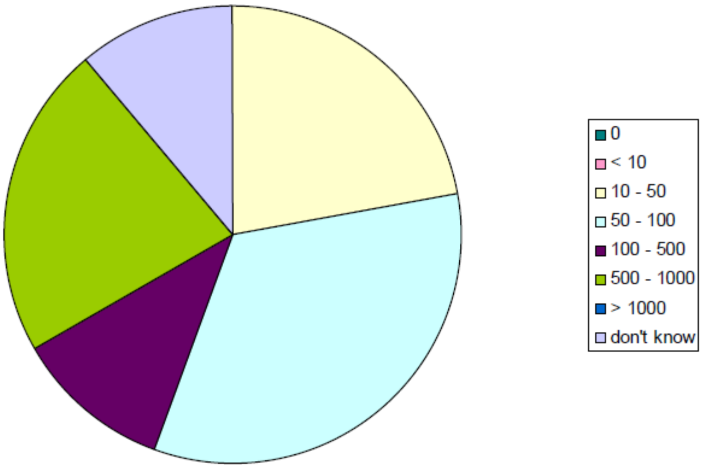
Results



Question 8

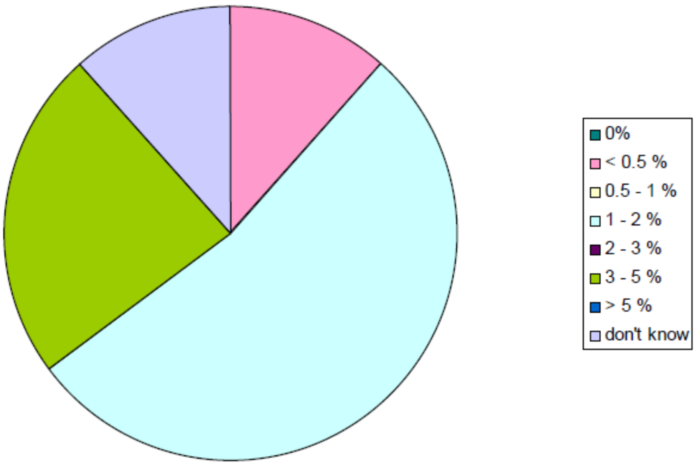
What is the average annual budget for research and development (R&D) activities of your company in the last 15 years (thousands of euro)?

Results



Question 9

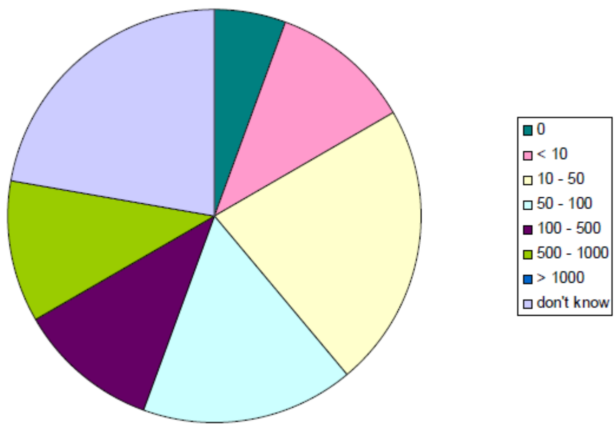
What is the percentage of average annual budget for research and development (R&D) activities of your company in 15 years with respect to the yearly turnover?



Question 10

What is the average annual budget for experimental tests of your company in the last 15 years (thousands of euro)?

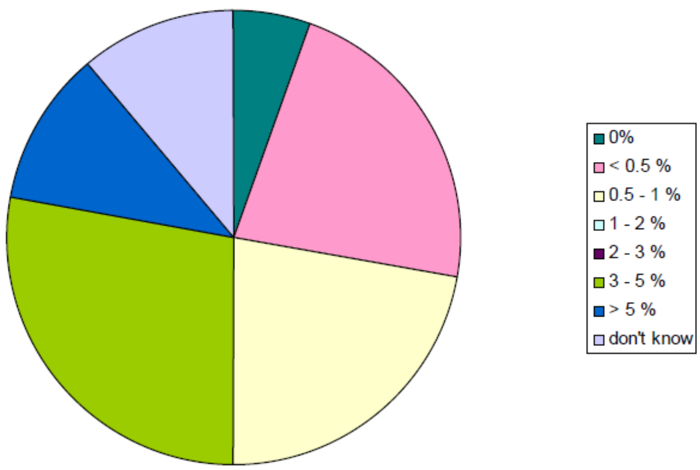
Results



Question 11

What is the percentage of annual budget for experimental tests of your company in the last 15 years with respect to the overall R&D budget?

Results

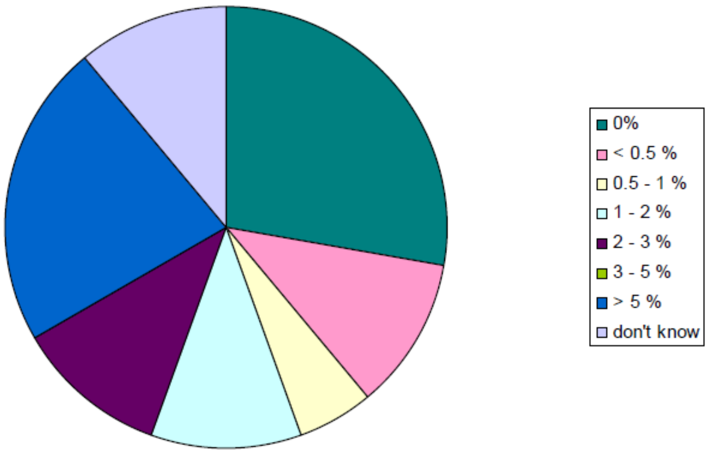


Question 12

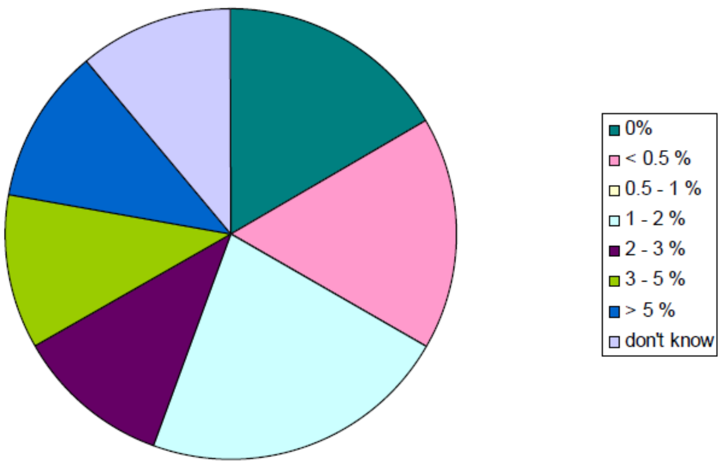
What percentage of your company budget for experimental tests was devoted to seismic testing of structures or equipments in the last 15 years?

Results

Main structures:



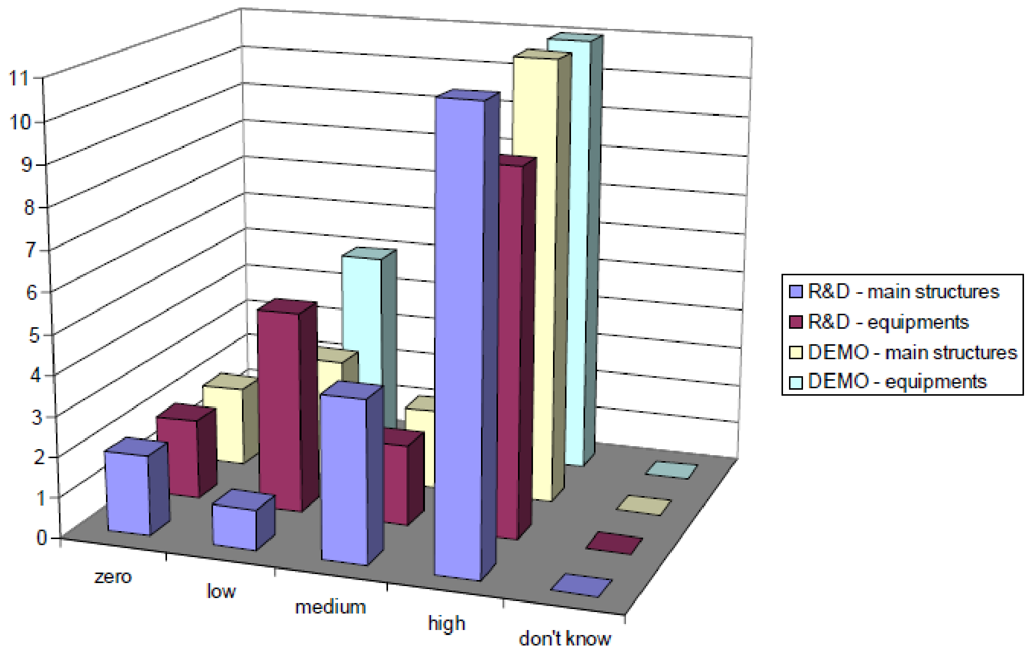
Equipments or secondary structures:



Question 13

According to the experience and to the policy of your company what is the interest of seismic tests that are used for research and development (R&D) or demonstration and qualification purposes for structures and equipments?

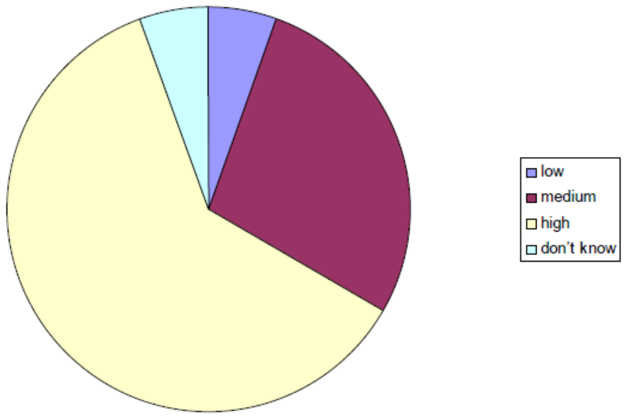
Results



Question 14

What could be the interest of your company on an experimental facility that allows large-scale tests for earthquake response simulation?

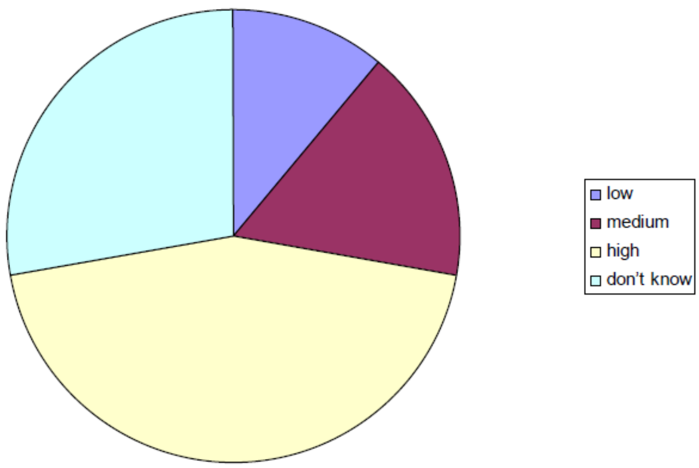
Results



Question 15

What could be the added value for your institution of an experimental facility having a multiple point earthquake input capability?

Results

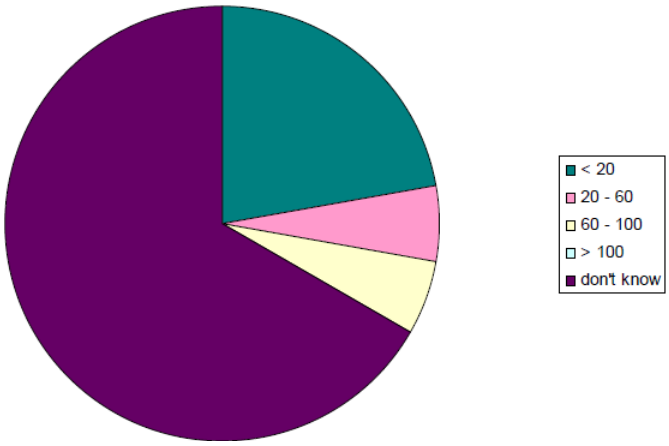


Questions 16

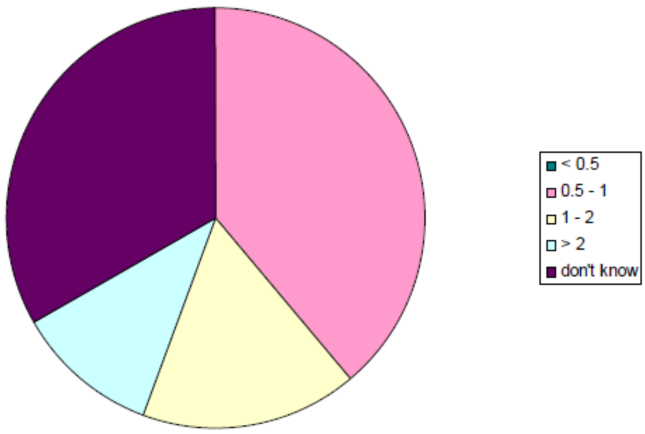
What are the characteristics of the most demanding test your company could be interested in?

Results

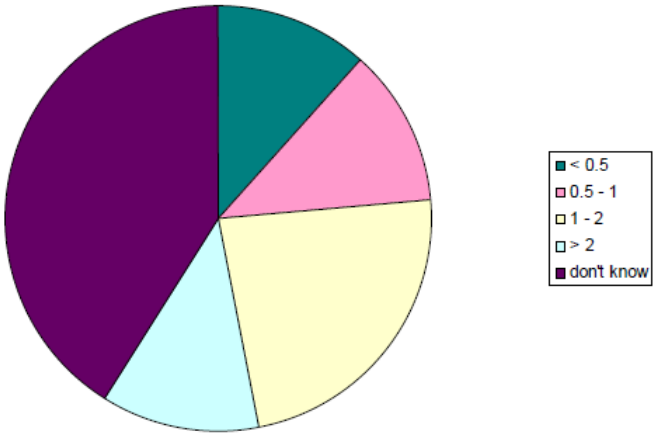
Mass of specimen (tons):



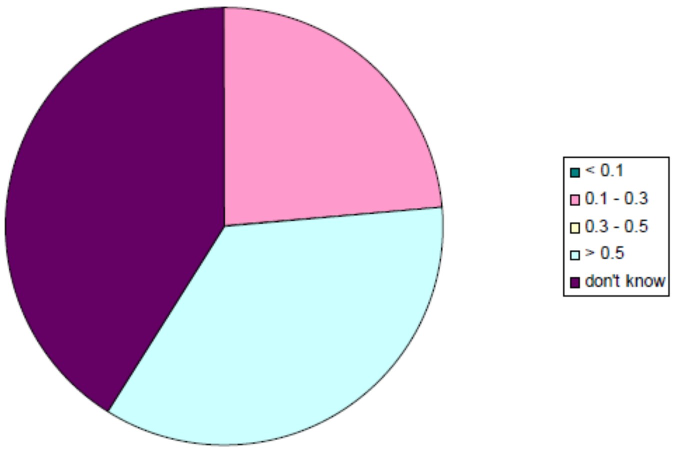
Peak acceleration (g):



Velocity (m/sec):



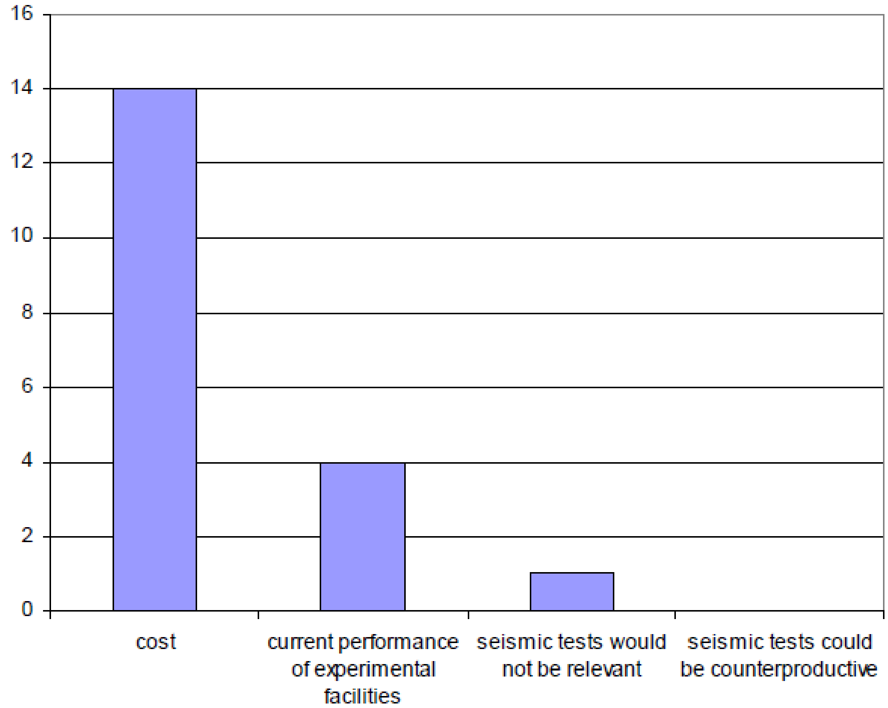
Displacement (m):



Question 17

What is the main reason your company does not use seismic testing facilities more often?

Results



1.1.6 Conclusions

Seismic testing laboratories:

- Regarding the maximum weight, length, width and height, often the upper values are for Reaction Walls (RW) facilities, the lower values for Shaking Tables (ST) facilities. Regarding the maximum displacement that the testing facility can realize, it is interesting to notice that some facilities cannot perform tests in the transversal and the vertical direction.

- Most of the times the tested specimens light, small in length and height. These specimens are often tested with small displacements. Only a few were tested in transversal or vertical direction.

- There is a wide possibility for multi-axial tests, but only a few tests were performed in the past with vertical or lateral displacements. On one hand, this is probably a problem of cost. On the other hand, a question arises: are multi-axial tests really a need?

- Asynchronous multiple-support excitation, multidirectional excitation, sub structuring techniques, inter-facility distributed testing and telepresence are not yet common practices even if there are some laboratories which have already started to apply them.

Nuclear energy and chemical industry activities (and also construction companies):

- Seismic risk is very important for most of the respondents, probably also because most of the interviewed are directly involved in seismic activities. There is a high demand for tests, but only a few ones were performed in the last years. ST is more used for equipments than for main structures. PSD is more used for main structures than for equipments. The main problem is cost, but also the lack in the current capability of the testing facilities is a reason why seismic testing is not used more often. Maybe there is also a lack of accessibility.

- Surely there is a high demand for large-scale tests, both for main structures and for equipments (but most of potential users have no clear idea about the desired masses and maximum accelerations).

- These tests have the dual role of improving the research and to serve as demonstrative projects.

1.1.7 Comments, further developments and possible improvements

After this first phase of the inquiry, it is possible to make some considerations about the way the inquiry has been conducted.

The number of questions for each type of inquiry and their complexity were kept as low as possible. On the other side we wanted to obtain a complete set of information, the more accurate and precise we could. The balance between the required time for completing the form and the obtained amount of data seems to be not perfect: some questions could perhaps be cut off. For example, questions about the level of interest received very often a positive answer, but a positive answer was perhaps given also by people not so much interested. Why to say there is no interest if it doesn't cost anything to say yes? A more realistic demand could have been: How many tests would you expect to commit if you could afford the cost?

Text fields for comments have been seldom used by compilers. Nevertheless, their use for the statistical analysis was impossible. It was also very hard to analyze them in an analytical manner. However, these comments are useful to detect if the question is inappropriate.

Free text fields created problems for several reasons: apart from possible insertion errors, somebody used only integer numbers, some other used decimal numbers with a comma as a decimal separator, and others used the point as the decimal separator, there were respondents who put comments just after the answered number and somebody finally answered with formulas instead of numbers. These observations suggest also that questions should always ask for range values; for this purpose, multiple choice questions are the best.

About the first question in the inquiry to laboratories, many of them have several kinds of facility simultaneously. To make the compilation easier, we should have referred the questionnaire the main facility of each laboratory.

2.CHALLENGES, NEEDS AND OPEN QUESTIONS IN SEISMIC TESTING. SUMMARY AND CONCLUSIONS OF THE 1ST EFAST INTERNATIONAL WORKSHOP (JRC)

2.1 OBJECTIVES OF THE WORKSHOP

The new infrastructure could consist of a European class new single-site facility integrated with selected existing ones and, possibly, upgraded to meet new network requirements. The aim of the 1st EFAST Workshop was to elaborate design guidelines in the gross for the aforementioned facility. To this end an inventory of the needs of the scientific community and of the industry was needed that would allow the partners of the EFAST project to better determine the characteristics of the facility to meet the expressed needs. During the Workshop more than 30 experts from all around the world made presentations regarding the needs, the technologies, the design and the operation of seismic testing infrastructures. Round tables on these topics have been held in order to stimulate open debate. The conclusions of this workshop will contribute to specify recommended solutions and required performances.

2.2 ORGANISERS

The Workshop was jointly organised by the JRC in collaboration with all the partners of EFAST project.

Coordinator:

Francisco Javier Molina

European Commission • JRC-– IPSC – ELSA

Tel. +39 0332 786069 • Fax +39 0332 789049

E-mail: francisco.molina@jrc.it

Scientific secretariat:

Francesco Marazzi

European Commission • JRC-– IPSC – ELSA

Tel. +39 0332 783510 • Fax +39 0332 789049

E-mail: francesco.marazzi@jrc.it

2.3 PROGRAM AND PRESENTATIONS

The detailed program of the workshop is given in the following two pages. The following link refers to the available slides presented by the invited speakers:

http://efast.eknowrisk.eu/EFAST/index.php/events/workshop1/w1-presentations

A brief summary of each talk and the related questions and answers are reported hereafter for each speaker. The final part of this document refers to the conclusions of the two round tables.

2.3.1 List of participants

Dr.	Ioannis	Anastasopoulos	National Technical University of Athens
Dr.	Diana	Ancas	Technical University of Iasi
Dr.	Fausto	Argeri	MOOG
Prof.	Gabriela Maria	Atanasiu	Technical University of Iasi
Prof.	Marcial	Blondet	Universitad Catolica Pontificia of Peru
Prof.	Stathis	Bousias	University of Patras
Prof.	Oreste	Bursi	University of Trento
Prof.	Michele	Calvi	EUCENTRE
Dr.	Eduardo	Carvalho	GAPRES - SA
Dr.	Chiara	Casarotti	EUCENTRE
Dr.	Allen	Clark	MTS
Dr.	Ema	Coelho	Laboratório Nacional de Engenharia Civil
Dr.	Filippo	Dacarro	EUCENTRE

Dr.	Roberto	Dalpedri	ALGA S.p.A.
Prof.	Mauro	Dolce	University of Basilicata
Prof.	Uwe	Dorka	University of Kassel
Prof.	Michail	Fardis	University of Patras
Prof.	George	Gazetas	National Technical University of Athens
Prof.	Michel	Geradin	JRC-ELSA
Dr.	Florin	Leon	Technical University of Iasi
Prof.	Wensheng	Lu	Tongji University
Dr.	Georges	Magonette	JRC-ELSA
Dr.	Francesco	Marazzi	JRC-ELSA
Dr.	Agostino	Marioni	ALGA S.p.A.
Dr.	Francisco Javier	Molina	JRC-ELSA
Prof.	Charalampos	Muzakis	University of Athens
Dr.	Paolo	Negro	JRC-ELSA
Dr.	Keizo	Ohtomo	CRIEPI
Dr.	Livia	Pardi	AUTOSTRADE S.p.A.
Prof.	Alberto	Pavese	EUCENTRE
Dr.	Pierre	Pegon	JRC-ELSA
Dr.	Artur	Pinto	JRC-ELSA

Prof.	Paolo	Pinto	University of Rome
Dr.	Ioannis	Politopoulos	CEA
Dr.	Jean-Claude	Queval	CEA
Prof.	Andrei	Reinhorn	State University of New York at Buffalo
Dr.	Vito	Renda	JRC-ELSA
Dr.	Pierre	Sollogoub	IAEA
Prof.	Haluk	Sucuoglu	Middle East Technical University
Prof.	Colin	Taylor	University of Bristol
Dr.	Bradford	Thoen	MTS
Prof.	Keh-Chyuan	Tsai	National Taiwan University
Prof.	Lelli	Van Den Einde	University of California at San Diego
Dr.	Nguyen	Van Thuan	University of Kassel
Dr.	Francois	Voldoire	EDF
Dr.	Glen	Wardrop	INSTRON
Prof.	Mihai Horia	Zaharia	Technical University of Iasi
Prof.	Roko	Zarnic	University of Lubjana

Table 2.1 List of participants at the 1st EFAST Workshop

2.4 Overview of the presentations including questions and answers

2 March 2009 morning

Workshop welcome

Stephan Lechner, IPSC Director

Presentation summary (no slides)

Specialists from all over the word, and particularly from Europe, are present at this workshop. It is important for JRC, and for ELSA in particular, to show and see that there is a strong support from the earthquake engineering community. A wide and real discussion on practical problems related to testing is very important. The presence of a so wide scientific community is also important from both a scientific and a political point of view. It may appear that physical testing activities have been already fully explored, but this field of research has still many unknowns and very advanced techniques and competencies are necessary to make a step further. Physical testing activities in structural mechanic are very important for IPSC. ELSA, with its physical tests, has succeeded in attracting a larger group of experts than other groups working in IT. JRC General Director shares these ideas and Lechner will insist on them to him. The workshop can also act as a catalyst in the implementation of a European dimension of testing and will be contribute to focus the JRC program towards these activities.

Michel Geradin, IPSC, ELSA Unit Head

Presentation summary (no slides)

The workshop is organized in the framework of EFAST project and in close collaboration with EFAST partners. This workshop will be successful if we will be able to meet the needs of all the earthquake community.

PRESENTATIONS ON EFAST PROJECT

EFAST project overview

Ioannis Politopoulos (CEA – France)

Presentation summary

An overview of the EFAST project is presented. A comparison among the budget devoted to seismic testing in the main developed countries clearly shows that, even if the seismic risk in Japan and USA is similar to the European one, our budget is considerably smaller. Important testing installation are working or under construction in Japan, U.S.A., China and Taiwan. New testing techniques are emerging. All this pushes for a new testing facility in Europe. EFAST project will generate a preliminary design of a new testing facility to be inserted into the ESFRI roadmap.

Questions

Magonette: To what extent we are entitled to modify the submitted plan? Can we change it accordingly with the workshop outcomes and guidelines?

Politopoulos: We can modify the program of the demonstration tests, but we cannot modify the deliverables and the milestones because there is a contract with the Commission describing them.

Renda: USA and Japan has two different approaches: NEES and E-Defence. The first is mainly focused on networking facilities, the second one on having a very big facility. What will be our model and there will be room for networking with the existing installation in the word?

Politopoulos: The collaboration is a general wish. Regarding the type of installation, we are now at the beginning of the project and the things are not yet so clear.

EFAST inquiry

<u>*Francesco Marazzi*</u> (JRC – EC)

Presentation

A brief summary about the EFAST inquiry has been reported. More than 300 inquiry forms were sent in the past months to contact persons of the leading seismic testing laboratory (reaction walls, shaking tables, centrifuges), of the nuclear and chemical industries and of the construction companies. The feedback was acceptable for testing laboratories (30%) and for nuclear and chemical industries (22%), but low for construction companies (8%). The results will be updated in the next months, so that an increased percentage of returned inquiries is expected. Some provisory conclusions are already pointed out:

i) Laboratories:

- wide possibility for multi-axial tests, but only few tests performed with vertical and lateral displacements: multi-axial tests are not a big demand or are avoided when possible,
- asynchronous multiple-support excitation, multidirectional excitation, telepresence and substructuring techniques are not yet common practices.

ii) Nuclear and chemical industries (construction companies?):

- there is a high demand for tests, but only a few were performed: it is only a problem of high costs or also a lack of accessibility to large facilities?
- high demand for large-scale tests,
- high demand for both main structures and equipments tests to be used for both research and demonstrative purposes.

Questions

Renda: There was an explicit question about the need for networking in Europe?

Marazzi: No, it is surely an interesting question, but a balance between the information requested and the time to complete the inquiry was carefully taken into account.

Molina: This is a very preliminary analysis of the results based on the data received up to a week ago; we will publish a complete report in the following weeks.

FAST input to EFAST

Jean-Claude Queval (CEA – France)

Presentation

A review of current European testing facilities and of the major new projects worldwide was presented as the scenario for the elaboration of the FAST project by CEA before the EFAST project was conceived. The problems and limitations encountered in the past were discussed and gave a preliminary idea of the expected needs with special attention to CEA. For Civil Engineering purposes a 1-DoF shaking table can be adequate, but for qualifications tests a 6-DoF table with high acceleration capacity is required. The FAST project technical solution was described into details.

Questions

Ohtomo: Do you have any idea of how to combine a shaking table with a pseudodynamic test?

Queval: Yes, we can use hybrid testing. In this way we will reduce the costs and avoid the problems related to scaling.

Molina: In the past, CEA transformed his largest shaking table from 3-DoF to 6-Dof. Do you think it is useful to have also the vertical DoFs, what were the advantages and disadvantage to have MDoF in your experience?

Queval: Yes, especially for qualification tests, for equipments and for the aeronautic industry, it is important to have vertical excitation also. It is true that it is not important for all types of tests to have vertical excitation, but if we don't have the capability to do such kind of tests, we will surely never do them.

Molina: Was the quality in the reproduction of the seismogram the same when you increased the DoFs?

Queval: Yes, in principle it is the same, but obviously this depends on the weight of the specimen.

EFAST test program

<u>*Uwe Dorka*</u> (Univ. Kassel – Germany)

Presentation

Some possibly available specimens for testing in the laboratories of the project partners were described as well as the ideas for multiple shaking tables testing, for substructure testing with shaking tables, for combining shaking tables with other on-site facility and for geographically distributed substructure testing. EFAST being not a research program, the amount of resources for testing is limited.

Questions

Renda: Is there a cross-interaction between the test program and the design of the facility?

Dorka: The testing program will be adjusted accordingly with the real possibility of the testing facility. The described testing program is based on the state-of-the-art review, we also need advises from experts in order to better define it.

TESTING NEEDS

Testing needs from the point of view of ECTP and cultural heritage protection

Roko Zarnic (Univ. Lubjana – Slovenia)

Presentation

The first part of the presentation deals with the Focus Area Cultural Heritage (FACH) of the European Construction Technology Platform (ECTP) (Prof. Zarnic acts as coordinator). There are no Eurocodes on Cultural Heritage (CH) interventions. Such interventions must be low intrusive and based in long term consequences. Regarding the needs, some are related to on-site investigation (long-term monitoring, decay of building fabric, accidental actions, non-destructive, semi-destructive and destructive testing) with the advantage of working with the real materials. Other ones are connected with laboratory investigation (materials, structural elements, models and prototypes). EFAST can help these last ones. Introduction of new materials in repair and structural strengthening is also important. The idea of "low intrusive intervention" needs more research on FRP materials, structural glass behaviour and wood-based composites. Restoration actors ask for demonstration tests. It is very important to involve SMEs into research, so networking is also very important especially for transferring university knowledge into industrial and operational knowhow. A list of the available laboratories should be elaborated.

Questions

Molina: Has CH sector some special needs with respect to other research sectors?

Zarnic: In principle I should say no, but in practice CH deals with sensitive buildings. In this case the multi disciplinary approach is a must.

Dolce: During your presentation you said that in situ tests are very important because of the ageing effects and of the boundary conditions. Could you please comment further about this?

Zarnic: Yes, it is very important to perform in situ tests; if we conduct laboratory tests we must be aware of their limitations.

Needs of large scale testing in developing regions

Marcial Blondet (Catholic Univ. – Peru)

Presentation

In developing countries, most people live in non-engineered low-rise constructions made of poor materials. This implies that most researches performed in developed countries are not directly applicable to developing countries. In developing countries, buildings are highly vulnerable to natural forces. This means that earthquakes usually cause a large amount of destruction and deaths, whereas in developed regions the damage is more related to infrastructures. Research conducted at Catholic University of Peru has significantly improved the knowledge about safer constructions, but they have failed in transmitting this knowhow to people. Large-scale experimental test programs are essential to develop reliable, economical and acceptable solutions for safe housing in developing countries, but testing facilities are expensive. It makes sense to share the facilities with researchers from developing countries through joint research projects aimed to improve the living conditions of millions of people.

Questions

Negro: Is it better for you to improve your laboratory or to have a more easy access to international facilities?

Blondet: We have a 1DoF shaking table. To have a better testing facility is needed.

Taucer: You need new and different facilities and new type of measurement devices or you have already enough?

Blondet: No, we need much more; we have a 1DoF shaking table with only 22 acquisition channels. We need to measure more and also to simulate what happens in the few seconds during the test.

Politopoulos: Of course the measurement techniques are essentials, they raise the quality of tests.

Zapico: Do you think that EFAST should emphasize results dissemination?

Blondet: It is as important as the research itself, we must change the people culture; we must convince people to apply new developments and to change their habits. We need a very multidisciplinary approach.

Dorka: It is important to perform test for developing countries in Europe, U.S.A. and Japan.

Tsai: It is very important to be able to analyse the in-plane and out-of-plane behaviour of brick masonry.

Molina: If you had the money and the possibility to choose between a larger SDoF shaking table and a small MDoF one, what would you choose?

Blondet: If the money is only for installation, I would choose the first one because the maintenance cost would be lower.

Nuclear Industry demands regarding a European Facility for Advanced Seismic Testing

Francois Voldoire (EDF – France)

Presentation

The first part of the presentation deals with the state of the art of the earthquake engineering and research in the nuclear context and summarise what has been done in the structural engineering field. An important point for future is to increase the efficiency of the research by strengthening the analyses combining in silico (simulations), in labo (tests in laboratory) and in situ (on the field) approaches. Another key issue is to better study the soil-structure interaction (SSI). The behaviour of seismic isolation systems and of RC building and the structural behaviour of the equipment must be further analysed. In order to fully exploit the capabilities of the testing techniques, refined measurements methods are needed. Experiments are also needed in order to discover unexpected failure modes. The sharing of expertises among labs, research teams and seismic structural analysts is also a key issue.

Questions

Renda: What do you think about the re-evaluation of the existing nuclear power plants? Do you think there is a need for specific tests? If yes, do you have an idea about the maximum dimensions, the maximum payload, the characteristics that the shaking table should have?

Voldoire: It is difficult to give a detailed answer. We need two classes of tests: for demonstration and for research purposes.

Renda: We have now in Europe medium size shaking tables. Do you think we need greater ones?

Voldoire: Presently, I don't know.

Reinhorn: Small shaking tables are enough for validation purposes. The testing facility must be integrated with a computational facility to extrapolate results.

Dorka: EC has a network for simulation and computation; EFAST is not a partner of this network.

Taylor: There is a European forum about build & share expertise for the next future.

Tsai: I suggest considering that the nuclear industry could finance the new EFAST facility, funding is always a serious problem.

2 March 2009 afternoon

Problems and certainties in the experimental simulation

Michele Calvi (Eucentre – Italy)

Presentation

The presentation begins with the statement that it is much better to invest a few hours of calculation and theoretical considerations rather then to spend several months of testing in the laboratory. Physical testing faces with the problem of scaling the specimens: the two options are usually to reduce the specimen size for shaking table testing or to keep the original dimensions for pseudodynamic testing (but in this case some problems regarding the velocity of testing arise). The type of testing method affects the choice of the simulation model: quasi static tests are not affected by viscous damping, but for simulating a shaking table tests an equivalent viscous damping must be considered: it should be proportional to initial or tangent stiffness? The observed behaviour of the tested structures is usually better than what is predicted by force-based codes. So, the most important parameter is the strength, not the PGA. There is still a lack of knowledge in non-structural elements, for example in masonry infill in RC frames. They are non-structural, but they can change considerably the structural behaviour and the structural demand. There is nowadays the capability of acquiring a large amount of data, but it is always the brain that filters and interprets them.

Questions

Negro: These tests on infill structures have been already performed about 15 years ago. Uncertainties in the properties of non-structural elements are known. Which kind of research is still needed for infill structures?

Calvi: Non structural elements don’t contribute at the Ultimate Limit State (ULS). So, the requested level of damage must be specified, the target performance must be stated in advance. A highest earthquake will surely destroy the infills. The behaviour of structures with not yet destroyed infill walls must be further analysed.

Reinhorn: What about to weaken the structure to reduce demand? For example, what about the idea of placing isolators beneath for reducing the inter-storey displacements?

Calvi: Changes affect both demand and capacity. In fact, if we change the situation, we modify also the capacity demand.

Reinhorn: Was there anybody in charge for modelling and data analysis? What is the role of modelling?

Calvi: Modelling increases considerably the possibility of having good data, but the interpretation of measured data is still a concern. We are lucky if, at the end, we have measures at the right positions.

Reinhorn: We are happy when an experiment doesn't follow exactly the simulation; this means that with that experiment we are learning something new.

Bursi: A special care on the quality of acquired data must be considered for EFAST project. Error propagation analysis in fast testing methods is missing today.

Testing needs according to IAEA

Pierre Sollogoub (IAEA – Austria)

Presentation

There are some open problems in the field of nuclear safety. There are evidences of a seismic hazard at the site higher than the design earthquake due to new or additional data. Sometimes there is a lack or inadequate seismic design, generally due to the age of the facility. Seismic design approaches are in evolution with emphasis on margins evaluation, fragility quantification for structures, systems and components, risk-informed design. In order to prevent the consequences of cases such as the K-K accident in Japan, the safety margins need to be better known. Fragility testing requires high acceleration capacities, control capability until failure and testing methodologies and procedures. There is also a strong need for the development of new approaches (as for example base isolation and damping devices) and for validation of upgrading techniques. Nuclear core components are heavy with large dimensions, so large testing facilities are needed. These needs request a facility that should be large-scale, in real time, with controlled input until failure, with high level of input. It should be used also for qualification of active components.

Questions

Ohtomo: Do you think that vertical displacement is important?

Sollogoub: Yes, it is important for equipment. In any case, even if it will be not relevant for all tests, it is an important feature that the new testing facility should have.

Testing needs for soil-structure interaction

George Gazetas (Univ. Athens – Greece)

Presentation

The presentation deals with old and new needs for understanding better the Soil (Foundation) Structure Interaction (SFSI). It is very important to understand the strong foundation inelastic behaviour: this is especially true for slender structures, soft soils and strong shakings. Taking into account the real behaviour of the soil will allow assuming a more realistic structural behaviour, so making the design cheaper. It is also important to study pile foundations, caisson foundations, deeply embedded foundations with basement walls. Another important aspect is to be able to simulate liquefaction and soil "flow" and their effects on piles, structure, etc. A state-of-the-art large scale facility should be capable of reproducing the SFSI at least at a scale of 1:4. So, large laminar boxes are needed. There are several options for laminar boxes, but no perfect solution exists. Laminar boxes with Plexiglas walls are very useful because they allow to see what is going on and to take optical measurements. Rigid boxes are only useful for calibration of numerical models.

Questions

Pavese: How can you scale the hydrostatic pressure inside the soil?

Gazetas: You can adjust it effectively only with centrifuge facilities, but you can also add some loads on the soil surface.

Pavese: What is the requested minimum dimension of the shaking table for avoiding scaling problems?

Gazetas: Scaling problems in soils are surely greater than for structures.

Pavese: Do you think that it is possible to simulate the boundary effects between the edges of the laminar box and the ideally remaining soil?

Gazetas: In geotechnical engineering we are not so precise, a large laminar box is sufficient.

Taylor: You can also have active controlled walls using actuators.

Politopoulos: These actuators can give damping problems when used for vertical testing.

Testing needs for Civil Protection

Mauro Dolce (Civil Protection – Italy)

Presentation

The presentation gives an overview of the Civil Protection activities. It summarises the experience in the prevention, event and post event phases. An extensive description of the research project conducted in the past years is presented with focus on the development of protecting devices. The main needs for further research in the prevention phase are related to the behaviour of non structural elements, of the inside objects (as for example cultural heritage, high social or economical value instrumentations, dangerous furniture, etc.) and of the infrastructural systems. For the event phase the main need is to be able to properly monitor the soil and the structures (optimisation of the instrumentation and parameter identification and calibration for remote damage assessment). Regarding the post event phase, it is important to evaluate the residual strength of slightly and severely damaged structures, to evaluate the effectiveness of provisional works, to study the safety of temporary shelters and finally to study the possible seismic rehabilitation of damaged structures.

Questions

The presentation was very exhaustive and did not leave room for questions.

Testing needs for civil infrastructures

Livia Pardi (Autostrade – Italy)

Presentation

The first part of the presentation describes the Autostrade S.p.A. group and its activities. Then the needs are specified. First of all there is a strong request for further experimental and theoretical studies on the seismic response of bridges and viaducts with special attention on the three-dimensional character of their response, the constraint devices, the flexibility of their foundations and the actual behaviour of the most critical elements. Soil-structure interactions and non-synchronous ground motions must also be deeply investigated. This is true not only for the new bridges, but also for the existing ones due to degradation and higher demand level (for increased traffic, for increased seismicity etc.). Testing in deteriorated (corroded) specimens is also needed. Finally, anti-seismic devices must be developed and tested. In the final part of the presentation some case studies are described.

Questions

Renda: Regarding the assessment of the residual life, is it important, in your opinion, being able to perform asynchronous tests?

Pardi: Yes, I think so.

Molina: The seismic hazard maps have been changed. How do you assess old structures within the re-evaluated zones? Are you able to do a new assessment without experimental testing?

Pardi: We are trying to assess old bridges and other structures by experimental testing on old components, but it is a difficult task. It is much simpler with new structures.

Future of EUROCODE8 and interaction with experimental needs

Eduardo Carvalho (GAPRES – Portugal)

Presentation

After a brief overview about the Eurocodes and of Eurocode 8 in particular, some open questions are presented. The priority for Eurocodes is now to come into force by 2011, but further improvements are needed is several parts. Regarding specifically Eurocode 8, these aspects require a deeper experimental research activity:

- buildings with flat slabs should be further tested for eventually increase their class of ductility;
- the use of precast RC elements in floor structures needs to be codified;
- national parameters for masonry must be further harmonised, reducing their number to a minimum;
- the out of plane behaviour of masonry structures and rules for "simple buildings" should be assessed;
- the beneficial role of infill in framed structures is still not taken into account;
- some aspects strictly connected with the numerical activity are the improvement of provisions for response in torsion and irregular in-plan structures, soil-structure interaction, displacement-based design for new buildings, non structural elements behaviour.

Questions

Blondet: Which type of masonry does the Eurocode refer to: reinforced or confined?

Carvalho: Three types of masonry are present on the Eurocode 6: reinforced (with vertical or horizontal reinforcements), not reinforced and confined (with vertical parts or precast). Materials can by stones, bricks or blocks. For low seismicity zones non reinforced masonry is allowed.

Blondet: What are you wishing to test?

Carvalho: There are a lot of national determined parameters, such as the number of stones, or the selection of shear or compression for the design, that must be harmonized. It will be useful to try to make the parameters converge to a much smaller number. It would be important also to consider and validate the different national design methodologies. The focus now is to put the Eurocodes in force and, afterwards, try to improve them with experimental verifications.

Zapico: Soil-structure interaction and response in torsion are handled in an analytical or numerical way. May the experimental approach be interesting also?

Carvalho: It might be interesting but the problem must be treated first in an analytical way because it is very complex. It is the case of the "accidental" torsion, for example, that appears in some structures that are meant to be symmetric when they are not. Often, the strength eccentricity is different from the stiffness one.

Molina: What are the technologies that may have some advantages and disadvantages in earthquake engineering testing? Can you give us some advice based on your experience as a laboratory manager?

Carvalho: Shaking table and PsD tests have their own merits and applications. The best think would be to do not scale the specimen, so use a 1:1 scale factor. But the shaking table has the problem of the limitation on the weight and mass and running a test of a big specimen at a high velocity may result really expensive. Since it is not possible to change the specimen construction material, we must use scaled specimens. This implies further limitations. On the other hand, using the PsD method, the problem with the mass disappears. The need of power is smaller as the test is carried out much slower. In any case there are advantages and drawback in both methods.

TESTING DEVICES MANUFACTURERS

MTS

Allen Clark, Bradford Thoen (U.S.A.)

Presentation

The presentation begins with a presentation of MTS activities, then some examples of realisation in the field of earthquake and civil engineering testing are presented. The main focus is on shaking table testing facilities. The second half of the speech deals in details with the current technology of MTS systems. This technology was developed during a long time with some of the most prestigious university in the word. A SCRAM Net (Distributed Shared Memory) Network is used to connect controllers, acquisition nodes, simulation nodes and MATLAB workstations in real time.

Questions

The presentation was very exhaustive and did not leave room for questions.

MOOG

Fausto Argeri (Italy)

Presentation

The presentation shows some examples of realisation in the field of earthquake engineering with special focus on the pseudodynamic testing method. The actual technology of MOOG systems is described. The MOOG actuators are driven by a digital controller connected with the pseudodynamic algorithm. An agreement between JRC and MOOG was signed in 2006 to promote pseudo-dynamic testing in several research centres (currently they are 4).

Questions

The presentation was very exhaustive and did not leave room for questions.

INSTRON

Glen Wardrop (Germany)

Presentation

The INSTRON activities in the field of earthquake engineering testing are briefly presented with some examples of realised testing facilities. The related technology is described. The final part of the presentation describes the developed software for testing and for acquisition and treatment of the measured data.

Questions

Molina: Do you have experience in the combination of several shaking tables?

Wardrop: No.

Molina: Do you have experience in the control of shaking tables with more than one DoF?

Wardrop: Yes, we have that experience and it works very well in the automotive sector. However, it takes a lot of time to tune everything to make it work properly.

3 March 2009 morning

TESTING METHODS AND TECHNOLOGY

Challenges in distributed and collaborative testing

Keh-Chyuan Tsai (NCREE – Taiwan)

Presentation

The first part of the presentations contains an overview of the NCREE experimental and numerical activities on collaborative hybrid tests, numerical simulation platform, substructure and distributed tests, field tests. The second part deals with the open challenges and problems in seismic testing, in particular the necessity to impose proper boundary conditions, the requirements for performing real-time or fast hybrid simulations and the need to take into account the possibility of expansion of the existing facility. Experimental techniques should be coupled with proper computational and visualisation tools that can provide simultaneous 3D display in platform for networked structural experiments. A detailed description of the extension of the existing testing facility is given. The MATS (Multi-Axial Testing System) testing facility concept is illustrated as an example of hybrid testing. A discussion about the existing problems in hybrid testing and fast hybrid testing techniques concludes the presentation.

Questions

Renda: You raised the advantage of sub-structuring and hybrid testing developed in house. According to your experience, is distributed testing important when performed in many laboratories? Are you able to run hybrid testing in your laboratory? And, once one is able to run hybrid testing, is it difficult to pass from hybrid to distributed testing?

Tsai: Distributed testing and hybrid testing are important when it is too expensive to test the full structures. In that case the structure is cut in two parts. The biggest problem is how to impose the boundary conditions. The advantage of distributed testing is collaboration, working together, exchange of ideas between partners. You need also a good structural model to justify distributed testing. Is not difficult to move from hybrid testing to distributed testing, as long as there is an Internet connection. The main improvement is that test data will be automatically recorded. This will revolutionize the test: all data are available in real time.

Bursi: Does the assumption of damping affect the results of test? Why was the issue raised?

Tsai: The assumption on damping depends on the quality of the experimental set up. Each design will vary in its quality. Low cost designs may introduce friction, resulting in data recorded from the test being contaminated. It is important to identify the sources of friction because this will determine the assumptions on damping.

Molina: My question concerns real-time hybrid testing on aspects regarding hardware. In general hybrid testing is not very appropriate (with current technology) to study degradation. Most hybrid testing studies have been performed on simple systems that do not change (remain almost linear). Then, having this limitation in mind, what could be the real application of real-time hybrid testing with current technologies?

Tsai: We do no have a lot of experience on real-time testing. When there is sudden failure of a connection there is a sudden drop of the restoring force, which a fast hybrid algorithm may not be able to handle. A sudden degradation may be difficult to handle.

Open questions on multiple shaking tables and reaction walls

Andrei Reinhorn (Univ. Buffalo – U.S.A.)

Presentation

The presentation starts from classical hybrid simulations testing techniques and arrives to more advanced real time dynamic hybrid simulation schemes. Reasons for the need of real-time simulation include the appropriate representation of strain-rate effects, inertial effects and the behaviour of non structural elements. This technique is evolving and refining, but some challenges are still present: actuators providing forces at the boundaries must move as dictated by the base motion, but must provide small relative drifts (difficult to control accurately). Implementation of displacement or force commands requires accurate models of hydraulic (nonlinear equipment). Complex interface forces, moments and torques increase the number of necessary actuators and synchronization issues. Computational substructures must be solved in “real-time” at rate of excitation or faster – particularly challenging are large structures and nonlinear structures; synchronization is possible but requires compensation for inherent time delays in physical implementations. Computing acceleration at base boundaries must include the effects of earthquake excitations and of the mass system above. Explorative approaches divide into physical (through hardware) and computational ones and have been studied at SUNY in recent years. Another important discussed issue is the synchronisation of two shaking tables. They can operate separately or can be connected and driven together for large experiments.

Questions

The presentation was very exhaustive and did not leave room for questions.

Design and construction issues of a shaking table array

Wensheng Lu (Univ. Tongji – China)

Presentation

After a short overview of Tongji University activities, the existing shaking table facility is described. This facility is now insufficient for the current needs in China, for instance to have a multi earthquake excitation for testing great-span bridges, lifeline engineering and other great-span structures in civil engineering. These reasons push for the conception and realisation of a new shaking table array facility (3Dof tables). The main characteristics of the new installations are then described and discussed. For example, they expect to have a phase lag of some 5 to 10 degrees between the responses of two shaking tables.

Questions

Geradin: What is the budget of the project?

Lu: 80 million dollar for design, construction and devices.

Bursi: Was there a competition for the choice of the shaking table provider? Or was the choice direct?

Lu: 3 years ago there was a bidding process in the world: 5 suppliers responded and only 2 were technically feasible, offering support and financial quotations. MTS got the job.

Pavese: Was the reaction mass determined by the total mass of tables? If the total reaction mass is of 30 thousand tonnes, the associated cost is 21 million euro, which is a large sum. Why did not you consider a lighter mass with a different system of isolation? Or was the mass determined by geometric constraints?

Lu: The old shaking table was 4x4 m. The new tables for bridge testing are 4x6 m occupying a total area of 30x70 m: for performance reasons this geometry required a mass of concrete much larger than that strictly necessary.

IT challenges in EE cyberinfrastructures

Lelli Van Den Einde (UCSD – U.S.A.)

Presentation

The presentation focused on the technical characteristics of NEESit and on the implementation problem that the project has encountered up to now. The analysis of these drawbacks stimulates several recommendations. It is necessary to get the community to shift culture to more collaborative, multi-disciplinary, highly distributed teams. In order to stimulate the use of the data repository, it is better to offers "carrots and sticks" to encourage usage and participation. The database should be targeted to a heterogeneous earthquake engineering community, with different levels of sophistication and requirements. A balance between academic IT development and production quality software development must be achieved. In the final part of the presentation, a detailed list of available IT resources for software and resources is presented. Most of them are based on an open source philosophy, so they can be downloaded and used by all the users.

Questions

Reinhorn: To deal with requirements and solutions separately is a mistake, they are strictly interlaced and must be jointly analysed.

Molina: Do you have any recommendation for Europe?

Van Den Einde: You should develop open source tools and to be ready to collaboration, to share. Deal with every user case by case and do not try to arrive at a consensus. Database should be centralised if they are not supported locally or should be decentralised if they are supported locally.

Sollogoub: How are available IT resources used?

Van Den Einde: The data are usually inserted into the database with some delay, it takes time before people put their data into the database. The data utilisation is also usually difficult. Every NEES partner should put their data on the database, but this does not always happen easily. So, the actual strategy is to adopt a founding mechanism related to the fulfilment of this request. Data repository can be accessible at different levels to different users with different rights (for example access restricted to project partners). About telepresence: it is especially useful after the experiment for observing the test.

Questions raised in operating a very large shaking table

Keizo Ohtomo (CRIEPI – Japan)

Presentation

A brief overview of the E-Defense shaking table facility is presented. The main expectations from such a large facility are to be able to characterise the structures up to the complete collapse and to eliminate the scale effects. Some problems still persist as, for example, those related to the boundary conditions (of buried structures, of soil and shallow foundation interaction, of soil and deep foundation interaction etc.). Another point is that a collapse test usually needs a support frame as well as a structure being tested. If the support frame is designed rigid enough so that it prevents the spread or the tilting of a target structure, the support frame may occupy a large part of the test set up and contribute significantly to the payload. Sometimes it can be difficult to simulate the desired ground motion if the specimen mass is huge and if its response is highly nonlinear. The development in the field of substructure hybrid testing for underground structures concludes the presentation.

Questions

Bursi: The shaking table runs in feedforward or feedback mode? Is there a parallel hybrid calculation?

Ohtomo: The shaking table works in feedback.

Reinhorn: Are there a reaction force measurements?

Ohtomo: Yes, we obtain them from the shaking actuators measuring acceleration, velocity and displacement.

Sollogoub: Was there any interesting outcome by studying non scaled structures, i.e. with scale 1:1?

Ohtomo: The soils-structure interaction tests are always influenced by the boundary conditions.

Pavese: Could you please quantify the costs of a test on the E-Defence shaking table?

Ohtomo: The public authority pays for tests.

Testing of seismic protection devices

<u>*Agostino Marioni*</u> (ALGA – Italy)

Presentation

The main standards for anti-seismic devices are commented at the beginning of the presentation. Two types of classification are described: the first is related to the performance of the devices, the second one on their type. According to these classifications, standards require specific tests. ALGA has an experimental laboratory for the most common production tests. For non common products or for research purposes the tests are performed at Eucentre, where a dedicated testing facility is operative for these devices. For exceptional products, however, only one U.S.A. laboratory is suitable. Moreover, the demand of tests on anti-seismic devices will tend to increase with entering in force of the European Standard EN 15129 and the increase of the number of structures incorporating such devices. The need for a facility that can perform such kind of tests is evident.

Questions

Reinhorn: What happens if the quality control tests give negative results? You will do additional tests?

Marioni: If the quality control tests fail, the number of tests is increased; if it is still negative, the whole lot is eliminated. This procedure is codified in ISO standard rules.

Reinhorn: Do you perform tests during the life-time of your devices?

Marioni: Ageing simulation tests are foreseen only for rubber materials. Fatigue and wear tests are requested for the seals of hydraulic systems.

3 March 2009 afternoon

Visit to the IPSC ELSA laboratory

The visit includes a presentation given by Javier Molina about the main historic achievements of the laboratory. Then, the ELSA researchers give explanations about the devices and specimens in place.

ROUND TABLE ON TESTING NEEDS

Chairman: *Pierre Pegon* (JRC – EC)

The elaborated text of the agreed document of the first round table is given in the conclusions. Some of the personal comments expressed during the discussion were the following:

Carvalho: Masonry structures on real scale have been already tested with the Pseudodynamic method at JRC. Tests with shaking table have been realised on scaled model or limited portions of the real structures. A large shaking table facility could sensibly improve our knowledge on these type of structures because it will allows to test up to 2 or 3 storeys masonry building in both directions. Large scale tests are especially required for validation. Masonry and infills should be tested in shaking table because of gravity forces and out-of-plane effects. European techniques and materials are very different, so many tests are foreseen. This kind of tests could be very expensive, we should have cost-effective tests. Soil structure interaction it is also a very important subject. Scaling problem in this field are even more important than with masonry structures.

Zarnic: Tests on new materials are necessary. Full scale tests can be very useful to evaluate the global behaviour of a part of a monumental structure retrofitted with new materials: it is important to know how they work together.

Pegon: You said yesterday that it is very difficult to reproduce a cultural heritage structure into laboratory. So, why do you think a new testing facility will be important for that sector?

Zarnic: We must convince the restaurateurs that new techniques and materials can be effective. Architects want to insert new materials, restaurateurs don't want, as engineer we have to demonstrate that these new materials and techniques are good.

Taylor: Tests on piles conducted on 1:20 scaled specimens: the general results were quite good. Probably is more important to study the mechanism of the soil with a bigger box facility.

Blondet: There should be promoted collaboration with poor countries for testing their houses. Access should be given to the facility. Collaboration is important. Remember the cost of maintenance of a big platform.

Pavese: PsD and Shaking Table capabilities should be included, but this is the last step, before is necessary to make any preliminary study for proper evaluation of the correctness of the experimental conception (numerical simulations, preparatory tests etc.).

Negro: A unique facility cannot solve all the problems. European laboratories have always collaborated, so probably is not necessary to have a big facility where all tests can be performed, but it is more important to develop telepresence, distributed tools and so on, all that is collaboration between laboratories.

Pegon: EFAST will not cancel what is already present in Europe.

Reinhorn: We are strong sustainers of the open-source philosophy for gradually improve our knowledge. We developed OpenSees for this purpose. A close interaction with the numerical capabilities should be guaranteed. The more sophisticated will be the platform, the simpler will be the structure that you can really test without being involved in errors.

Taylor: Numerical capabilities will sensibly increase in the future. Flexibility is also very important.

Tsai: Think at expandability as well.

Van den Einde: The foundation of the facility must be larger than required in order to accept future amendments.

Sollogoub: The future testing facility should be flexible and multi-input. 3D excitation capabilities are important for qualification tests. For example, it is very important to be able to study the control loop system that stops the nuclear reactor. This system is complicated and probably will be changed on the new nuclear power plants so the new platform must be flexible. It is important to have high accelerations, high velocities and high displacements; testing frequencies must be higher than 20 Hz (i.e. those possible till now).

Reinhorn: 30-50 Hz is what is requested in American standard.

Voldoire: Full scale testing is important for reproducing local effects, boundary conditions must be well considered.

Politopoulos: Vertical excitation is important? How much? When?

Sollogoub: The fact that we are not sure whether vertical excitation is important, pushes towards a deeper research about it. Independently to nuclear power plants, in the past there were some important failures that can be explained only by considering also the vertical acceleration. Consider also the case of slabs, where some important instrumentation (as the electrical ones) is placed: it is important to consider the effects of the vertical acceleration. In transportation structures it is important to be able to perform 3D shaking table tests in order to account of everything.

Lu: Qualification tests require accelerations of up to 4g and working with relatively low payload. Frequencies should be between 0.1 and 50 Hz. In general is not important to have simultaneously high velocities and high accelerations. Heating and ageing effects should also be considered.

Marioni: There is a lack in the laboratories regarding the possibility to have high testing speeds. There are no labs capable for testing high performance devices at 2.2 m/s as requested by European standard and reduced-scale models are not valid because of the heat phenomena. Factories cannot perform exceptional tests.

Pavese: Eucentre has 1.7 m/s velocity. Lack is in velocity and acceleration. Even if standards have specifically requirements for some specific tests, if the will be performed only 1 or 2 times a year, there is no interest to spend money to perform such a reduced number of tests.

Marioni: This is true, but in this way there is not solution because scaling is not possible.

Pinto: Non-structural elements must also be mentioned. Do we need something more, i.e. a new platform, or must we use better the existing facilities to test these elements? Probably it is more important to make the results of our tests available to all the community, not only at the university level. We should give a relevant educational role to the facility, we must think well about the impact of our research.

Geradin: Testing of new construction techniques and materials should be included, as for example structural glass.

Voldoire: We need more to identify the boundary conditions between the shaking table and the structure. We must control better the motion of the shaking table. It is important to control the reliability of the tests. Special tests are needed for this.

Reinhorn: We should improve the application of the image technology learning from the medicine diagnosis applications. Real-time data viewer is very important: the role of real-time must be a very important task. From the safety point of view, the collapse of the structure must always be foreseen and a catch system must be implemented.

Tsai: We also are developing instrumentation and techniques for optical measurements.

Pegon: An important point is also to foreseen a protection system for the shaking table when tests arrive to the structural collapse.

Ohtomo: Numerical analysis is important before the tests.

Taylor: We must also pay attention to the generational overturning of the researcher.

Pegon: A team should conduct the new testing facility.

Renda: The facility should offer full-scale testing for developing countries. It must be integrated with the existing ones but going beyond.

Taucer: The databases should be complementary among themselves.

Taylor: Each test reveals the known unknown but also the unknown unknown.

Ohtomo: Scaling problems are very important, but also detailing aspects should be considered carefully.

ROUND TABLE ON TESTING METHODS AND TECHNOLOGY

Chairman: *Georges Magonette* (JRC – EC)

The elaborated text of the agreed document of the second round table is given in the conclusions. Some of the personal comments expressed during the discussion were the following:

Magonette: We need your comments. Not all technical aspects can be defined now, but we need to have some ideas from you. There are many possible solutions and possibilities are very broad. For example are there some advices concerning the working space?

Sollogoub: You need to be able to construct the specimens not so close to the testing space and to transport them on the shaking table.

Queval: It is important to have working space around the facility to be able to fix actuators and equipments.

Negro: The transportation system for the specimens in the lab must be a part of the design. The actuation system must be flexible.

Magonette: It also very important to have a dedicated area for demolition.

Dorka: The facility must be as large as a football court and part of it without any roof. We should have some green spaces around the laboratory to be able to extend it.

Politopoulos: For soil-structure interaction it is very important to have a very big shaking table and very stiff. A low deformation is necessary to perform accurate tests.

Magonette: There is the need for a strong coupling between the experimental and the numerical activities. Not only the staff, but also the computers much be coupled.

Zarnic: The ECTP can give support to the EFAST facility promotion and financing within the 8th FWP. The facility should be extended to research in protection against other types of disasters.

Magonette: We must discuss about the general structure of the testing facility. For example, we need one large 1D shaking table or a 6 DoF for nuclear purposes?

Reinhorn: Real-time (dynamic) substructuring has added value even when it cannot be applied to specimens submitted to degradation. It is worth to have at least the hardware capabilities for this kind of tests.

Molina: We should first clarify which technology we want to apply. We may agree that, regarding the Pseudodynamic testing, we have already in Europe what we need. The ELSA laboratory is at the highest level in the word. So the proposal of CEA of a shaking table is the most suitable.

Geradin: The most versatile tool would be an installation with multi-axial excitation and strongly coupled with numerical simulation. It is a problem that each team develops software in its own environment and this might create problems. On the other hand the new testing facility should provide something that does not exist in Europe.

Dorka: There are nice shaking tables around the world and they should cooperate. It is a mistake to double something that already exists. With good software we can simulate successfully ground motions and environments. We have to see how to connect the system to high power software.

Politopoulos: I must remember that EFAST is a design study. There is no much room for research; we must use the state-of-the-art in this field.

Clark: The proposal of CEA comes from a feasibility study, so it is based on the state-of-the-art. If we want to test a real building which should be shaken at the foundation, may be the SDOF system is interesting.

Reinhorn: The versatility is the best approach, for example using some 20 small shaking tables that can be eventually linked with space trusses. Further studies are needed to fully synchronise the shaking tables. At this preliminary stage it is important at least to estimate how much to extend the testing facility. The foundations should reflect it. Several solutions can also be considered.

Sollogoub: Flexibility is important. The nuclear sector asks for a rigid shaking table with 6 DoF. The rigid requirement is especially needed for qualification tests.

Magonette: A good balance between what is actually requested by our costumers and the adaptability to new testing techniques available in the future must be searched.

Reinhorn: We have a facility for quality testing. In the meantime we are developing the hardware to be ready for new developments.

Tsai: We recently decide to upgrade the controllers, we are investing on them. Technology is now ready for using shaking tables in hybrid testing.

Molina: Does people operating shaking tables know what instrumentation is needed to assure the quality of the tests, for example in order to measure the amount of pitching?

Reinhorn: We should distinguish between qualification (demonstrative) and research (exploration) tests. For the latter we should measure all the motions of the table and all the responses of the specimen. All the possible inputs produced by the shaking table should be measured. Image techniques should complement the measurements. For qualification tests the weight of the specimen must be smaller in order to guarantee better accuracy in the input, these tests are usually the most critical and difficult.

Taylor: Adaptable control improves the situation but non-linearity is difficult to compensate with a fast adaptation. The quality of the piston bearings is very important.

Reinhorn: We have reference traceable load cells that we use to calibrate our cells. Our load cells are constructed by ourselves. The possibility of having load cells embedded in the system must be studied.

Lu: It is important to consider also the possibility of testing real structure outside the laboratory. We should improve our devices which can be used for in-situ testing.

Carvalho: The design study must consider the constructions costs as well as the operational costs.

2.5 CONCLUSIONS

The discussed matters during the two round tables were summarised during the post-workshop meeting held on the 4th of March 2009 at ELSA laboratory. This meeting was attended by all the partners and the three members of the Scientific Committee. The draft document prepared by the chairmen of the two round tables held the day before during the 1st EFAST workshop was analysed and discussed. Participants suggested amendments and improvements of the proposed text. What follows is a more elaborated version of those documents.

ROUND TABLE ON TESTING NEEDS

The elaborated text of the agreed document of the first round table contains the following points:

- A better knowledge of the behaviour of flat-slab buildings, pre-stressed framed structures, masonry structures, structures with masonry infills, cultural heritage buildings and bridges is needed. In particular:
    i) **For Eurocode8** a very important issue are masonry & masonry infill structures with more than 2 storeys. These structures can be tested with the pseudodynamic method, but, because of their distributed masses, the best choice is probably to test them on a shaking table if it can be done in real size. Several tests should be conducted because of the variability of construction techniques and materials.
    ii) **For cultural heritage** a main need is to test structures retrofitted with innovative techniques.

- A stronger validation and closer harmonization for **Eurocodes** national parameters. This is a short term need in the sense that it should be fulfilled in the following years, so probably with the existing testing facilities. Nevertheless, to achieve these goals, further studies regarding assessment and retrofitting of buildings are needed. Full scale and multiple-support test are also requested. Most of the tests on large-scale specimens are needed for demonstrative purposes and are more feasible pseudo-dynamically because of the difficulties and cost of dynamic tests on huge specimens.
- Access to the facility by **emerging countries, with low cost,** must be facilitated (for testing, for example, one storey stone houses in real scale).
- **Soil-(Foundation)-Structure Interaction** (S(F)SI) must be deeply studied. Tests must be as close as possible to real scale in order to avoid scaling effects; this means using large boxes (for example: height 4 m, length 8 m, depth to be specified) + the

specimen. Even with such large bows, it is unlikely that pile tests will be feasible on a shaking table. In same cases the pseudo-dynamic method can be used or tests can be done, with a dynamic shaker or outdoor, on a real soil to provide suitable results for calibration of numerical models. However this type of tests cannot deal with the full interaction problem since the input is imposed to the structure thus disregarding the kinematic interaction.

- Some requests are specific for **nuclear industry**: there is a need to test structural components & equipment & processes (both for demonstrative full scale aspects and for a better understanding of the behaviour in the non-linear range). Vertical acceleration and floor amplification are very important. Due to floor amplification, components must be tested with high acceleration (4g) in the frequency range form 0.1 Hz to 50 Hz. Vertical excitation must often be taken into consideration (3D tests). The behaviour of tanks, vessels with fluids, complex connected slender structures as well as S(F)SI are some key points for nuclear industry.
- Some important aspects related to **secondary structures** (sensitive equipments "integrated engineering systems", high value equipment) must be addressed. These complex structures are characterised by having multiple supports, this fact affects the overturning moment and payload.
- It is important to be ready for the **qualification** of protection devices. There are only a few high capacity demanding tests required by codes. The remaining, less demanding tests, are carried out either by the manufacturers themselves or in the existing facilities. However Europe should get the capacity for doing also these large scale tests in the future.
- Jointly with the experimental activities, it is important to assign importance to pre-test, post-test and between tests **computation** in order to better conduct the test (design of the specimen and the set-up, analyse final but also intermediate results, asses the quality of measurement and detect probable improper function of a sensors etc.). This work may be done in the experimental facility itself (if there is sufficient computational capability) or by networking in cooperation with specific computational facilities or other laboratories. This stresses the importance of networking & complementarity.
- It is very important to have a proper acquisition system and a proper network of sensors. New measurement technologies should be also considered that allow **field measurements** (optical measurements, but not only).
- To conduct a meaningful probability risk assessment available actual margins of the structures have to be estimated. To this end tests with high excitation level up to collapse or resulting in a relevant significant damage level must be carried out. This implies that the new facility should have the capability to reproduce high intensity excitations (high acceleration, velocity and displacement).

- The research community asks for more exhaustive and reliable results and needs to maximize the **impact of research**. To easily share the data, new "Informatics Technologies" (IT) should be adopted.
- Last but not least, a better use of **existing facilities** and **integration** with EFAST should be foreseen. Once more, the importance of networking and cooperation is pointed out.

ROUND TABLE ON TESTING METHODS AND TECHNOLOGY

The elaborated text of the agreed document of the second round table contains the following points:

- A key feature of the future testing facility must be its **versatility**: wide working space, adequate room for construction, an outside demolition area, possibility to extend the laboratory accordingly to future needs, capability for applying **multi-axial loading** and for **substructuring** testing. The possibility of some outdoor tests should also be investigated.
- The initial design of the facility must enable future extensions and improvements (for example: only 1 DoF is realised at the beginning, but basement is already prepared for 6 DoF, so the facility can be upgraded in a following time).
- It is important to have a strong coupling between the experimental and the **numerical** aspects. Software **harmonization** should be promoted.
- Information, **dissemination** and **collaboration** must be stressed.
- The reaction wall could be conceived as composed by **modular** and **light** elements so that to enable modification of its configuration depending on the requirements for different tests.
- Uni-axial, bi-axial, tri-axial and **6DoF** shaking table facilities are needed for different kind of tests, but for Nuclear Industry qualification tests a rigid 6DoF is compulsory.
- Even if fast and real-time **substructuring** (hybrid) techniques are still under development and yet impossible in practice for degrading specimens, the new testing facility must be designed taking them into account, so having the required hardware capacity to do it.
- Besides the main testing facility, some **dedicated Testing Facilities** (MATS - Multi-Axial Testing System, testing of non structural components) should be considered. If the aforementioned machines are not constructed from the beginning, the design of the facility must be thought so that they could been integrated in a second phase.
- During the design phase of the new testing facility, **networking** should be considered.

- The **spurious pitching** (and other input errors) of the shaking tables must be minimized at the best today attainable level for qualification tests. It must be bounded between reasonable values for other tests and in any case it should be always measured and reported.
- **Instrumentation** issues should be studied jointly with the design of the testing part of the facility in order to have a proper calibration hardware and software: some certified elements, some partially certificated elements, optical hardware and methods for field measurements.
- A special care must be devoted on the estimation and quantification of the **construction costs** and of the **maintenance costs** (all aspects must be considered: infrastructures, operation costs, the numerical and IT tools and teams etc.)

3.STATE OF THE ART AND FUTURE DIRECTION IN SEISMIC TESTING AND SIMULATION (UNI KASSEL)

The main objective of Work Package 3 (WP3) is to study various advanced testing and simulation methods for possible application in the new E-FAST facility and to develop the criteria for the equipment of E-FAST deriving from them. The methods studied in this context define the tasks in WP3:

- Task 3.0: Specimens with multiple shaking tables. All partners.
- Task 3.1: Substructure testing with shaking tables. UNIKA, CEA, EUCENTRE.
- Task 3.2: Combining shaking tables with other on-site facilities. EUCENTRE, CEA, UNIKA, TUIASI.
- Task 3.3: Geographically distributed testing. JRC, CEA, UNIKA.
- Task 3.4: Instrument and data acquisition systems. CEA, EUCENTRE, JRC.
- Task 3.5: Cost evaluation of protocols development. CEA, Eucentre, TUIASI.

This report on the "***State of the art and future direction in seismic testing and simulation***" is deliverable D3.1 of WP3 and is organized in 5 chapters, each elaborating on the topics that are dealt with in the above mentioned tasks.

For many years now the use of shaking tables has improved our knowledge about the behaviour of civil engineering structures, especially under seismic loading (Chapter 3.1). Large tables like E-Defence near Kobe, Japan, can test full-scale buildings of up to ~ 6 stories. Table arrays like the one under construction in Bejing, China allow multiple inputs at varying locations at the base of a structure. Still, all this sophistication and testing power still confines us to model scales since most buildings and bridges are much larger. In fact, the seismically vulnerable buildings are above 6 stories and are often irregular in plan and elevation. No facility in the world can produce reliable test results for such structures unless it can perform a so-called substructure test combining numerical models of a structure with specimens. Therefore, performing such tests (sometimes also called hybrid simulations) with shaking tables (Chapter 3.2) has recently gained more attention.

Slow motion substructure testing is already well established for other types of large testing facilities like the reaction wall of the ELSA laboratory at JRC Ispra, Italy. If acceleration and velocity dependent effects can be modelled even for the specimen, a pseudo-dynamic test is typically performed where actuators may not even run continuously (stop-and-go control). This reduces energy and capacity demand on the testing equipment and enhances observation. Where these effects cannot be modelled, dynamic tests, sometimes with extended or even shortened time scales (time scale defined here as testing time vs. real world time) are required. Shaking tables may be used in both, pseudo-dynamic and dynamic testing but are really made for dynamic testing, especially for time scale factors of 1 (real-time). This puts additional demands not only on the hydraulic system but also on the accompanying computers and time integration algorithm which is at the heart of a substructure test.

A number of time integration algorithms are available which can all be traced back to Zienkiewitz's finite element formulation in the time domain and applying a weighting function which defines a particular algorithm. The Newmark algorithm appears to be the most accurate in many cases and is therefore very popular. Its explicit form (which does not require the knowledge of values from the future and therefore can be applied in a straight forward manner) has a stability limit but can be used with small time steps on advanced control systems for pseudo-dynamic tests on most civil engineering structures. The implicit form is required in most dynamic substructure tests leading to a linear equation to be solved within each time step. To approximate the forces at the end of each time step which are required for the solution and are not know a priory, estimator-corrector methods may be used but simple digital feed back during the time step seems to be the most effective and versatile way since it does not require any prior knowledge of the specimen.

Unbalanced forces at the end of a time step and phase or time lag of the hydraulic system create instabilities in dynamic substructure tests. A number of currently available methods can handle these problems with varying degrees of success. The future here lies in adaptive compensation based on online system identification techniques. They have been applied in recent real-time substructure tests with shaking tables at the University of Kassel, Germany (UNIKA) and the TAMARIS laboratory at CEA Saclay, France.

Although this demonstrates the mature state of the algorithms controlling such tests, important challenges remain especially when large shaking tables have to be used. Current actuator technology for large tables still has phase lag or time delay in the order of several integration time steps (one integration step typically is 10ms for civil engineering applications). Even sophisticated adaptive compensators cannot handle this. New actuator concepts like hybrid electric-hydraulic actuators promise to improve the situation in the near future. The E-FAST project looks at these in WP4.

When shaking tables are used in combination with other testing facilities (e.g. reaction systems) or in arrays, typical standard table control is insufficient and may lead to control instabilities and loss of specimen (Chapter 3.3). The well-known "spurious modes" of a table may become un-controllable, for example. Furthermore, hydraulic actuators operating in real-time with current control technology are plagued by lack of fidelity in signal reproduction owing to distortion in the feedback signals by non-linearities in the servo-valves and sensors (dead-zones, backlashes and hysteresis). And there are effects from the specimen on the control, among which the presence of heavy resonant specimens, the changing (often sudden and abrupt) of specimen dynamic response during the shaking are only the more important issues.

To avoid such problems in standard shaking table tests, tuning of control parameters is nowadays performed before each test. Ideally, this process includes the specimen on the table, but this is not always possible, since even low-level excitation causes cumulative damage and if the operator makes a mistake, the resulting instability can destroy the specimen. But even with a good initial tuning, sudden damage during the test may lead to unsafe and dangerous loss of control of the table.

A virtual pre-test using numerical models for the testing system and the specimen is a new possibility to reduce this problems. It allows to address these control issues offline and thus avoids possible disasters. Software platforms like OpenSees are available for this task. Sophisticated testing system models have been developed for typical shaking tables and can be validated using system identification techniques (e.g. for the table at the TREES laboratory of EUCENTRE, Pavia, Italy) but the modelling of specimen raises a number of questions, since the behaviour of a specimen is largely unknown (otherwise: why test?), especially when a non-linear response is expected e.g. during a seismic test. A virtual pre-test program in the form of a sensitivity study may reduce this problem in some cases but this is very time consuming and not available in a standardised approach.

Geographically distributed testing (Chapter 3.4) is a particular kind of substructure test using geographically distributed facilities, sometimes even at "the other end" of the world like in a test performed between Koyto, Japan and Berkeley, USA. The biggest challenge is the communication which has to be secure enough to prevent any loss of specimen. Non-continuous pseudo-dynamic tests (stop-and-go) have been performed successfully using simple explicit integration algorithms. Continuous tests are still a challenge and real-time tests (none has been performed so far) may only be performed between facilities in close proximity (less then ~100 km) because communication cannot be faster than the speed of light.

The internet has been used initially for such tests but in the mean time several communication platforms and protocols have been developed notably by the NEES consortium in the US, NCREE in Taiwan and UK-NEES (UK Network for Earthquake Engineering Simulation) in UK. They have improved security and response time markedly. It is now possible to sustain secure communication within 20 ms intervals over a distance of 300km.

Because different facilities typically use different software for data acquisition, control and numerical simulation, software platforms that can integrate different facilities have been developed. Among them is UI-SIMCOR, a development within NEES, which may be the most advanced to date. It allows easy integration of different software (even proprietary) for numerical substructures and different time integration algorithms. The basic communication layer can easily be adapted to future developments which currently concern faster communication protocols like the recently developed NHCP (NEES Hybrid-simulation Control Protocol).

For possible integration of the E-FAST facility in geographically distributed testing, an advanced software platform like UI-SIMCOR is required. Still, only tests with extended time scales may be considered viable but are still a challenge. Continuous pseudo-dynamic tests are necessary, since the typical creep and relaxation effects in civil engineering specimens greatly distort the results of stop-and-go tests. A shaking table or array of shaking tables may be used in connection with a reaction system to apply displacements continuously to specimens that are not sensitive to acceleration and velocity effects and it is in this context that the future E-FAST facility should be able to participate in continuous geographically distributed testing.

The use of advanced instrumentation and data acquisition systems (Chapter 3.5) is an important requirement for the new E-FAST facility not only because there is a clear need to collect more and more detailed data (e.g. to validate complicated numerical models even locally), but also to improve the control of experiments. In this context, optical sensing technology and image processing has already reached a level that allows improved system identification and damage diagnosis in elaborate specimen. Also, a large number of distributed small-scale sensors (e.g. MEMs) even inside a column or wall are feasible today but place a huge demand on data processing to avoid the infamous "data grave yards". Another issue is the combination of experimental with numerical data, not only in the context of substructure testing but also when validating sophisticated numerical models with experiments which is of course on of the main purposes of large scale testing. New software tools are required in this context to give the user instant access to the wealth of information that has been created. Virtual reality environments are one technology that is already applied successfully in this context in other engineering fields but not yet in large scale testing of civil engineering structures.

3.1 SHAKING TABLES IN CIVIL ENGINEERING APPLICATIONS

Uwe Dorka, Van Thuan Nguyen, UNIKA

A shaking table implies dynamic motions to the base of a structural model. Shaking table testing has a wide range of applications in civil-, aerospace- and mechanical engineering.

In seismic testing, shaking tables are used to test the response of structures, structural components and mechanical or electrical equipment to historic or generated ground motions and to verify their seismic performance. The seismic loading, restoring forces in the specimen as well as inertia and damping forces occur in a realistic fashion. Thus the dynamic response of a structure to a seismic event can be reproduced truthfully.

Today, large hydraulic shaking tables are typically used for seismic testing. Modern systems consist of a sophisticated hydraulic actuation system (hydraulic pumps, accumulators, hydraulic pipes, control valves and hydraulic actuators), a rigid table with 1 to 6 degrees of freedom and an electronic control and data acquisition system with advanced software control that is able to adapt to changes in the specimen during testing.

There are more than 50 shaking tables in the world (NEA/CSNI, 2004) and they are distributed in Asia (Japan, China, Taiwan, Korea), Europe and USA. The largest are:

Figure 1.1 Testing of full scale structure on shaking table of E-DEFENSE Laboratory, Japan

- at E-Defence Laboratory in Japan: 20 m x 15 m table with maximum payload of 1200 tons, http://www.bosai.go.jp/hyogo/ehyogo

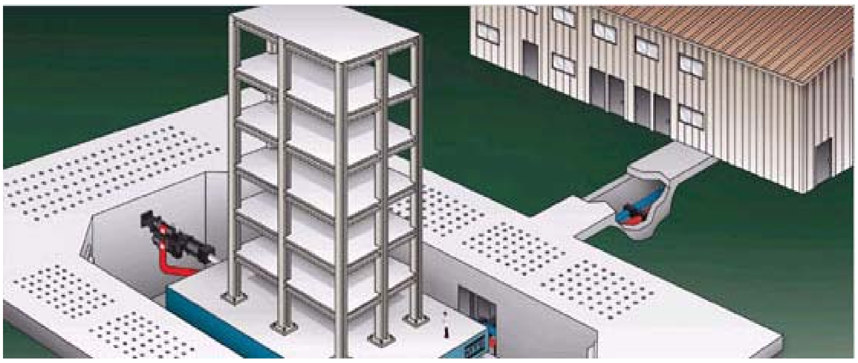


Figure 1.2 Outdoor shaking table at University of California, San Diego, USA

- at University of California, San Diego, USA: 12.2 m x 7,6 m table with maximum payload of 2200 tons, http://nees.ucsd.edu.
- in Europe the AZALEE table at CEA in France: 6 m x 6 m table with maximum payload of 100 tons, http://www-tamaris.cea.fr.

Although quite large and requiring a substantial effort to run, most existing seismic tables may only test scale models of actual buildings. Tall buildings or bridges cannot be tested directly at all. In some cases, such scale models are able to reproduce the performance of real structures quite well. This is the case when similarity laws can be applied. Because of the strong non-linear response of most structures under earthquakes, these laws cannot be applied fully in most cases and thus, the results of scaled seismic shaking table tests have to be treated with caution.

To test building structures realistically on shaking tables, the size and payload of tables need to be increased. Consequently, operating and maintenance costs will increase. And there is also the issue of excitation on multiple supports, like in bridges. Therefore, the concept of multiple tables that can work together in an array has been advanced in recent years. Some recent examples are:

Figure 1.4 Two-shake table system at State University of New York, Buffalo, USA

- the twin table system at University of Buffalo (USA), http://nees.buffalo.edu

Figure 1.3 Thre-shake table system at University of Nevada, Reno, USA

- the three-table system at University of Nevada, Reno, http://cceer.unr.edu/
- the three-table system at Pusan National University, South Korea, http://english.pusan.ac.kr

- a set of four moveable tables at Tongji University in China (under construction). http://www.tongji.edu.cn/english/Research/index.asp
- multiple tables at Beijing University of Technology in China (under construction) http://bjut.edu.cn/bjut_en/index.jsp

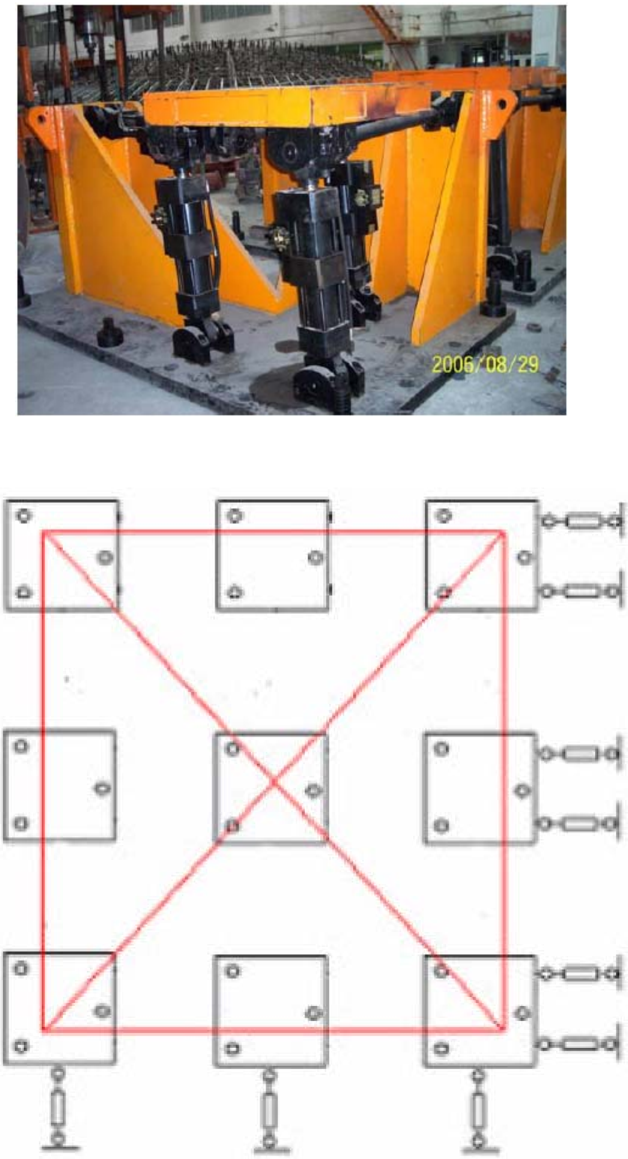


Figure 1.5 Shaking table array at Beijing University of Technology, China (top: single shaking table, bottom: one possible configuration, Lu *et. al*, [2009]

Combining shaking tables with other facilities such as reaction systems is known as a good option for new large testing facilities. Moreover, substructure testing allows the expansion of the testing capabilities of shaking tables and collaboration between structural laboratories. Different configurations of combining shaking tables with other facilities and their control issues are currently studied in work packages WP3 and WP4 of E-FAST.

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3.2 SUBSTRUCTURE TESTING (HYBRID TESTING) WITH SHAKING TABLES

Uwe Dorka, Van Thuan Nguyen, UNIKA

3.2.1 Introduction to substructure testing

The method of substructure testing is to divide the entire structural system into experimental and numerical parts. The numerical parts cover those parts of a structure which can be represented realistically by numerical models; the experimental parts cover those that cannot be modelled. They are represented by specimens. Numerical models and specimens are connected through a stepwise time integration algorithm. The specimens are typical building components like columns or bridge bearings allowing for the use of reasonably sized testing equipment. Thus, the seismic response of a large structure like a tall building or bridge can be realistically assessed which otherwise is impossible.

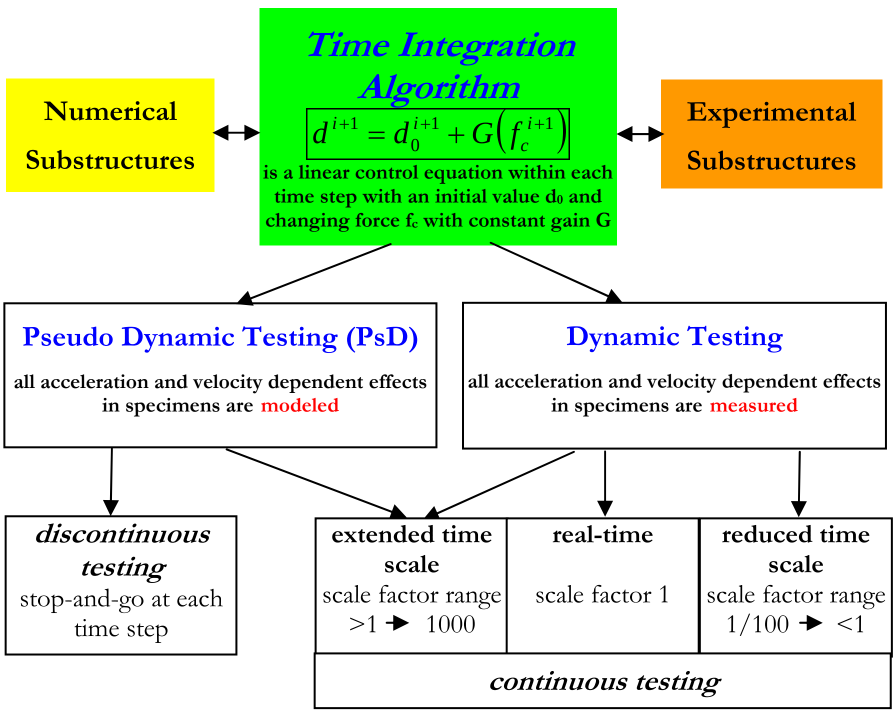


Figure 1.6 Classification of substructure tests. Scale factor defined as $\frac{t_{test}}{t_{world}}$

The method enhances the testing capabilities of existing facilities, complementing different testing equipment (hydraulic actuators, shaking tables, reaction systems, etc.)

and allows for a collaboration of different laboratories to perform one large scale test through distributed testing.

The stepwise time integration algorithm that controls the test uses the forces computed with the numerical models and measured at the specimens to compute the displacements to be applied to both of them in the next time step. If the inertia (acceleration dependent) and damping (velocity dependent) forces are only modelled, the process is called "pseudo-dynamic" (PsD). If inertia and velocity dependent damping are important in the specimens (especially in vibrating specimens), a dynamic real-time substructure test is required in general but under certain specific circumstances can be performed with an extended time scale. If reduced model specimens are required because of testing system limitations, even reduced time scale tests may be required since specimen frequencies are higher than in the real world.

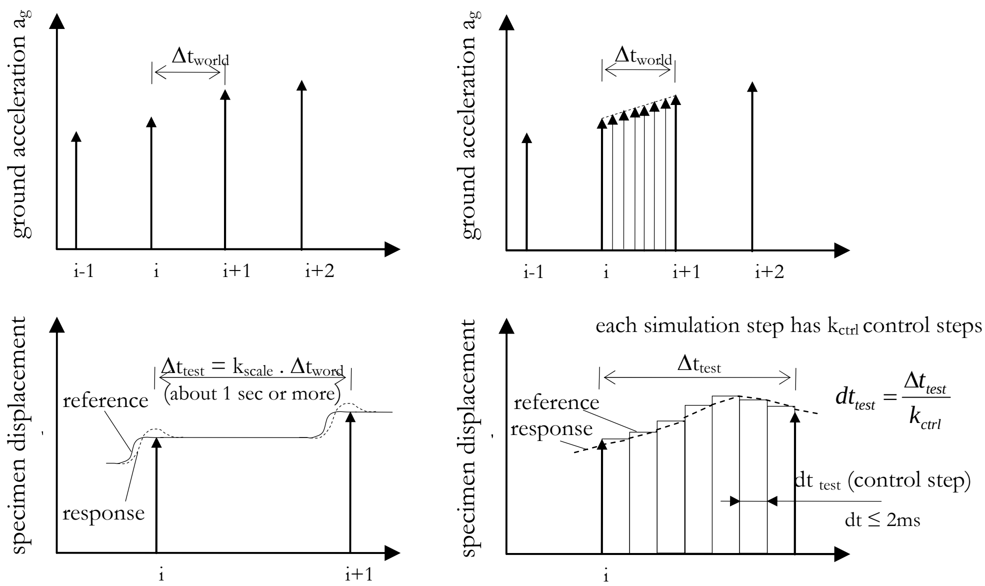


Figure 1.7. Discontinuous classical (left) and continuous (right) PsD method at ELSA, JRC, where the short control interval of a continuous test does not require an implicit integration algorithm

The different kinds of substructure tests are classified in Figure 1.6. The time scale factor for continuous tests is defined as testing time ttest over world time tworld such that, a test with a scale factor of 10 runs ten times slower than under real world conditions.

Whereas discontinuous substructure testing is a straight forward matter and has even been done by positioning the actuators by hand, continuous testing requires a control loop for the actuators of only a few milliseconds (typical is 2 ms) to obtain smooth actuator motion. With modern electronics it is possible to perform stable explicit integration (discussed in section 3.2.3) within this time step for most building structures.

Figure 1.8 A PsD test on a civil engineering structure at ELSA, JRC, Italy.

If response time is critical like in very fast and real-time tests (which is a main objective when using shaking tables in substructure testing), actuator control loop steps and integration steps must remain separate because of the computational demand from the numerical models and separate control demand. This is therefore the domain of numerically stable implicit integration schemes (discussed in section 3.2.4) with integration time steps of around 10 to 20 ms.

With smaller time scale factors, unbalanced forces at the end of each integration time step and phase lag in hydraulic actuating systems become increasingly important because of an increasing mismatch of generated and actually applied control signals. Both may destabilize a test and regardless of the integration method used, should be compensated. This is discussed in sections 3.2.5 and 3.2.6.

3.2.2 Background stepwise time integration algorithms

The core of a substructure test is a stepwise time integration algorithm. Many have been proposed over time but Zienkiewicz [1977] already demonstrated their common root which is therefore recovered here. It is a weighted residual approach with a finite element approximation of the dynamic equilibrium equation in time:

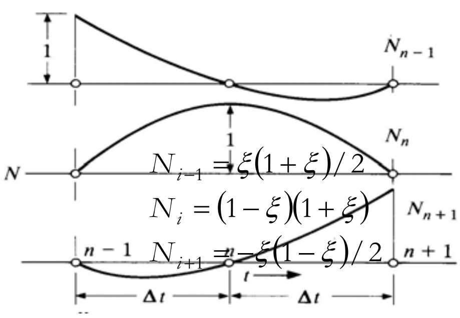
$$M \tfrac{d^2}{dt^2} d(t) + C \tfrac{d}{dt} d(t) + Kd(t) = f_l(t) + f_c(t) \tag{1.1}$$

where $f_c(t)$ is the vector of restoring forces measured at the interface between numerical models and specimens, M, C and K are the mass-, damping- and stiffness matrices of the numerical models and d(t), $f_l(t)$ are the displacement vector and loading.

Applying appropriate shape functions over three time steps (Figure 1.9) and a general weighting function W, Equation (1.5) is approximated at discrete points in time by Equation (1.2).

$$\int_{-1}^{1} W \begin{bmatrix} M\left(d^{i-1}\frac{d^2}{dt^2}N_{i-1} + d^{i}\frac{d^2}{dt^2}N_{i} + d^{i+1}\frac{d^2}{dt^2}N_{i+1}\right) \\ +C\left(d^{i-1}\frac{d}{dt}N_{i-1} + d^{i}\frac{d}{dt}N_{i} + d^{i+1}\frac{d}{dt}N_{i+1}\right) \\ +K\left(d^{i-1}N_{i-1} + d^{i}N_{n} + d^{i+1}N_{i+1}\right) \\ +f_*^{i-1}N_{i-1} + f_*^{i}N_{i} + f_*^{i+1}N_{i+1} \end{bmatrix} d\xi \qquad \textbf{(1.2)}$$

Where d^i is the displacement vector at discrete time steps i, W is a weighting function (see Figure 1.10), $\xi = t / \Delta t$, $f_* = -f_l - f_c$ and N_{i-1}, N_i, N_{i+1} are shape functions (Equation (1.3)).



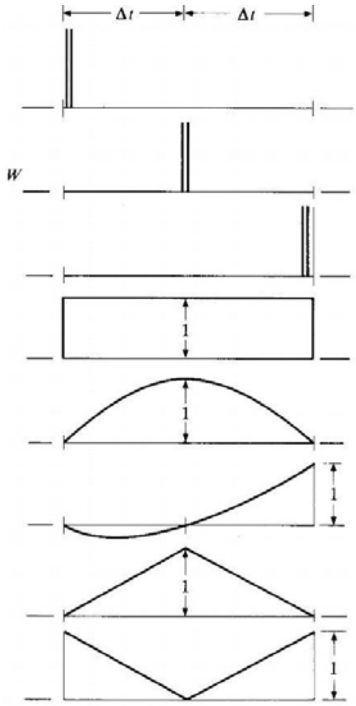
$$\begin{aligned} N_{i-1} &= \xi(1+\xi)/2 \\ N_i &= (1-\xi)(1+\xi) \\ N_{i+1} &= -\xi(1-\xi)/2 \end{aligned} \qquad \textbf{(1.3)}$$

Figure 1.9 The shape functions over time (Zienkiewicz [1977])

Performing the integration with various weighting functions yields all major stepwise time integration algorithms that use three time steps:
γ and β are constants defining a particular algorithm (Equation (1.5) and Figure 1.9).

$$d^{i+1} = \left[M + \gamma \Delta t C + \beta \Delta t^2 K\right]^{-1} \cdot \left\{ \begin{array}{l} \left[2M - (1-2\gamma)\Delta t C - \left(\frac{1}{2} - 2\beta + \gamma\right)\Delta t^2 K\right] d^i \\ - \left[M - (1-\gamma)\Delta t C + \left(\frac{1}{2} + \beta - \gamma\right)\Delta t^2 K\right] d^{i-1} \\ + \beta \Delta t^2 f_*^{i+1} + \left(\frac{1}{2} - 2\beta + \gamma\right)\Delta t^2 f_*^i \\ + \left(\frac{1}{2} + \beta - \gamma\right)\Delta t^2 f_*^{i-1} \end{array} \right\} \tag{1.4}$$

Historically, these algorithms have been derived by other reasoning and the general 3-point scheme (Equation (1.5)) is also known as Newmark-ß method. Zienkiewicz's



γ	β	
$-\frac{1}{2}$	0	
$\frac{1}{2}$	0	Central explicit
$\frac{3}{2}$	1	Backward
$\frac{1}{2}$	$\frac{1}{6}$	
$\frac{1}{2}$	$\frac{1}{10}$	Linear acceleration
$\frac{3}{2}$	$\frac{4}{5}$	Galerkin
$\frac{1}{2}$	$\frac{1}{12}$	Fox Goodwin
$\frac{1}{2}$	$\frac{1}{4}$	Average acceleration

Figure 1.10. Classification of integration methods in different weighting functions and integration parameters [Zienkiewicz, 1977]

formulation is the underlying fundamental approach and allows a systematic design of algorithms with different behaviour. Their stability and accuracy can be studied by investigating the amplification factor ρ (Equation (1.6)) of the free response of a linear SDOF system. Considering that all linear systems can be separated into independent SDOF systems by mode decomposition, general statements can be made on period elongation and numerical damping caused by an algorithm.

The oscillation is bounded and stable if |ρ|≤1. When |ρ|=1, there is no damping and the solution is exact; when |ρ|<1 numerical damping is present. Applying three point schemes on a SDOF system, the amplification factor is the root of Equation (1.7).

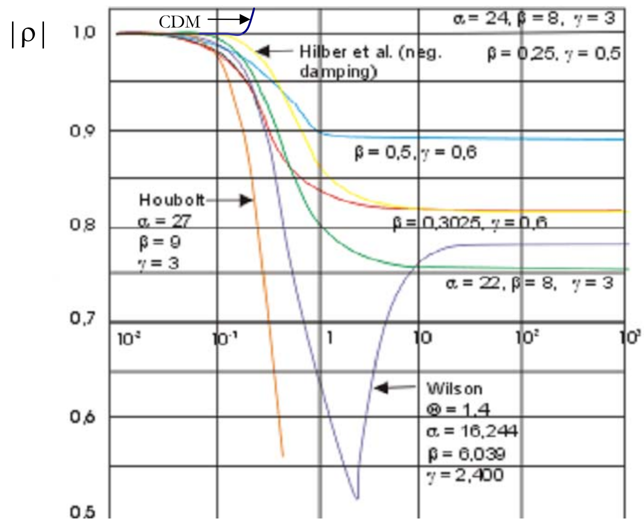


Figure 1.11. Numerical damping for 3-step and 4-step algorithms (Zienkiewicz, 1977, extended by Dorka, 2002)

$$\begin{cases} \gamma = \int_{-1}^{1} W\left(\xi + \tfrac{1}{2}\right) d\xi \Big/ \int_{-1}^{1} W d\xi \\ \beta = \int_{-1}^{1} W \tfrac{1}{2}\left(1+\xi\right)\xi d\xi \Big/ \int_{-1}^{1} W d\xi \end{cases} \tag{1.5}$$

By evaluating the |ρ| over Δt/T (Figure 1.11) and period distorstion ΔT/T over Δt/T (Figure 1.12), the performance of a new design can be compared to existing ones.

$$d^{i+1} = \rho d^{i} \tag{1.6}$$

As can be seen in these figures, the well known Newmark-β scheme with parameters γ = 0.5 and β = 0.25 is the only unconditionally stable algorithm that has zero numerical damping and provides the smallest numerical softening. This is why it is the most popular scheme today.

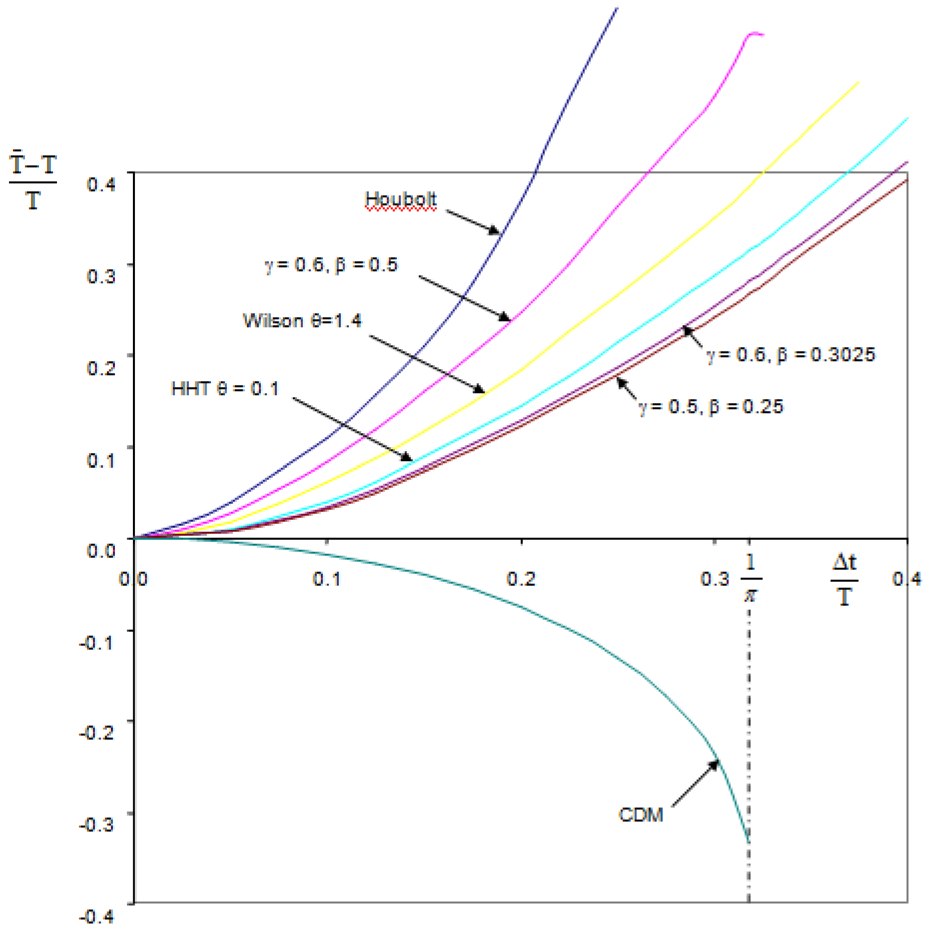


Figure 1.12. Period distortion in free vibration of a SDOF system for different algorithms ([Zienkiewicz, 1977, Nakashima 1984], extended by Dorka [2002]

$$\begin{aligned}&\rho^2\left[m+\gamma\Delta tc+\beta\Delta t^2k\right]+\rho\left[-2m+(1-2\gamma)\Delta tc+\left(\tfrac{1}{2}-2\beta+\gamma\right)\Delta t^2k\right]\\&+\left[m-(1-\gamma)\Delta tc+\left(\tfrac{1}{2}+\beta-\gamma\right)\Delta t^2k\right]=0\end{aligned} \quad \textbf{(1.7)}$$

The general formulation can easily be extended to more then 3 time steps. A 4-step procedure then yields 3 integration constants (see Figure 1.9 and Figure 1.10). In most cases, there is no reason to bear the extra numerical effort required by a 4-point scheme unless additional numerical damping is desired. This may be the case where higher order frequencies are present which may result from a numerical model with dynamic DOFs which cannot be reduced or condensed further. In such cases, higher order frequency "noise" may develop in many algorithms which can be avoided by utilizing the numerical damping properties of 4-point schemes (see Figure 1.11).

Equation (1.10) has the general form (see Figure 1.6, also holds for any n-point scheme):

$$G = -\beta \Delta t^2 \left[M + \gamma \Delta t C + \beta \Delta t^2 K \right]^{-1} \tag{1.9}$$

$$d_o^{i+1} = \left[M + \gamma \Delta t C + \beta \Delta t^2 K \right]^{-1} \cdot \begin{Bmatrix} \left[2M - (1-2\gamma)\Delta t C - \left(\frac{1}{2} - 2\beta + \gamma\right)\Delta t^2 K \right] d^i \\ -\left[M - (1-\gamma)\Delta t C + \left(\frac{1}{2} + \beta - \gamma\right)\Delta t^2 K \right] d^{i-1} \\ -\beta \Delta t^2 f_l^{i+1} - \left(\frac{1}{2} - 2\beta + \gamma\right)\Delta t^2 (f_l^i + f_c^i) \\ -\left(\frac{1}{2} + \beta - \gamma\right)\Delta t^2 (f_l^{i-1} + f_c^{i-1}) \end{Bmatrix} \tag{1.8}$$

$$d^{i+1} = d_0^{i+1} + G\left(f_c^{i+1}\right) \tag{1.10}$$

This is an initial value problem for each time step (d_0) with continuously changing force f_c. The gain G is constant throughout the test. d_0 can be calculated at the beginning of each time step and applied in various ways over the time step.

Equation (1.10) is implicit since it requires the knowledge of forces at step i+1. It becomes explicit, if G is zero and the displacements of the next time step can be computed from current information. This is the case for a number of algorithms. Whereas implicit ones can be unconditionally stable, explicit ones always have a stability limit defined as a ratio of time step Δt to the shortest period T in the test. If this limit is of no concern during a test, such methods provide simple and efficient solutions.

3.2.3 Explicit algorithms in substructure testing

One of the simplest and therefore most popular explicit method is the so-called Central Difference Method (CDM) due to the nature of its weighting function (see Figure 1.10) which provides integration parameters $\beta = 0$ (thus $G = 0$) and $\gamma = 0.5$. It has a stability limit and the stability condition is given in Equation (1.11). The method does not add numerical damping when the condition Equation (1.11) is satisfied but extreme negative numerical damping is added when Δt exceeds the limit value (Equation (1.11)). The period distortion curves of CDM are given in Figure 1.12.

$$\Delta t \le \frac{T}{\pi} \tag{1.11}$$

CDM has been used for the first discontinuous PsD tests (the first "stop-and-go" PsD test was performed as early as 1969 by Hakuno *et al.* [1969] in Japan, according to Horiuchi *et al.* [1996]) and is still a viable method for many substructure PsD tests with extended time scale, since inertia and damping effects do not play an important role in the specimens when the PsD approximation is applicable. Because of extended time scales, not only observability is enhanced, but time steps of only a few milliseconds ensure stability even for rather detailed civil engineering structures with higher frequencies. Thus, at the ELSA laboratory of the European Joint Research Centre (JRC) at Ispra, Italy, not only full-scale tests, but also a number of substructure tests with non-vibrating specimens like bridge piers have been performed successfully with this method [Negro *et al.*, 1994].

3.2.4 Implicit algorithms in substructure testing

When it comes to specimens that require time scale factors near or equal to 1, CDM or other explicit methods fail to produce stable tests and implicit schemes are required. This is especially true when shaking tables are used in substructure testing.

Implicit algorithms require the knowledge of f_c^{i+1} for an exact solution which, in a test, is only available by measurement at the end of the time step. In purely numerical simulations, iterative procedures are used to minimize the error at the end of each time step. Such iterations cannot be used in substructure testing since they would produce high-frequency oscillations. Methods that have been suggested to deal with this problem can be grouped into predictor-corrector - and feed-back techniques.

3.2.5 Predictor-Corrector techniques

A predictor-corrector scheme must estimate f_c^{i+1} of Equation (1.10) (e.g. through a stiffness estimate) and then correct it at the end of the time step when the actual force is available. This correction can be done for example using unbalanced force compensation techniques as outlined in section 2.5 for any implicit integration algorithm.

To avoid this kind of estimation for the specimen, the *explicit* displacement d_0^{i+1} of the operator in Equation (1.10) is applied directly to the specimen and after measuring the response $f_{c,0}^{i+1}$, the *implicit* force f_c^{i+1} is corrected using an approximation (Equation (1.12)). This approximation may not only depend on $f_{c,0}^{i+1}$, but also on its previous values.

$$f_c^{\,i+1} \approx \ell(d_0^{\,i+1}, f_{c,0}^{\,i+1}, f_{c,0}^{\,i}, f_{c,0}^{\,i-1}, ...) \tag{1.12}$$

These *corrector-only* methods are commonly known as *operator-splitting* or OS methods since they split the basic operator (Equation (1.10)) in an explicit part to be applied to the specimen and an implicit part for the numerical integration.

Several integration algorithms and correction strategies have been devised over time. The classic OS method [Nakashima *et al.,* 1990] uses the unconditionally stable Newmark

$$f_c^{\,i+1} = \left[I - K_I G\right]^{-1} f_{c,0}^{\,i+1} \tag{1.13}$$

integration algorithm with γ=0.5 and β = 0.25 and a correction based on the initial stiffness of the specimen K_I, which may be derived from measurements or estimated by analysis (Equation (1.13)):

where **I** is the identity matrix.
An extension of the classic OS method is the α-OS method [Pegon *et al.,* 2000, Pinto *el al,* 2004] which uses the 4-point Hilber-Hughes-Taylor integration (HHT [Hilber *et al.* 1977]). Here, the specimens' restoring forces at time n-2 enter the correction which may lead to a better representation of the specimen's response and thus more accurate results. As mentioned in section 3.2.2, 4-point algorithms allow for numerical damping in higher frequencies and thus may suppress unwanted contributions of such modes.

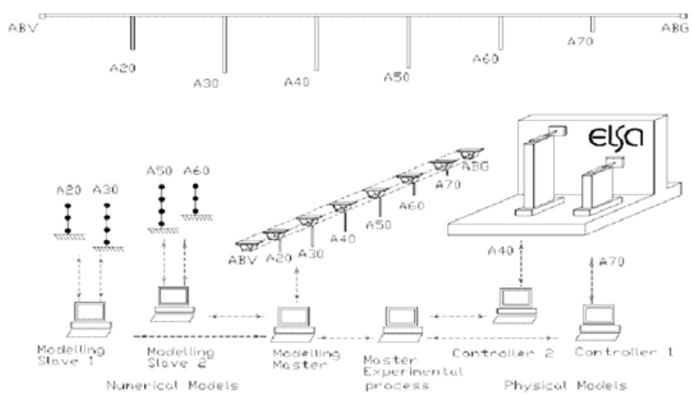


Figure 1.13 Model of Warth bridge in Austria with column specimen at ELSA for continous PsD testing using the α-OS method [Pinto *et al.*, 2004]

Studies [Bursi and Shing, 1996, Combescure *et al.,* 1997] have shown that the α-OS method has high accuracy. However, the results may not be as good as the classical method since HHT introduces a larger period error (see Figure 1.12).

The ELSA laboratory at JRC Ispra successfully performed continuous substructure PsD tests with this method on a bridge ([Magonette, 1998, Pinto *et al.*, 2004] see Figure 2.8). Large integration time steps where synchronized with short actuator control steps.

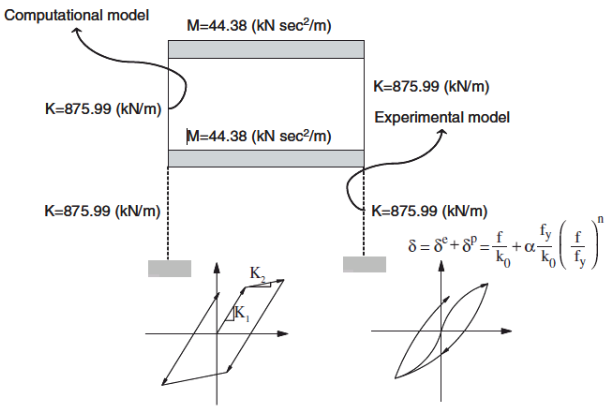


Figure 1.14 Substructure model with inelastic properties [Ghaboussi *et al.*, 2006]

Similar to the α-OS method, Shing [Shing *at al.,* 1991] also used HHT integration. This method is called α-C method [Bursi and Shing, 1996]. In this method, the implicit force is approximated using a numerical-experimental iteration. However, this method is not suitable for continue PsD testing because of vibrations in high frequencies.

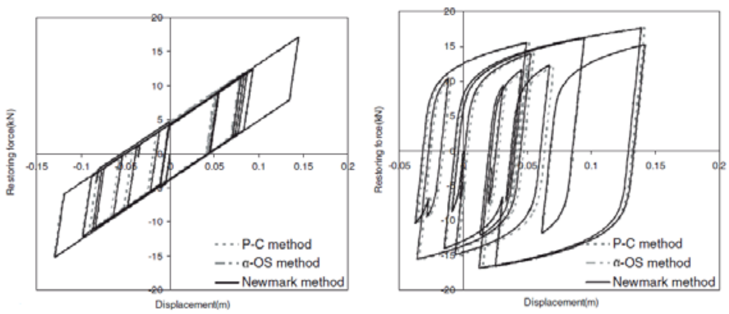


Figure 1.15 Response of two-storey shear building model with no experimental error, cases with bilinear (left) and Ramberg-Osgood (right) inelastic properties [Ghaboussi *et al.*, 2006]

In an experimental study, Bursi and Shing [1996] showed that both, α-OS method using an experimental error compensation (the I-modification [Nakashima *et al.,* 1987]) and the α-C one provide better result in comparison to the α-OS in terms of suppressing noise in displacement control.

Ghaboussi *et al.* [2006] uses the tangent stiffness instead of the initial stiffness in Equation (1.13) to correct the implicit force. They applied this successfully in substructure tests with non-linear numerical models (Figure 1.14 and Figure 1.15).

3.2.6 Analogue feedback technique

A more direct way of solving the linear control equation (Equation (1.10)) within the time step is through a force feed back. This avoids any assumptions with respect to specimen properties which may change dramatically during a test. The initial value d_0 can be calculated at the beginning of each time step and applied in a continuous fashion while the force f_c is measured. Applying the displacement Gf_c in analogue fashion is known as analogue feedback [Thewalt and Mahin, 1987]. The analogue feedback system consists of amplifiers whose gains represent the coefficients of the matrix G in Equation (2.8). Within each step, the explicit term d_0 (in Equation (1.10)) is generated continuously as an analog ramp function.

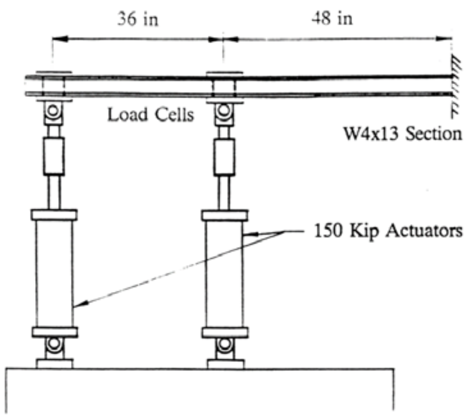


Figure 1.16 PsD test of 2-DOF cantilever using analog feedback technique [Thewalt and Mahin 1987]

The method was used on a 2-DOF cantilever steel beam (Figure 1.16) which was subjected to the NS record of the 1940 EI Centro earthquake [Thewalt and Mahin, 1987]. The 4-point HHT method was applied as stepwise time integration algorithm.

The method has a perfect feedback mechanism. However, it is difficult to apply it in general because of the need to use analogue hardware and set correct gains for each test.

3.2.7 Digital feed back technique

Instead of analogue feed back, the force f_c in Equation (1.10) may be fed back digitally at discrete sub-steps within each time step [Dorka, 1990]. The term d_0 may be applied linearly at each sub-step (Figure 1.17).

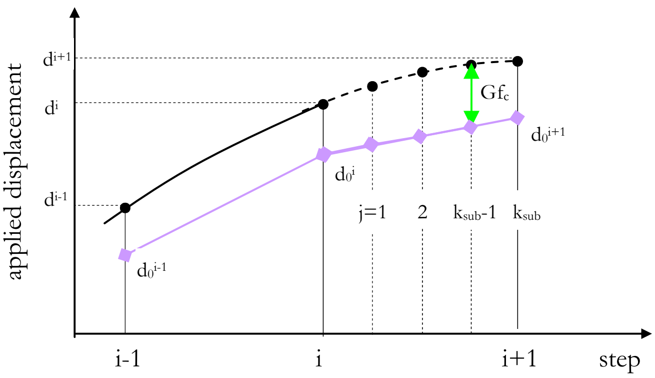
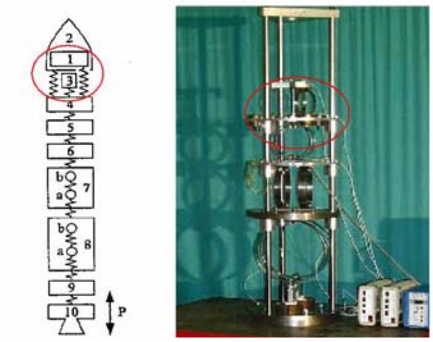


Figure 1.17 Digital feed back technique (illustration for the case of ksub=4)

Because the last force f_c to be fed back is at k_{sub-1}, an error may be introduced. This may create an error force in linear systems that can excite the highest frequency in the test. Thus, stability of this method depends on the number of sub-steps. With increasing sub-steps, this error is rapidly reduced and the method converges to the stability and accuracy of the selected stepwise time integration algorithm.



Fequencies of model	
1st frequency :	7.22 Hz
2nd frequency :	16.47 Hz
3th frequency :	35.40 Hz
4th frequency :	48.63 Hz

(a) (b) (c)

Figure 1.18 Arian IV model with payload (a), derived specimen (b) and its range of frequencies (c) for the substructure tests [Dorka *et al.*, 1998]

The first continues PsD test using this technique was performed on a concrete wall with friction joints using a time scale of 10 [Dorka, 1990]. The method has been further developed and applied in real-time substructure tests (time scale 1) in an aerospace application where a 2 DOF payload model specimen was coupled to an Ariane IV numerical model (Figure 1.18 and Figure 1.19). The tests where performed with an electro-dynamic actuator in acceleration control [Dorka *et al.,* 1998, Bayer *et al.,* 2005]. The well-known unconditionally stable Newmark scheme with $\gamma = 0.5$ and $\beta = 0.25$ was used as stepwise time integration algorithm.

The results (Figure 1.19) demonstrate the excellent performance of this method.

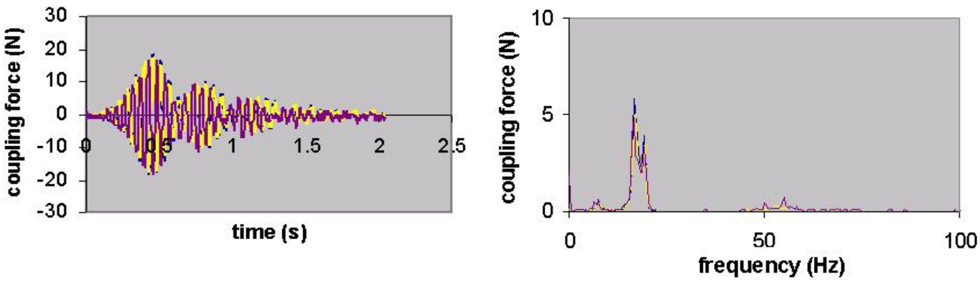


Figure 1.19 Real-time substructure test with Arian IV model: Comparison of coupling force between payload (specimen) and launcher (numerical model) for an algorithm with Δt=2ms (blue: exact, yellow: simulation, magenta: test). [Dorka et al. 1998]

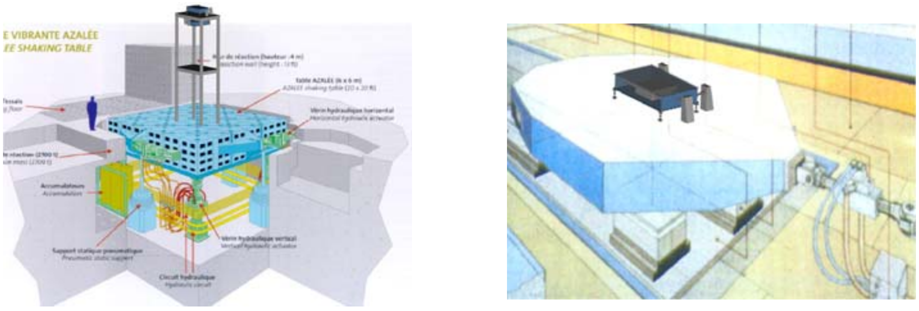


Figure 1.20 Shaking table test of full model on AZALEE table (left) and real time substructure tests of TMDs on two other tables (Vesuve and/or Tounersol) (right) in CEA, Saclay [Dorka *et al.*, 2006]

Further real-time tests were done with this method at CEA in Saclay (Figure 1.20) using two linear TMDs as substructure specimens on two shaking tables and a numerical model of a 2-storey steel frame [Dorka *et al.,* 2006, Nguyen and Dorka, 2007]. Here too, the unconditionally stable Newmark scheme with $\gamma = 0.5$ and $\beta = 0.25$ was used.

A comparison with reference tests where the complete structure was tested on the AZALEE shaking table (Figure 1.20 left) demonstrated a good match of displacements (Figure 1.21 top) despite some high-frequency pulses in the coupling force measurements which had little effect on the results (Figure 1.21 bottom).

In addition, there were spurious vibrations of the tables which also did not affect the results significantly. All this underlined the remarkable robustness of the method.

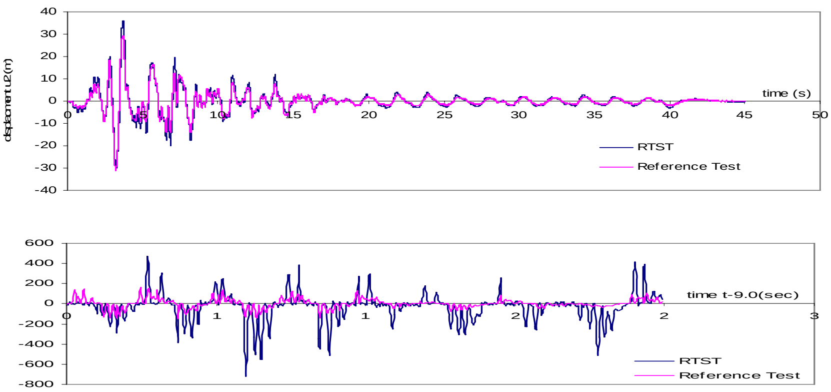


Figure 1.21 Substructure test of TMD in Vesuve table, in CEA: Comparison of displacements (top) and coupling force (bottom) between real-time substructure test and reference test, algorithm with Δt=10ms [Dorka *et al.*, 2006]

These tests demonstrated the feasibility of real-time substructure testing using hydraulic shaking tables in combination with a digital feed back algorithm. They also emphasized the importance of phase lag in hydraulic substructure testing which was hardly present in the aerospace simulations. This has important implications for the design of E-FAST.

3.3 UNBALANCED FORCE COMPENSATION IN SUBSTRUCTURE TESTING

Regardless of the chosen integration method, it is always possible to calculate the unbalanced force that may occur at the end of a time step (Equation (1.14)).

$$f_u^{i+1} = (f_l^{i+1} + f_c^{i+1}) - (\mathbf{M}u^{i+1} + \mathbf{C}u^{i+1} + \mathbf{K}u^{i+1}) \tag{1.14}$$

This is not only a good indicator of the actual stability and accuracy of a test and therefore should be reported in any case, but it can also be used to improve the results, if this force is compensated as Equation (1.15).

$$\mathbf{M}\ddot{u}^{i+1} + \mathbf{C}\dot{u}^{i+1} + \mathbf{K}u^{i+1} = f_l^{i+1} + f_c^{i+1} + \Delta f^{i+1} \tag{1.15}$$

Where f_c^{i+1} is the coupling force that may be incorrect due to errors of the substructure algorithm, and $\Delta f^{\,i+1}$ is the compensating force at the next step.

3.3.1 PID compensation

Dorka [Dorka *et al.,* 1998] introduced a compensation based on a PID minimization widely used in standard control applications (Equation (1.16)).

$$\Delta f^{\,i+1} = P\left[f_u^{\,i} + I\Delta t\sum_i^i f_u^{\,i} + \frac{D}{\Delta t}\left(f_u^{\,i} - f_u^{\,i-1}\right)\right] \tag{1.16}$$

Where P, I and D are freely selectable proportional, integral and differential gains, f_u is the unbalanced force and Δf^{i+1} the compensation force to be applied in step i+1.

The PID compensation has been applied in simple form with 0<P<1, I=0 and D=0 in real-time tests on an aerospace model representing the Ariane IV rocket with payload (Figure 1.15). Usually, the value of P is recommended around 0.9 and should not exceed 1.0 to prevent amplification of noise. The test results show that a simple PID compensation can significantly improve stability and accuracy of the test.

As in standard PID control applications, P, I and D depend on the properties of the specimen. A numerical simulation of the test usually allows the finding of a good set, even if this simulation is not too accurate.

3.3.2 Adaptive compensation based on online system identification

The method proposed by Nguyen and Dorka [2007] is based on on-line system identification. Since the compensating force $\Delta f^{\,i+1}$ is strongly related to the dynamics of the test system, it can be estimated from the previous response. The method uses a data model (for example AMARX data model) to model the relationship between the displacement and/or its derivations (as input) and the compensating force (as output).

$$\Delta f^{\,(i+1)} = \varphi^{(i+1)\,T}.\theta \tag{1.17}$$

where, $\varphi^{(i+1)}$ is the vector of variables, θ is the vector of adaptive parameters.

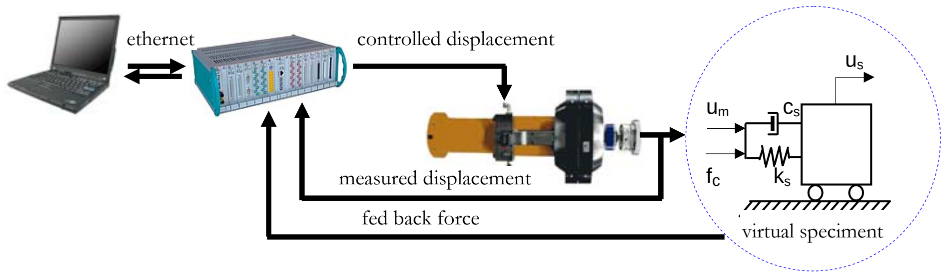


Figure 1.22 Virtual real-time substructure testing system using hydraulic actuator and virtual specimen in the structures laboratory at University of Kassel

The adaptive parameter θ is identified on-line using linear recursion with forgetting factor λ [Söderström *et al.,* 1989, Ljung, 1999]. The compensating force Δf^{i+1} at each integration step is estimated and the error of compensation (including the estimating error and noise) is minimized.

With an error minimization mechanism that is capable of adapting to time varying and nonlinear systems, there is no need to separately identify the test system. The method has been tested using numerical steel frame models and virtual TMDs as substructures with a real-life substructure testing system including hydraulic cylinder, controller and measurement systems in the structural laboratory at University of Kassel (Figure 1.22).

3.4 PHASE LAG COMPENSATION IN SUBSTRUCTURE TESTING

The problem of phase lag (also called time lag or time delay) of actuators in continuous substructure tests has been discussed in many publications [Horiuchi *et al.,* 1999, 2001, Darby *et al.,* 2001, Wallace *et al.,* 2005; Spencer *et al.,* 2007]. Phase lag of hydraulic systems induces negative damping [Horiuchi *et al.,* 1999]. This causes not only errors but may result in unstable tests. In civil engineering applications, hydraulic systems usually have a time lag of 8 ms to 40 ms [Horiuchi *et al.,* 1999, Stoten *et al.,* 2001, Spencer *et al.,* 2007]. With integration time steps of around 10 ms and control steps of 2ms, phase lag compensation is a critical issue in continuous substructure tests.

3.4.1 Phase lag compensation based on polynomial extrapolation

This kind of compensation was first suggested by Horiuchi [Horiuchi *et al.*, 1996, 1999]. The phase lag compensation is done by setting the predicted value of displacement one time lag ahead to the control signal. With an assumption that time lag of the test system is known before testing and it does not vary significantly during the test, the formulation to calculate the control signal at time t by using a polynomial extrapolation is shown in Equation (1.24).

$$d_{ctrl,t} = \sum_{i=0}^{n} a_i d_{in,t-i\delta t} \tag{1.18}$$

where $d_{ctrl\ t}$ is the control signal (displacement) at time t, , $d_{in,t-i\delta t}$ is the input signal (displacement) at time t-iδt, δt is the time lag, a_i are coefficients of the prediction and n is the order of extrapolation. Depending on the order of approximation, the constant coefficients a_i are listed in [Horiuchi *et al.*, 1999].

Order n	a_0	a_1	a_2	a_3	a_4
0	1	-	-	-	-
1	2	-1	-	-	-
2	3	-3	1	-	-
3	4	-6	4	-1	-
4	5	-10	10	-5	1

Table 1.1 The coefficients of the polynomial extrapolation (Equation (1.18))

Horiuchi [1999] was successful with the third order of polynomial in real-time substructure tests on an energy absorber and compared its results to those of a shaking table test on the full SDOF structure (Figure 1.23).

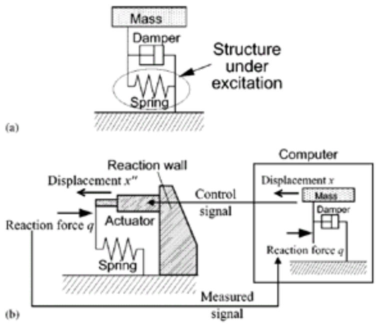


Figure 1.23 Real time hybrid experiment for SDOF system, (a) – a SDOF structure, (b)- substructure specimen coupled with numerical model [Horiuchi *et al.,* 1999]

The polynomial extrapolation Equation (1.18) with third order is equivalent to the assumption that the variation of acceleration is linear with respect to time [Horiuchi *et al.*, 2001]. Horiuchi *et al.* [2001] proposed an alternative method in which the acceleration at one time lag ahead is predicted in the same manner with displacement in Equation (2.19) with the first order; then, the displacement one time lag ahead is calculated using linear variation of acceleration. This new compensation method [Horiuchi *et al.*, 2001] is more advanced than the compensation in Equation (1.18) in term of accuracy and stability.

There is no adaptive ability of these compensation methods for time-varying time lag, therefore its applications are limited.

Based on polynomial approximation, Wallace [Wallace *et al.,* 2005] proposed an adaptive compensation that uses the least-square polynomial fitting [Kreyszig, 1999]. In this method, the control signal is calculated as Equation (1.19).

$$d_{ctrl} = g_a \sum_{i=0}^{n} a_i (k_{\delta t})^i \tag{1.19}$$

Where, g_a is an adaptive gain for compensating amplitude error, a_i (i=1, …, n) are fitting coefficients, n is the polynomial order, $k_{\delta t}$ is an adaptive parameter for time lag (Equation (1.20)). It is noted that "i" in the term a_i means to an index while the "i" in the term $(k_{\delta t})^i$ means to exponent.

$$k_{\delta t} = \frac{\delta t}{dt} \tag{1.20}$$

Where δt is time delay of the test system, dt is control step.

Without prior knowledge of the test system, initial values of the adaptive parameters can be $g_a = 1$ and $k_{\delta t} = 0$. If the time delay δt is estimated before hand, the initial value of $k_{\delta t}$ can be calculated from Equation (1.20).

At each control step, the fitting coefficients are determined by applying the least-squares polynomial procedure on n last displacements. In addition, at the end of each control step, the adaptive parameters for the next step are adjusted in following.

$$g_a^{\,j+1} = g_a^{\,j} \pm \nu_1 (e^j)^{\gamma_2} \tag{1.21}$$

$$k_{\delta t}^{\,j+1} = k_{\delta t}^{\,j} \pm \nu_2 (e^j)^{\gamma_2} \tag{1.22}$$

Where the indexes j and j+1 denote the current and next steps; e^j is displacement error at the end of step j ; ν_1, γ_1, ν_2 and γ_2 are constants that set the convergence of the adaptive mechanism, the operator "+" or "-" is selected depending on the rising or falling edge of the input displacement.

This compensation method has adaptive ability for time-varying delay. The method has been applied in real-time test on a SDOF system in a hydraulic test rig at University of Bristol, UK (Figure 1.24 and Figure 1.25).

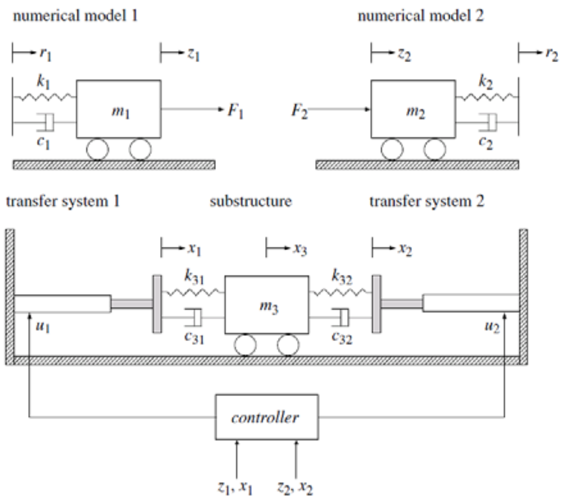


Figure 1.25 Substructure tests to study time delay compensation [Wallace *et al.*, 2005].

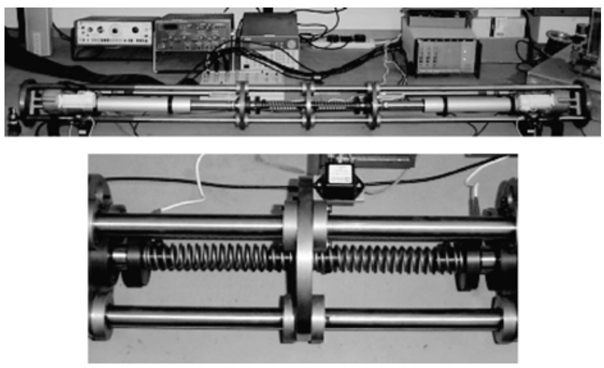


Figure 1.24 Experimental setup of substructure model in test of time delay compensation [Wallace *et al.*, 2005].

3.4.2 Phase lag compensation based on system models

Spencer [Spencer *et al.*, 2007] proposed a time lag compensation method based on system models. From the known transfer function of the test system, a displacement control with feed-forward and feed-back control is designed (see Figure 1.27). This method has been applied in fast hybrid testing of a Magneto-Rheological (MR) damper with a 3-DOF numerical substructure [Spencer *et al.* 2007].

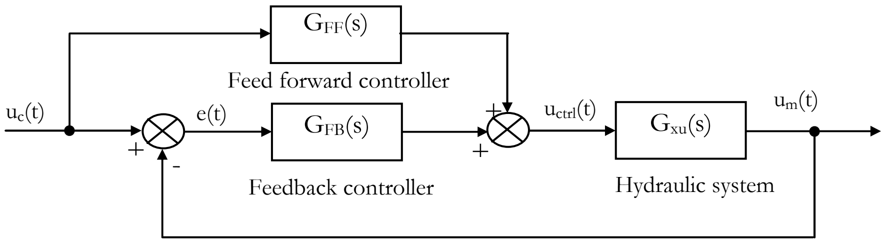


Figure 1.27 Hydraulic control using feed forward and feedback control [Spencer *et al.* 2007]

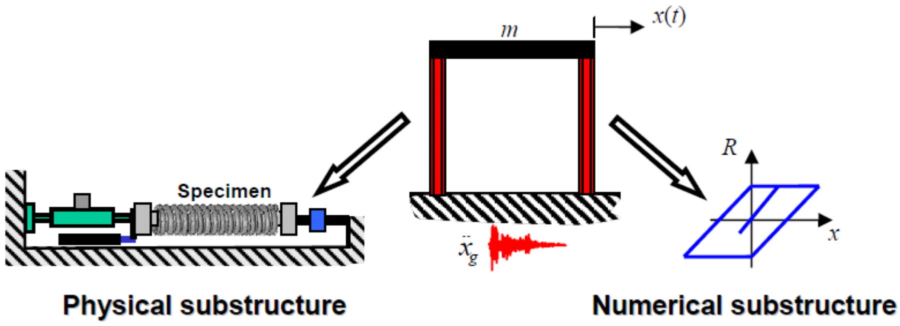


Figure 1.26 Fast hybrid test of an MR damper using delay compensation by feed-forward and feed-back control [Carrion *et al.* 2006]

The method can be used effectively to compensate time lag of hydraulic actuators where the system is known. The method does not have an adaptive ability and it requires extra tests for system identification.

3.4.3 Phase lag compensation based on on-line system identification

Nguyen and Dorka [2008] proposed an adaptive phase lag compensation based on on-line system identification. The method uses the ARMAX data model for presenting the dynamic relationship between the compensating value and the response of the system.

$$u_{ctrl(ii)}{}^{jj} = u_{(ii)}{}^{jj} + \Delta u_{ii}{}^{jj} \tag{1.23}$$

$$\Delta u_{ii}^{jj} = [\varphi_{ii}^{jj}]^T . \theta_{ii}^{jj} \tag{1.24}$$

where Δu is compensating displacement, φ is vector of variables, θ is vector of adaptive parameters, the indexes ii denotes identification step while index jj is control step.

The adaptive parameters are estimated on-line using linear recursion with forgetting factor λ [Söderström *et al.,* 1989, Ljung, 1999] at each identification step. The displacement error including estimating error and noise is minimized.

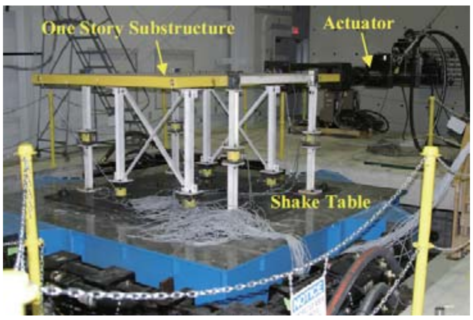
With the transfer function implicitly identified through the adaptive parameters of the data model, the compensation can deal with different frequency-dependent phase lags. Thus, it is applicable within a wide range of frequencies. The method can also compensate amplitude errors.

There is no need to separately identify the test system, having adaptive ability for time varying and nonlinear systems. The method has been applied in virtual substructure test of TMD in the real-time testing system at UNIKA (Figure 1.22).

3.5 USING SHAKING TABLES IN SUBSTRUCTURE TESTING

In recent years, shaking tables have come into focus for substructure testing because of the successes in algorithmic developments using implicit integration algorithms. With substructure testing, the capabilities of shaking tables can be significantly expanded, especially when they are combined with other test rigs or are connected in a network for geographically distributed testing.

2 storey frame (full model)



hybrid test of the first storey

Figure 1.28 Substructure testing using shaking table at State University of New York, Buffalo, USA (Reinhorn et al. 2004)

Shaking tables have been used already in substructure testing [Reinhorn *et al.* 2004, Dorka *et al.* 2006, Ji *et al.* 2009].

The hybrid test of the first storey (Figure 1.29 right) is a PsD test and its results have been compared to a reference test (Figure 1.29 left).

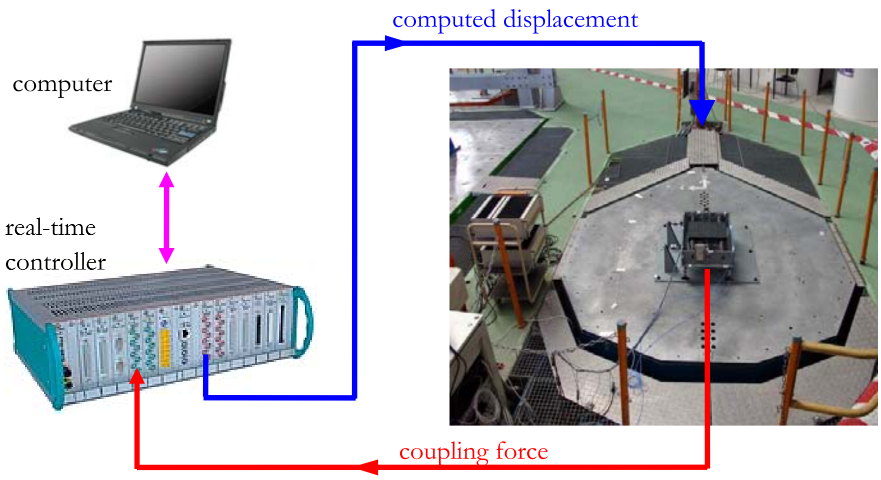


Figure 1.29 Real-time substructure testing of a TMD using the VESUVE shaking table in TAMARIS, CEA, France [Dorka *et al.*, 2006]

The real-time substructure test of TMD using shaking table in Figure 1.29 were also compared to reference tests (see Figure 1.20, left) and its results were discussed in (Dorka *et al.* 2006) as well as in section 3.2.4.

Different control strategies have been used in hybrid testing with shaking tables [Reinhorn *et al.,* 2004, Dorka *et al.,* 2006]. The PsD test in Figure 1.28 was performed with force control while the real time test in Figure 1.29 was performed with displacement control.

Although well developed, some challenges remain even for the substructure algorithms. This is especially true in real-time testing using large numerical models where computation time may reach a critical limit with respect to the time step. One possibility is to divide the numerical structure into substructures and process them on separate computers. This requires a high-speed network solution like SCRAMNet [Barrera *et al.,* 2004] which has been used successfully in this context [Shing *et al.,* 2004, Wallen, 2007].

To cope with non-linear structures and specimen, substructure testing systems should have adaptive capabilities. Currently there are some algorithms that provide these [Magonette *et al.* 1998, Ghabouss *et al.* 2005, Nguyen and Dorka, 2008], but research is still limited on non-linear substructure testing.

In substructure testing using shaking tables, it is important to properly introduce the coupling conditions between specimen and numerical model. This often requires particular force measurements which are not performed in standard shaking table tests. A particular problem in this context is not point-wise, but distributed force transfer. Further developments are needed to provide robust, yet accurate force transducers that act as a variable interface to a specimen. Preferably, these transducers should be integrated into the table.

Many substructures need large displacements and velocity. This combined with a small time delay of only a few milliseconds is a requirement not easily matched by hydraulic systems. In fact, no large shaking table today can meet this. New actuator technologies like combinations of hydraulic and electrical actuators promise to provide improved solutions for this in the near future.

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3.6 CONTROL ISSUES AND NUMERICAL MODELING OF SHAKING TABLES FOF OFFLINE TUNING

Alberto Pavese and Chiara Casarotti, EUCENTRE

Dynamic testing of real structures is a difficult task in many cases because of the demanded magnitudes of the specified inputs and the size of the structural models to test. When scientifically sound tests are performed, the size scale of the specimens tends to be as close as possible to the real one and the capacities of the testing facilities, such as shaking tables or reaction walls, are usually required to work close to their capacity limits.

Working under large displacements, velocities, accelerations, forces, moments or frequencies may drastically increase the size of the experimental errors during the test up to unacceptable limits, at which the results of the tests are completely useless. Moreover, those errors are very difficult to predict due to the complexity and nonlinearity of the specimen and the testing facility.

In order to provide a more complete picture of how earthquakes would affect large structures, including large buildings and bridges, without the need to physically test the entire structure, Real-Time Dynamic Hybrid Testing (RTDHT) is currently under study in a number of experimental facilities. The latter is a new form of testing in which shake table and dynamic force experiments on substructures are combined in real-time with computer simulations of the remainder of the structure.

Objectives of hybrid testing [Sivaselvan *et al.*, 2003] are to allow testing of full size structures or substructures, to allow to test strain rate effects, to develop inertial effects in distributed mass systems, to test integrally the computational tools as well as the physical specimens, and ultimately to produce computational tools validated by experiments.

Because the test is conducted in real time RTDHT features peculiarities such as the presence of the mass in the physical system, the modelling of distributed inertia and rate-dependent effects, the shake-table operated as acceleration device (with actuators in dynamic force control), sub-structuring force-based (with interface forces applied to specimen) and dynamic test.

On the other hand, a number of challeges are encountered, related to the dynamic force control, to the actuator / table–structure interaction, and to numerical algorithms stability and error propagation. Ideally flexible harware/software architecture would permit different other types of tests (e.g. pseudo dynamic test with shake-table as a displacement device).

One of the most challenging problems is the force control, since hydraulic actuators fitted with flow-regulating servo-valve constitute inherently a velocity source and are designed to be mechanically stiff for good position control. Moreover friction, stick-slip, breakaway forces on seals, backlash cause force noise, and stiff oil columns make force control very sensitive to control parameters often leading to instability.

Dynamic testing for earthquake engineering requires high precision application of discrete and distributed dynamic loads, ranging from several MNewtons (e.g for PsD testing of full-scale structures) to few kNewtons (e.g. in small-scale tests in a centrifuge). Servo-hydraulic actuators for the application of large dynamic loads have been so far the only viable option to provide a combination of large forces, velocities and displacements by linear actuation. Inevitably there are performance compromises: if high forces, velocities and displacements are required at the same time, the size of servo-valves needed to pass the large volume of oil reduces the actuator's high frequency bandwidth and fidelity. This is particularly important when controlling complicated shaking table and other multi-actuator tests. In such - often very expensive - tests, slight errors in the relative phase control of the actuators can propagate rapidly, corrupting the required input force time histories and ruining the whole test. This is most common in the high-frequency ranges, where small and very rapid control adaptations are required that servo-hydraulic actuators struggle to achieve. Particularly problematic are hybrid test techniques with physical and numerical models coupled together in real-time.

For all of the above discussed issue, large shake tables and hydraulic actuators operating in real-time with current control technology are plagued by lack of fidelity in signal reproduction owing to distortion in the feedback signals by non-linearities in the servo-valves and sensors (dead-zones, backlashes and hysteresis), effects of pressure drop at high flow demands, uncontrolled dynamics of inner/outer controller loops, effects of rigid blocks and surrounding soils and unknown interaction between equipment and specimen. Decoupling of the controller from the specimen for safety reasons, as well as commercial policies, have motivated development and use of black-box type controllers that do not profit from a-priori or on line physical knowledge of the specimen. Moreover, typical controllers are based on linear systems theory and are limited in their ability to scale non-linear effects.

Experimental testing is an essential tool for understanding how structures respond to dynamic excitation. However, high performance Shake Table testing systems feature unstable response, due to a number of issues, among which the presence of heavy resonant specimens, the changing (often sudden and abrupt) of specimen dynamic response during the shaking and the lack of speed or accuracy in computation and communication between actuation and control for real time adaptive control algorithms.

All of these factors may cause a table Response different than what is required and expected, unstable control or loss of control, and above all unsafety for people and equipment. Hence it is necessary to develop advanced virtual models of the test equipment-specimen system and combine them with the use of the latest advances in control in order to reduce the number of calibration pre-tests, optimise the number and location of sensors and improve test quality.

3.6.1 The NEFOREEE experience

The research network NEFOREEE (New Fields of Research in Earthquake Engineering Experimentation [Molina *et al.*, 2006]), funded by the European Commission has inherited the experience in this field from the previous networks ECOEST and ECOLEADER. The European Consortia for Earthquake Shaking Tables Studies (ECOEST) were formed by five institutions operating major shaking tables: the Laboratory for Earthquake Engineering of the National Technical University of Athens, Greece, the Earthquake Engineering Research Centre of the University of Bristol, U.K., the Laboratorio Nacional de Engenharia Civil, in Lisbon, Portugal, the Commissariat a l'Energie Atomique, in Saclay, France and Enel Hydro s.p.a., in Seriate, Italy, that made extensive studies on the control of shaking table tests. Afterwards, the European Consortium of Laboratories for Earthquake and Dynamic Experimental Research (ECOLEADER) was created by the former ECOEST partners, but then including also the new reaction wall facility of the Joint Research Centre at Ispra, Italy. In addition, the network NEFOREEE has included also the University of Trento, Italy, where a large reaction wall is recently available, and the University of Oxford, U.K. which is specialized in high speed on-line testing with substructuring.

One of the tasks of NEFOREEE [Severn, 2001] has been the development of benchmark tests to be executed on similar models at different facilities and by using different testing techniques such as shaking tables, reaction walls and substructured on-line testing. The works done for this purpose are described in this paper. An onedegree-of-freedom full-scale shear type K-braced steel frame, easily transportable from lab to lab, was conceived at the University of Trento. It was designed to allow two types of dissipation devices to be inserted. At the unprotected configuration the specimen behaviour is very linear but its damping is very low, which should put in evidence any alteration introduced by the testing methods such as control delays in the PsD method or spurious rocking on the shaking table. With non-linear dissipator devices, those deficiencies may be hidden by the large damping developed at the specimen, but an appropriate strain-rate effect compensation technique is necessary within the PsD method. In a similar way, that non linearity may impose limitations as well on the compensation techniques based on linear filtering of the reference signal and traditionally used at the shaking tables.

Two twin full-scale steel structures were constructed at the JRC Ispra. One structure was kept to be tested using the pseudo-dynamic method on the Ispra reaction wall. The second twin structure was sent by truck to the NTUA, in Athens, where it was tested dynamically on the shaking table. This second structure was afterwards dismounted and sent to the LNEC, in Lisbon, in order to repeat there the same tests as in the NTUA campaign [Bairrao *et al.,* 2004].

3.6.2 The SEESL experience

The University at Buffalo's (UB) Structural Engineering and Earthquake Simulation Laboratory (SEESL), which is the flagship laboratory in the Multidisciplinary Center for Earthquake Engineering Research (MCEER), will be a key node of a nationwide earthquake engineering "collaboratory"– the NSF-funded George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). Through this network, earthquake engineers located at different institutions will be able to share resources, collaborate on testing, and exploit new computational technologies. The intent of the NEES node project at UB has been to develop the most versatile earthquake engineering research facility possible, designed to provide testing capabilities that will greatly enhance the understanding of how very large structures react to a wide range of seismic effects. The SEESL new testing facility features the following characteristics [Reinhorn *et al.*, 2003]:

- A 13000 square feet laboratory that includes a 80'x40' strong floor, a large 80' long reaction wall, and a special trench to house the two new moveable shake tables described below.
- A set of two movable, high-performance, 6 degrees-of-freedom shake tables that can be easily and quickly repositioned in order to accommodate models of various lengths. Together, the tables are able to host specimens weighing up to 100 metric tons and measuring up to 120 feet, and subject them to fully in-phase or totally uncorrelated synchronous dynamic excitations.
- Large-scale, high-performance dynamic and static actuators, for dynamic and pseudo-dynamic testing. These actuators are intended for the development of new testing methodologies, including the effective force control testing method, in which large structures could be directly subjected to dynamic excitations without the need for shake tables, and, when used in combination with the shake tables and large reaction wall, Real-Time Dynamic Hybrid Testing (RTDHT). An example of a specimen that could be tested using the RTDHT is shown in Figure 1.30 [Bruneau *et al.,* 2002].

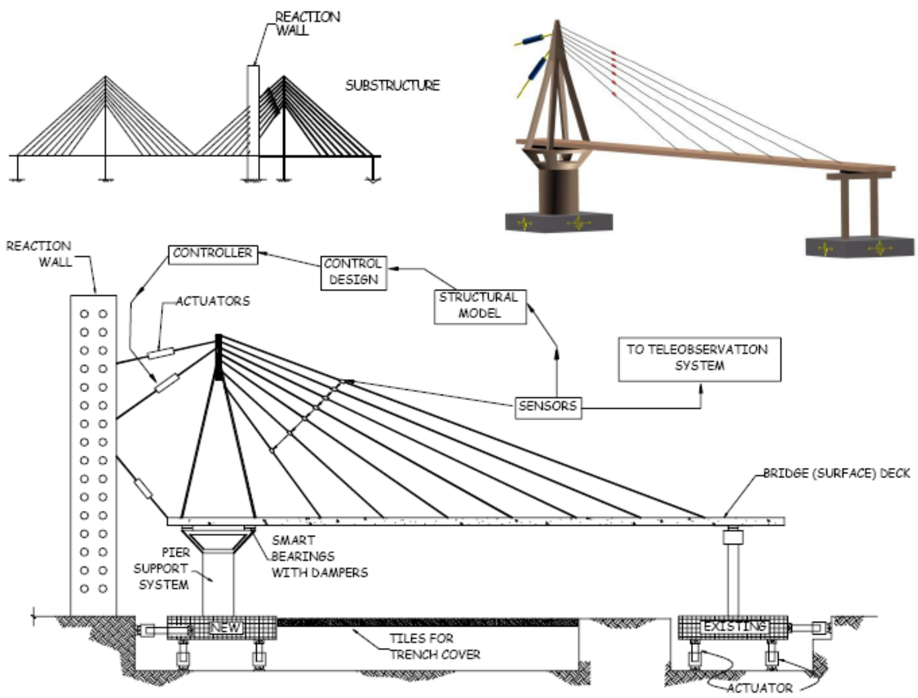

Figure 1.30 Example of test combining different testing facilities: Cable-stayed bridge segment with RTDHT using two shake tables, reaction walls, and large-scale high performance actuators

On Wednesday July 29 2009, a geographically distributed hybrid simulation of a four story steel moment frame building subjected to the 1995 JR Takatori record at 100% scale has been run (Figure 1.32). The building model is based on the four story steel moment frame building tested to collapse at E-Defense, Japan in September 2007. The frame is divided at the mid-height of the second story with the upper stories modeled numerically in OpenSEES. The lower portion is further divided into two experimental ½-scale substructures, one at Kyoto University and the second at the University at Buffalo NEES facility. Equilibrium and compatibility between the substructures are satisfied at the boundaries using the software framework for distributed testing developed at Kyoto University.

3.6.3 Offline tuning of shaking tables

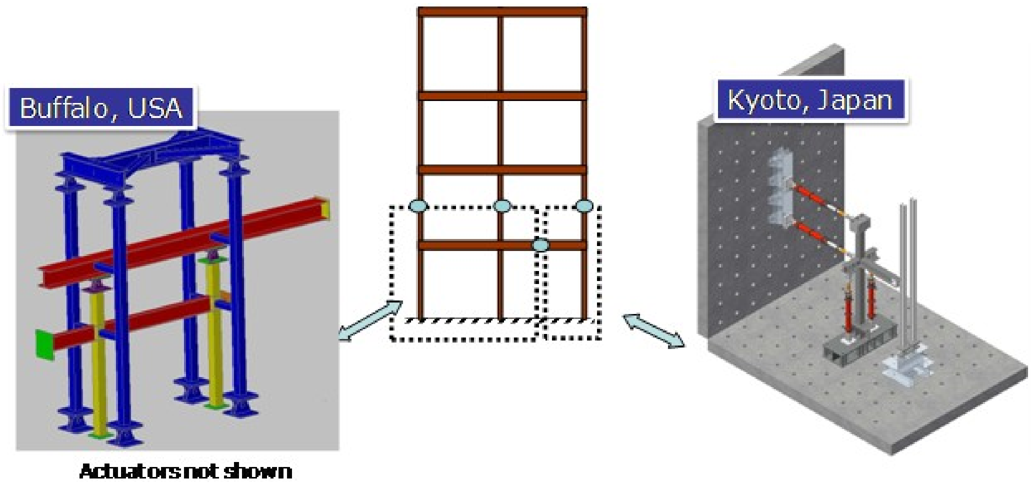

Figure 1.32 Hybrid Simulation of Steel Moment Frame to Collapse

In order to achieve the desired shake table performance, each test requires a different combination of a given set of parameters, which is called TUNING. The tuning operation is one of the most important and crucial aspect in the shaking table testing. It is an operation which allows matching command and feedback signals of the shaking table, which means obtaining unitary gain of the transfer function between command (cmd) and feedback (fbk) within the frequency bandwidth of interest, acting on a specific feedback component of the cmd/fbk error function (Figure 1.31). An additional tool to improve the table response is the ADAPTIVE CONTROL, which basically acts modifying the controller command to get the desired table feedback.

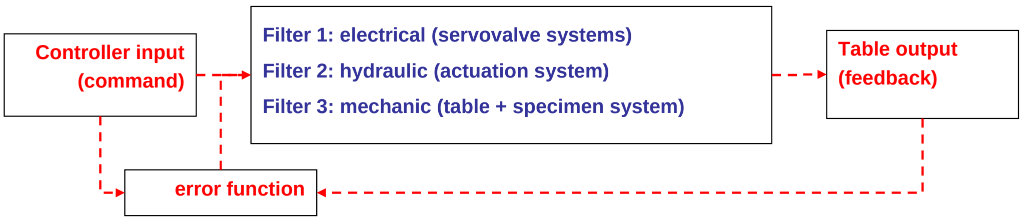

Figure 1.31 Filters between command and feedback signals

3.6.3.1 *The tuning procedure*

The tuning procedure consists of adjusting multiple control variables, such as gains, lead terms, and notch filters (Figure 1.34). The control performance of shaking tables is greatly affected by the interaction between table and specimen, and the set of parameters which flatten the cmd/fbk transfer function of the bare table, greatly differs from the set of optimal parameters for the system of the table with the specimen (Figure 1.33), rendering inappropriate to run the table with bare table controller tunings, and needing to retune the table with the specimen on.

On the other hand, it has to be noted that the re-tuning procedure features a number of shortcomings given by a long excitation on the specimen, since even low-level excitation causes cumulative damage to specimen. Moreover, if the operator makes tuning mistake, resulting instability can destroy the specimen and even with a good initial tuning, sudden damaging during the test may lead to unsafe and dangerous loss of control of the table. For all of these reasons, most operators prefer not to retune at all, or they simply detune by reducing the gain a fixed amount, which however does not lead to optimal test control. Advanced adaptive control algorithms may partially help in this case.

Adaptive Control is based on control compensation techniques that augments a fixed-gain controller to improve control fidelity, repeatedly updating the drive file to make it matching the desired input. Such control techniques are optimized to work with non-sinusoidal command waveforms and significantly nonlinear systems. Clearly, the rate at which the response converges to the desired command is a function of the plant nonlinearity.

The drive correction represents a best linear estimate of the amount of drive error that gave rise to the response error. However the error minimization is local, i.e. based on the state of the system at the previous iteration: this means that if the system encounters abrupt changes, the minimization should be based on the current (and eventually forward) state of the system, which may be far from the previous state AND IS NOT AVAILABLE TO THE CONTROLLER, and there may be a high RISK OF UNSTABLE CONTROL. Such techniques are clearly more effective with 'slowly evolving' nonlinear systems. An effective alternative is exploring all these issues in simulation before performing the test.

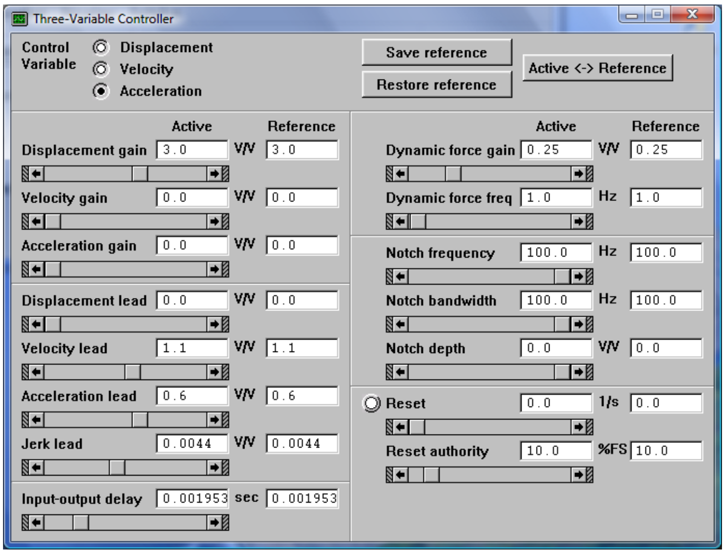

Figure 1.34 Three Variable Controller (TVC)

Figure 1.33 Specimen influence on the table response transfer function (TF)

3.6.3.2 *Control Enhancement for Seismic Testing*

Since seismic tests may be highly nonlinear, the basic idea is to tune the controller offline" using a specimen model (Figure 1.35) rather than the actual specimen (Figure 1.36), to use an actual controller to drive forward model and to provide the controller a reliable track of the evolution of the controller drive function and parameters in the neighborhood of which looking for optimal control.

In this way there will be also the possibility of "rehearsing" a test by performing an end-to-end check of hardware and software system components before turning on hydraulics, greatly enhancing the whole safety of the system. The offline tuning system, which has to be composed of advanced simulation elements (Figure 1.37), will allow creating a reliable track of the evolution of the controller drive function and parameters.

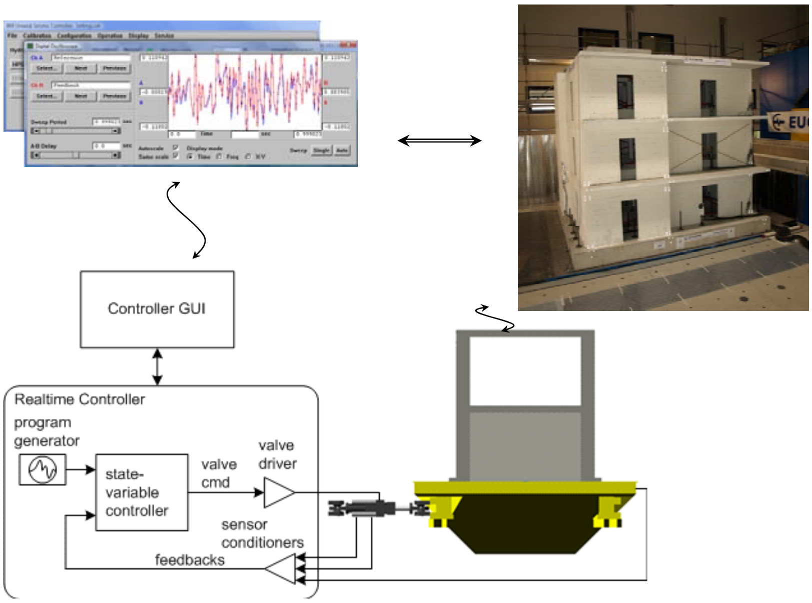

Figure 1.36 Actual online tuning system

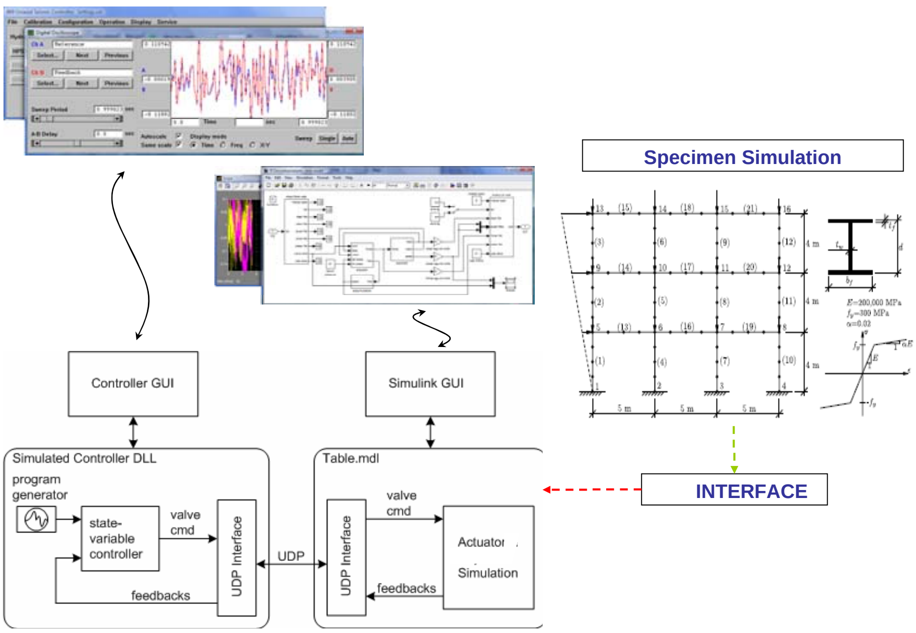

Figure 1.35 Simulated offline tuning system

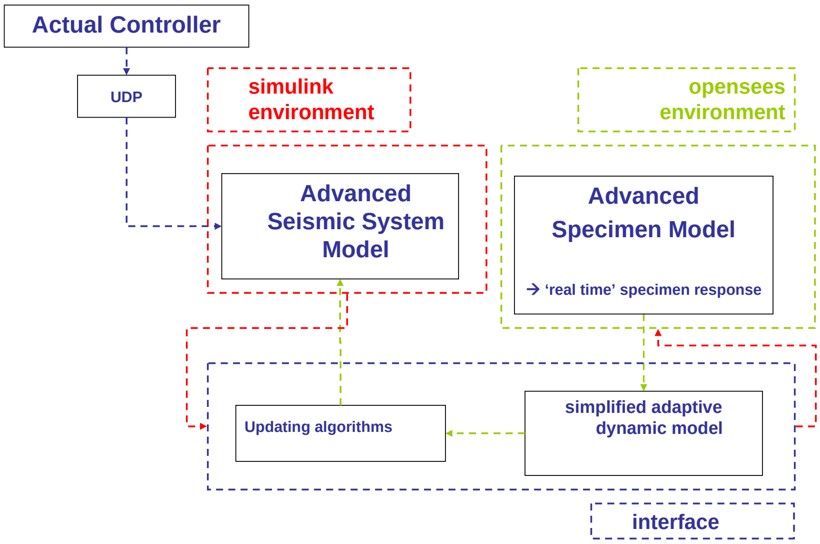

Figure 1.37 Offline tuning scheme

3.6.3.3 *Needs and objectives*

The elements constituting the simulation system are (Figure 1.38):

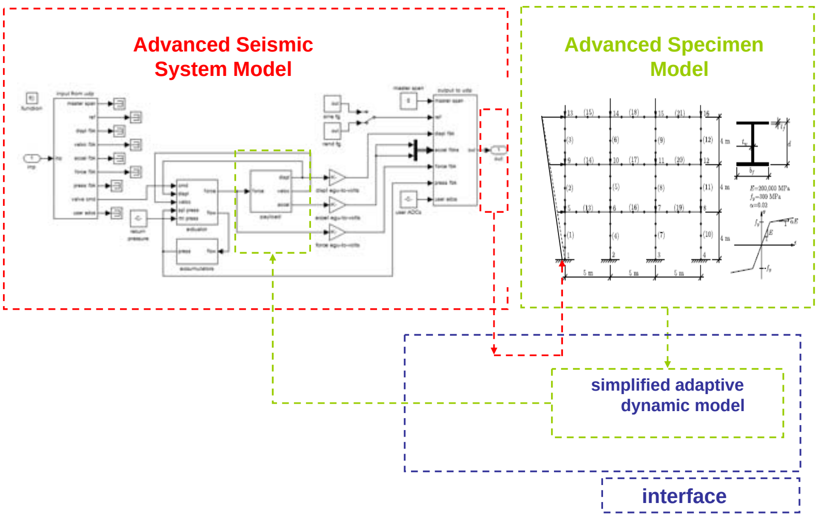

Figure 1.38 Elements constituting the simulation system

- A User Datagram Protocol to run controller in simulation mode (with simulated offline system)
- An advanced model of the whole seismic system
- An advanced model of the specimen
- An Interface between the two models
- A basic model of the Seismic System has been already developed, which can be enhanced by modeling what follows:
- Servovalve and actuator dynamics, including pressure switching, nonlinear flow gain effects, servovalve spool overlap/underlap, variable volume effects with piston stroke, kinematic and compressibility flows, cross-piston leakage, friction
- Actuator geometry cross-coupling
- Rigid body dynamics in 6 DOFs
- One specimen resonant mode
- Accumulator bank pressure change with flow
- Concerning an advanced model of the system, the following issues has to be considered:
- Higher table, specimen, and foundation resonant modes
- Hydraulic distribution losses
- Physical limiting, except inside servovalve & actuator
- Specimen nonlinearity (highly application specific - Opensees)

On the specimen side, a good approach has been deemed to be a object-oriented software like the Open System for Earthquake Engineering Simulation (OpenSees). The fundamental characteristic of object-oriented software is abstraction [Takahashi and Fenves, 2006]: identifying the important software behaviour needed to solve a problem and breaking it down into components, which are referred to as software classes (Figure 1.39). Software objects are instances of a class, which contain the specification for constructing and operating on objects constructed from the class. An object encapsulates data and operators on the data, thus hiding the implementation of the operators from the specification. An operator is invoked by sending an object a message; the object is then responsible for invoking the implementation of the operator based on its class. A framework is a set of inter-related classes that can be used to develop an application to solve a problem. The so conceived software is modular, flexible, and extensible.

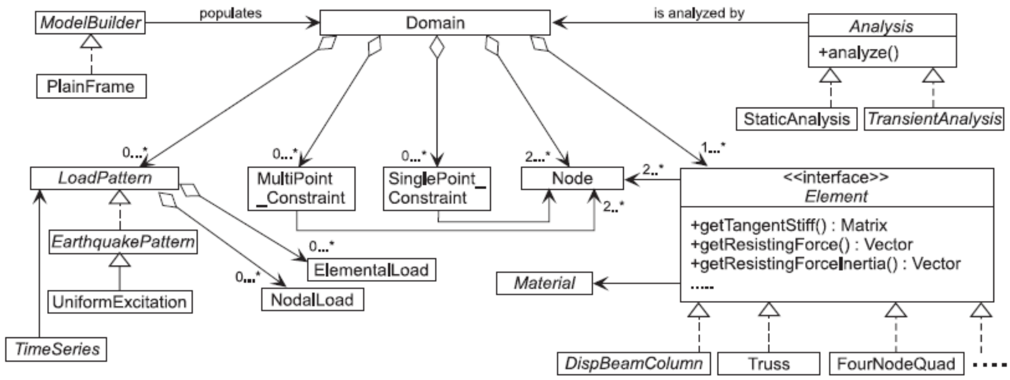

Figure 1.39 High-level classes in the OpenSees software framework for computational simulation

The communication interface has to be programmed for computing the control signals and customized for an experimental site and test method. A number of characteristics are listed below:

- the interface software must have the flexibility to interact with a variety of the components in the simulated set-up
- the interface software has to collaborate with computational simulation software, such as OpenSees, for solving the governing equations of motion for the specimen simulating structure.
- Simulation modes require the software to calculate the evolving of the nonlinear dynamic of the specimen. To accomplish this, OpenSees can provide the computational simulation needed for structural testing either locally or in a distributed manner.
- The OpenSees class Element has methods to compute the stiffness matrix, mass matrix and modes shapes, which has to be at each step translated by the interface software in a simplified payload model to update the table model

3.6.3.4 *Remarks*

The work to be developed will not aim at the perfect simulation of the test, because firstly even highly refined FEM models cannot exactly forecast the actual structural response in all its features and peculiarities, moreover testing would not be needed anymore (which will cause separation between scientific and applied research and would render purely abstract any model validation of performance of existing and new technologies). However, a reliable track of the evolution of the controller drive function and parameters will be of great help in:

- Allowing no or extremely light table tuning with the specimen on, avoiding pre-test damage
- Helping the actual adaptive control to be 'prepared' to sudden changes in the specimen dynamics, i.e. provide the controller with a evolving track around which looking for optimal tuning, especially in case of abrupt dynamics changes
- Test "Rehearse" by performing an end-to-end check of hardware and software before turning on hydraulics.
- Importantly enhancing people and equipment safety

3.6.4 Numerical modeling and identification of the shake table system

One of the key challenges to be overcome in performing an accurate shake table test is the faithful reproduction of the desired table motion. It is essential to develop a joint experimental-analytical approach in order to better understand the dynamics of the shake table system. In what follows, the experimental procedure for the identification of the TREES Lab at Eucentre shake table and its components (servovalve, actuator, payload, etc.) is described. Two numerical models of the shake table system were implemented using Simulink. The first one was obtained for the case of a simplified model of actuator and servovalve, while the second uses a more sophisticated analytical model including more detailed characteristics of the servovalve and actuator. The total shake table transfer function of the two models was then compared to that obtained experimentally.

3.6.4.1 *Shake table hardware*

The TREES Lab at Eucentre is equipped with an MTS Systems Corporation servo-hydraulic uni-axial shake table. It consists of 5.6x7.0 m^2 moving steel platform that is attached to a servo-hydraulic dynamic actuator of $\pm$ 1700 kN force capacity. The system is capable of simulating earthquake events and other ground vibration with $\pm$500mm maximum stroke and $\pm$2200 mm/sec pick velocity. Accelerations of $\pm$1.8 g are possible with maximum test specimens of 140 tons, and up to $\pm$6.0 g for bare table condition. The maximum over turning moment and yaw moment are 4000 kNm and 400 kNm respectively and the bandwidth of operating frequency is 0-50 Hz. The hydraulic power supply that supplies the shake table consists of 8 high pressure pumps that can deliver a total of 1360 liters per minute at 28 MPa and 900 liters of accumulators for peak demands. The Table is controlled by advanced Digital Controller MTS system 469D. It provides for the shake table a high-level fixed control techniques such as Three-Variable Control (TVC: displacement, velocity, and acceleration), built-in filtering and adaptive compensation techniques for high fidelity and faithful reproduction of the desired table motions.

3.6.4.2 *The simulation model*

The shake table system is represented using block diagrams. Figure 1.41 shows the relations between the different subsystems of the shake table. The major components that comprise the model are the valve and actuator system and the payload.

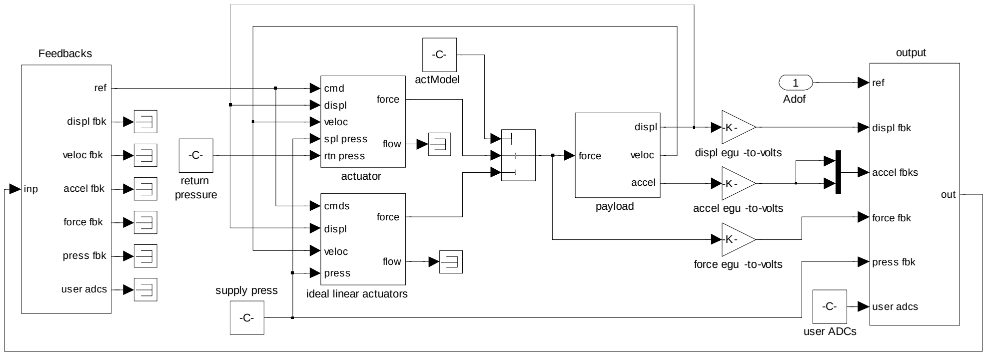

Figure 1.41 Seismic Table Model detail view

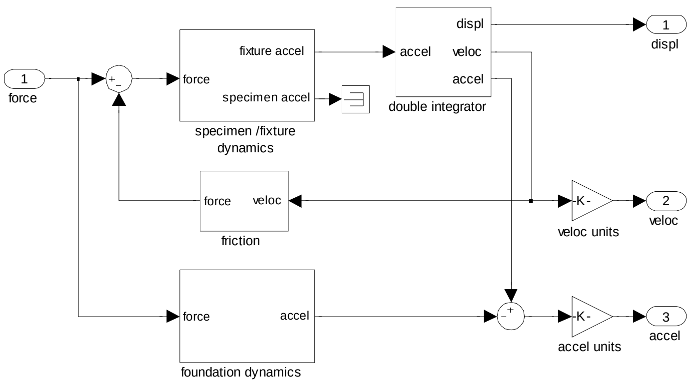

Figure 1.40 Payload model

Two types of valve and actuator models were implemented, the former, named "ideal actuator", in which the servovalve is represented as a time delay and the actuator with an approximate linearized flow continuity equation, while the latter, named "real actuator", uses a more sophisticated model that includes realistic representations of a large number of parameters.

The payload block models (Figure 1.40) the relationship between the table motion and the actuator force (minus friction force). Both the effect due to the flexibility of the foundation reaction mass and the presence on the table of flexible specimens have been modeled. The kinematics of the table (acceleration, velocity and displacement) are also calculated in this block model. Refer to Thoen and Laplace [2004] for a detailed description of the major components of the payload model.

3.6.4.3 *Parameter identification*

Modeling of the shake table requires the determination of many parameters. Some of them, mainly concerning the geometric and physical proprieties of the various system components, can be obtained from the manufacturer or through direct measurement. Some other parameters need to be determined experimentally, like nominal flow, effective bulk modulus, servovalve spool dynamics, table rigid mass, friction coefficient, and foundation dynamics. These parameters can be obtained by conducting bare table tests. The final set of parameters relates to the specimen dynamic characteristics, which can be determined using one of the experimental dynamic identification techniques such as hammer test.

In this study, a series of random and periodic (sine and triangular waves) tests were conducted on the EUCENTRE TREES Lab shake table in order to determine the bare table system parameters. Data acquisition was done using the MTS 469D digital controller. The selected channels to be recorded during the tests were stored in user selected file with sampling rate set to 512 Hz.

The parameter estimation process has been fully described in [Thoen and Laplace 2004], the same procedure was used here and only the results are presented in the following sections, except for the servovalve spool dynamics, for which more detailed descriptions are given in this paper.

The first test program consisted of three wideband white noise tests, one in displacement control and the other two in acceleration control, used to identify the servovalve spool dynamics, the rigid mass of the table, the oil column frequency and damping and the oil bulk modulus.

Typically the servovalve dynamics can be represented either by first order or second order models. Laplace transfer functions of these models are given below, for the first order and the second order models, respectively:

$$H(s) = \frac{k_s}{\tau s + 1} \tag{1.25}$$

$$H(s) = k_s \frac{\omega_v^2}{s^2 + 2\xi\omega_v + \omega_v^2} \tag{1.26}$$

where s is the Laplace transform variable, ks is the valve gain and τs is the response delay, while ξ and ω_v represent the damping ration and natural frequency of the servovalve, respectively.

To identify the dynamic parameters mentioned above a test was conducted to generate a frequency response plot of the servovalve. The table was excited with a wideband random program in displacement control mode. The experimental transfer function between the conditioned servovalve command and the third stage spool position of the servovalve was calculated and shown in Figure 1.42, where the frequency responses of the first and second order models of the servovalve are compared. The magnitude responses of both the models match very closely the magnitude of the actual table. The phase response of the second order model fits perfectly the experimental phase response over wideband frequency range (0-50 Hz), while the first order model matches the experimental phase response up to 10 Hz with reasonable accuracy. The following information was extracted from the experimental frequency response function:

- The valve gain, which corresponds to the asymptotical line of the magnitude response, was found equal to one (Ks = 1).
- The time delay for the first order model was found to be 0.0137 sec.
- An equivalent natural frequency of 20.5 Hz and a damping of 105% were found.

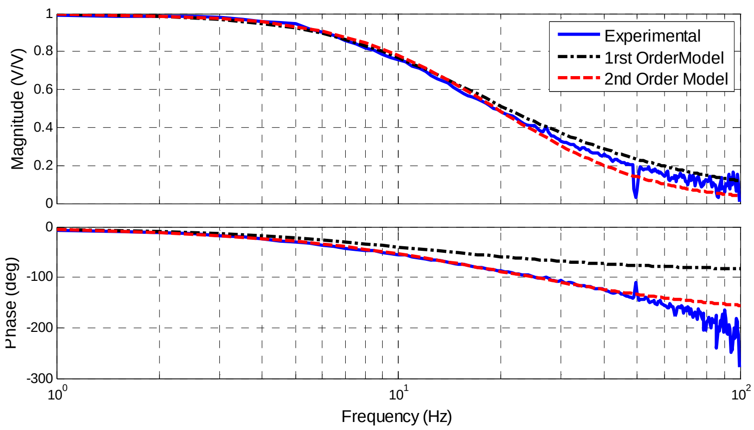

Figure 1.42 Measured servovalve dynamics

The table was then excited with a random acceleration command. The second-order filter between acceleration as input and force as output to yield rigid mass as a function of frequency (Figure 1.43). The rigid mass parameter is the magnitude of this filter at lower frequencies and is found to be 41.258 tons.

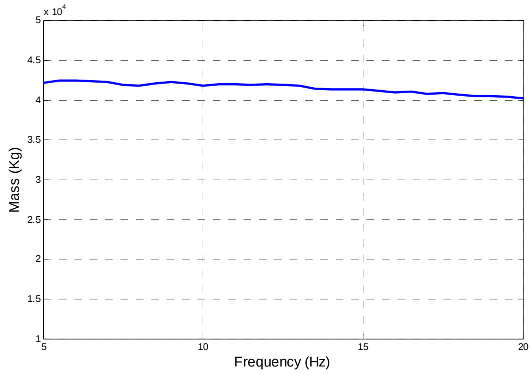

Figure 1.43 Table mass versus frequency

A random command in acceleration control mode was carried out on the table and servovalve spool position and force feedbacks were recorded. The oil column frequency and damping were then obtained by fitting the second-order filter to the recorded data. Once these parameters were estimated and knowing the total effective rigid mass already calculated in the previous section, the bulk modulus was then calculated. These parameters were estimated to be: oil column frequency foil = 14.169 Hz, damping ξ = 3.36% and bulk modulus β = 1.1920e+003 MPa.

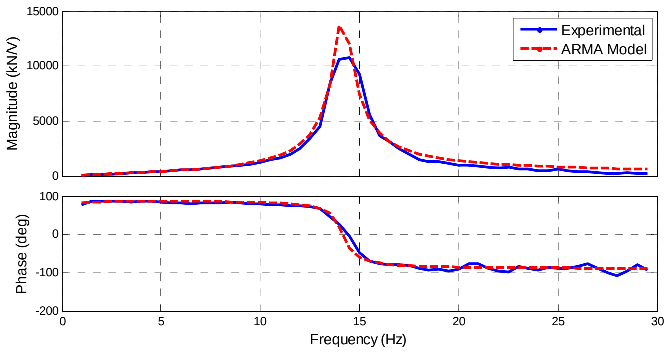

Figure 1.44. Oil column frequency response

The latter set of testing program using periodic (sinusoidal and triangular) excitations was used to identify the system table-payload model characteristics.

The dynamic equilibrium equation is used in order to represent the equation of motion of the mechanical system. The purpose is to take advantage from the periodic nature of the displacement, velocity and acceleration of the triangular or sinusoidal tests to calculate the horizontal stiffness, the friction and the total rigid mass of the shake table. The basic simplified conceptual model of the system can be expressed by:

$$F_I(t) + F_D(t) + F_E(t) = F_A(t) \tag{1.28}$$

Where F_A is actuator force, F_I, F_E and F_D are the table inertia, elastic, and damping forces, respectively. Equation (1.28) can be written as:

$$M_T(u).\ddot{u}(t) + F_D(\dot{u}) + F_E(u) = F_A(t) \tag{1.27}$$

Where M_T is the total effective rigid mass of the table and u(t), with its first and second derivatives represent the table kinematics (displacement, velocity and acceleration respectively). It should be noted that the considered mechanical sub-system does not include the compressible oil columns in the actuator chambers. The recorded actuator forces obtained from the pressures on both sides of the pistons already account for the oil column effect [Ozcelik *et al.*, 2007]. For the identification process one cycle of test data is selected in which the displacement is positive over the first half cycle . Then four time instants are considered $0 < t_1 < T/4$, $t_2 = T/2 - t_1$, $t_3 = T/2 + t_1$ and $t_4 = T - t_1$.

Applying equation (1.27) at the four instants and by considering the periodic nature of the table kinematics, these equations are used to determine the most important characteristic of the shake table, which are the effective horizontal stiffness, the rigid mass and the dissipative force.

For the particular case of triangular wave, the table acceleration is zero. Therefore equations the elastic force and the stiffness of the system can be easily calculated. Figure 1.46 shows the results obtained for triangular tests. It can be seen that the elastic force is nearly zero for all tests. All of the above considerations stand for displacements not close to the point of motion inversion, say for displacements up to the 80% of the maximum displacement. At the inversion of the motion in fact, a number of factors influence the stability of the purely triangular response: (i) first, sudden inversion of motion cause the oil column to be excited, then (ii) when the table invert the motion the effect of the static coefficient of friction cause the typical 'stick-slip' effect, which at the motion inversion increases the force required to move the table (which is immediately decreased to the steady value as soon as motion begins), and (iii) finally the actual inversion of motion is not characterized by the theoretical step in the velocity function, but by a very steep velocity change. For all of these reasons, mass, friction and table stiffness are estimated out of the motion inversion region.

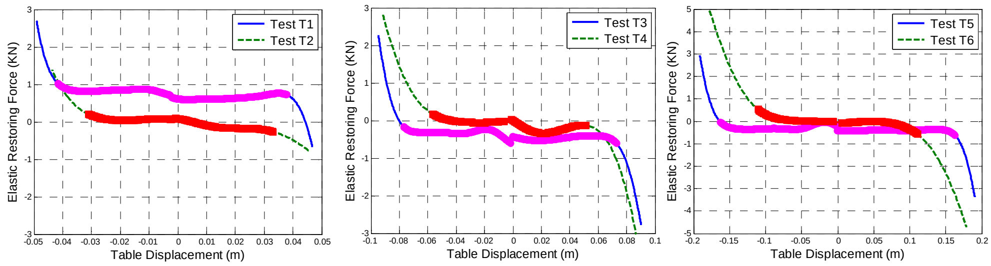

Figure 1.46 Estimates of the horizontal stiffness from triangular tests

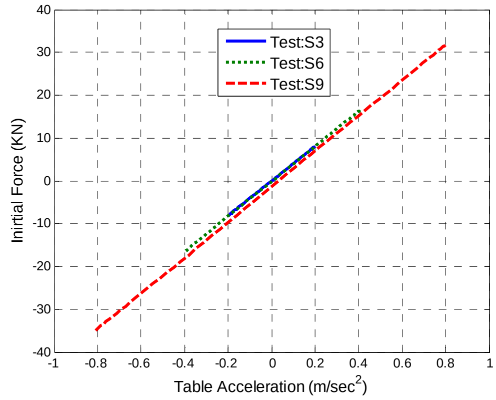

Figure 1.45 Estimate of effective mass obtained by loop approach from sinusoidal tests

Since the elastic force previously calculated is essentially zero, then sinusoidal input waveform tests were used to calculate the effective rigid mass of the shake table. Figure 1.45 shows the relation between the table inertial force with the table acceleration for the sinusoidal tests. As shown in the curves the inertial forces vary linearly with the total acceleration of the table for the three tests. The effective rigid mass of the table is the slope of the curves, and is found to be 41 tons, is in good agreement with the effective rigid mass of the table estimated with the random excitation.

Once the values of the rigid mass and stiffness are known, the total dissipative force can be simply extracted from the equation of motion. In theory the triangular waves are preferred to sinusoidal waves for the dissipative force calculation, mainly because being the elastic forces essentially zero, the dissipative force are simply equal to the total actuator force. However, this is not the case in practice, because of the occurrence of acceleration spikes at the time of change in velocity, producing additional forces difficult to quantify. For this reason sinusoidal tests are chosen for the dissipative force calculation.

Figure 1.45 shows the relationship between the total dissipative force and the table displacement as well as the relationship between the total dissipative force and the table velocity for sinusoidal tests. The experimental results are compared to the simulation of the friction model which uses the continuous viscoplastic friction law described by Bondonet and Filiatrault [1997] shows a good agreement between the measured and the simulated friction force namely for small velocities.

3.6.4.4 *Table transfer function estimation*

At this stage, all the parameters involved in the numerical model of the EUCENTRE TREES Lab shake table are defined. The transfer functions estimated by the Simulink model for both the cases of ideal linear actuator and real actuator are compared to the experimental one.

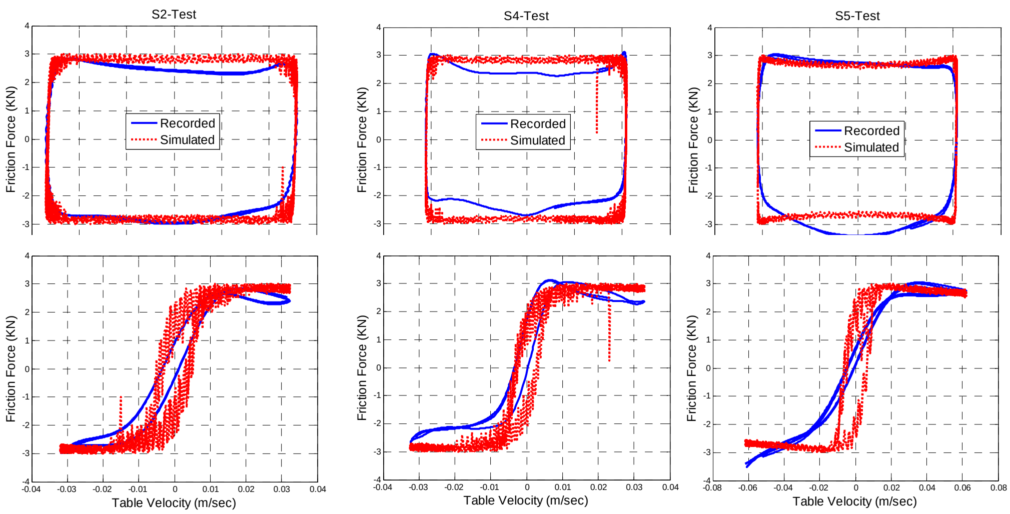

Figure 1.47 Recorded and simulated total dissipative forces vs table displacement and velocity

Figure 1.48 shows that the analytical transfer functions obtained for both the models of the shake table are in very good agreement with the experimental one. Moreover, the magnitude of the transfer function shows a big sharp peak at a frequency of 14.16 Hz, which corresponds to the oil column natural frequency. The oil column is extremely important factor in the behavior of transfer function phase: Figure 1.48 shows how the inversion of phase in the transfer function occurs exactly in correspondence with the oil column resonant frequency.

3.6.4.5 *Concluding remarks*

Two numerical models of the TREES Lab at Eucentre seismic shake table were established using the Matlab system-modeling package Simulink. The main difference

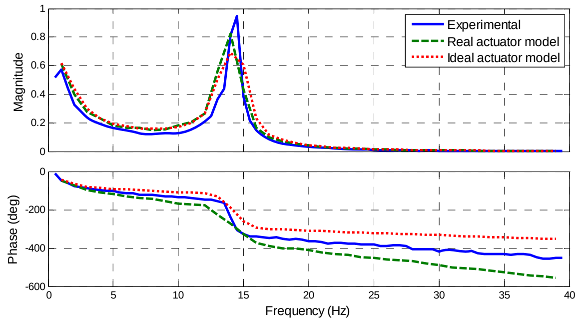

Figure 1.48 Shake table transfer functions

between the two models is in the servovalve actuator block system, which is the most critical part of the shake table because it is the part where mechanics, hydraulics and electronics are fully involved and interact. In the first model a linear approximation of the servovalve actuator system was used; the second model instead used a realistic detailed nonlinear system. The rest of the shake table system was modeled in the same way.

The particularity of this study lies in the two approaches used to calculate the shake table components. In fact, in the first approach explicit identification of these components using random tests was adopted. For the second approach the shake table and its subsystems were represented by a basic simplified dynamic equilibrium equation. Periodic tests were used to identify the table system's effective horizontal stiffness, rigid mass and total dissipative force.

A comprehensive set of tests, random and periodic, were conducted on the real shake table, in order to determine experimentally all of the parameters involved in the two models. Finally, the two shake table numerical models were validated by comparing their transfer functions with the one obtained experimentally on the real system.

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3.7 GEOGRAPHICALLY DISTRIBUTED TESTING

Pierre Pegon, JRC

3.7.1 Introduction on geographically distributed testing

3.7.1.1 *The need for hybrid testing and geographically distributed testing*

In 2007 JRC Ispra hosted the 2nd World Forum on Collaborative Research in Earthquake Engineering. Three working groups were organized, and the first one dealt specifically with "hybrid testing and distributed simulation". The following ideas, taken out from the summary and recommendations report [Pegon *et al.*, 2007] allow introducing the needs for hybrid testing and the geographically distributed implementation of hybrid testing, also known as geographically distributed testing.

Hybrid testing is a method for investigating the response of a structure to excitation, using an assembly of at least one physical substructure (to be tested at the laboratory) and at least one numerical substructure (to be simulated on a computer). *Hybrid testing* is important because it:

- Splits a complex problem into subparts allowing to profit of the complementary character of the existing testing methods (shaking tables, reaction walls, centrifuges & field tests),
- Integrates experimental testing and numerical modelling,
- Facilitates full scale specimen test,
- Brings existing facilities to a full potential.,
- Represents more realistically the seismic demand on critical parts of a structure,
- Enhances range of applications,
- Is not limited to seismic applications,
- Can now be done

Geographically distributed testing is important because it

- Encourages collaboration and sharing of resources, including funding and cost,
- Encourages specialization & its use within a network,
- Encourages integration of facilities for solving large and complex problems,
- Organizes a community of testing laboratories and give access to itIs not limited to seismic applications.

It is worth noting that all the geographically distributed tests realized so far are Pseudo Dynamic (PSD) tests using the classical PSD method, which may be run non synchronously (the laboratory duration of each time step of the accelerogram may be variable) and non continuously (the trajectory during the load step may include hold periods), and thus accommodate the highly non deterministic character of the communication on the internet.

3.7.1.2 *Brief history of geographically distributed testing*

Before 2000, some tests distributed over the internet but performed at the same location have been already performed. For instance Sugiura *et al.* [1998] in Kyoto University in Japan published a research work on network pseudo-dynamic technique and demonstrated a physical network experiment at several sites through Internet on Kyoto University Campus. We can also mention the pioneering work on large bridge piers performed at ELSA during the PREC8 program in 1995/96 with a test already distributed over the internet and using a TCP/Socket protocol [Pinto & Pegon, 1997]. Although challenging to realize, these tests do not include the collaboration difficulties of geographically distributed tests: differences in testing culture, local time, language, etc.

The first geographically distributed test was performed between two experimental laboratories (Kyoto University, Japan & Korea Advanced Institute of Science and Technology, KAIST, Korea) with data exchanged through shared disk units between Japan and Korea [Watanabe *et al.*, 2001]. Each laboratory simulates a bridge bearing (the EWS2 in KAIST and EWS3 in Kyoto University, see Figure 1.30). The displacement and resisting force data are exchanged through the shared disk unit at the laboratories. Figure 1.30 shows the network configuration of the experiment. The KAIST-Kyoto PSD experiment was very time consuming. In the 1000-step pseudo-dynamic test, each time step cost about 22 seconds in average (very long to be compared to the network performance test using the ping command between the two laboratories, which costs only about 0.24 seconds).

The second geographically distributed test campaign was performed in Taiwan (between the National Taiwan University (NTU) and National Center for Research on Earthquake Engineering (NCREE)) in 2003 for bi-directional PSD tests with substructuring of DSCFT bridge piers (Double-Skinned Concrete-Filled Tube Column Tests). The tests were performed using the so-called ISEE platform (Internet-based Simulations for Earthquake Engineering) in its two approaches, the database approach and the application protocol approach [Tsai *et al.*, 2003] and Figure 1.50).

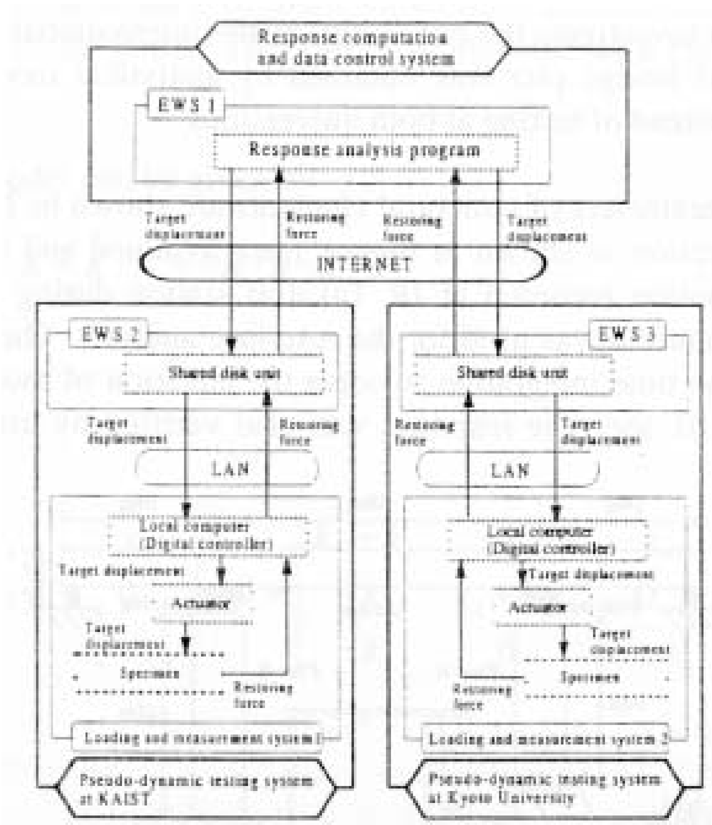

Figure 1.49 Network configuration of the KAIST-Kyoto experiment [Watanabe *et al.*, 2001]

The second approach leading to the PNSE (Platform for Networked Structural Experiments) will be discussed further in section 3.7.2.2. In fact, some simulations have been made using PNSE with the numerical structure located in Stanford (USA): an elapse experimental time slightly higher than 1s per PSD time step has been reached and the overload due to PNSE is comparable to the ping time (0.17s/time step).

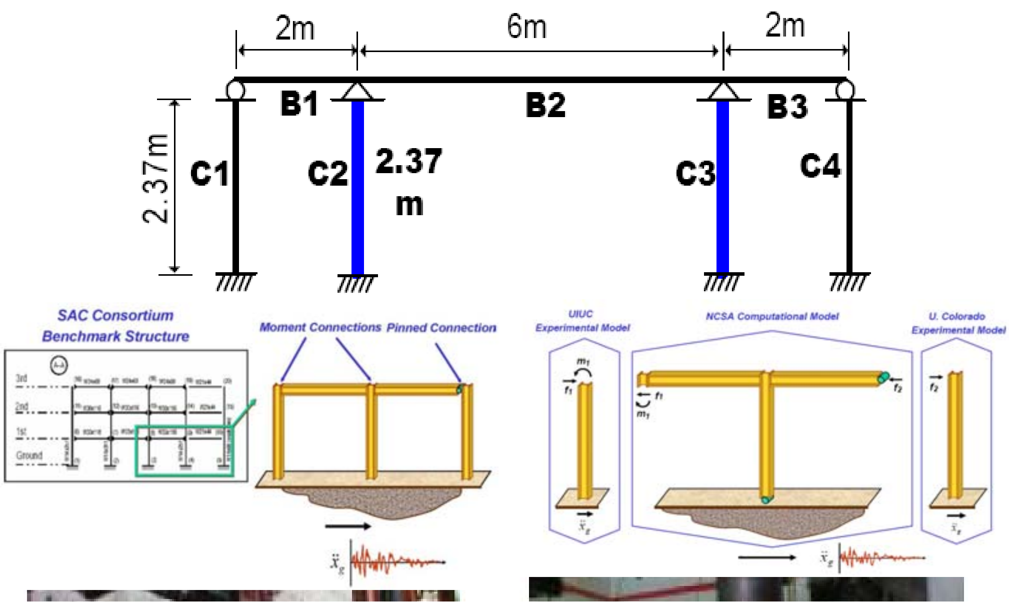

Figure 1.51 Sketch of the MOST experiment (from [Spencer *et al.*, 2004])

Figure 1.50 The DSCFT test campaign [Tsai *et al.*, 2003]

The third geographically distributed test is the Multi-Site On-Line Simulation Test Experiment ([Spencer *et al.*, 2004] and Figure 1.51), performed the 30th of July 2003 across the US in the framework of the NSF George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), and involving 2 experimental facilities (University of Illinois at Urbana-Champaign-UIUC & University of Colorado at Boulder) and a supercomputing centre (National Center for Supercomputer Applications at UIUC). This test used UI-SIMCOR and NTCP (or precursors of this environment and communication protocol, see Section 3.7.2.2). An average experimental elapse time of 13s/simulation time step has been obtained during the test.

Note that either UI-SIMCOR and ISEE used a monolithic approach and relied on the same time integration scheme (α-OS) as the one already used at ELSA in June 2001 for the VAB test, a substructured bridge test involving a highly non-linear fibre modelling, already distributed over the internet, but performed at the same location [Pinto *et al.*, 2004]. All these experiments used also the classical PSD ramp-and-hold procedure to load the experimental substructures. Other alternatives exist, leading to more continuous trajectory for the actuator motions. For instance the so called extrapolation-interpolation method of Nakashima & Masaoka [1999], and its application to continuous test in the presence of random communication delays [Mosqueda *et al.*, 2005]. Finally it is worth to mention that party iterative schemes have been introduced in order to better balance the equilibrium equations than using the Operator Splitting (OS) approach. They have been introduced in the so-called peer-to-peer (P2P) Internet online hybrid test system developed in Japan [Pan *et al.*, 2006] and used in conjunction with very non-linear analytical structures [Wang *et al.*, 2008].

Always in the framework of NEES, an object-oriented tentative to effectively integrate FE software and laboratory as a special element has been provided thought the middleware OpenFresco ([Takahashi & Fenves, 2006] and Section 3.3.2). OpenFresco has been used for intercontinental distributed experiments between US and Japan (Kyoto University & UC-Berkeley, distance 9000km). In 2004 the round trip communication time for packets between KU and UCB was about 200 ms with an average elapse experimental time of 3.6s per PSD time step (with 2.6s taken by a slow control system). More complex recent tests performed on bridge piers (and including highly non-linear fibre modelling) exhibit a performance of around 1s/step. These tests also illustrate one human difficulty associated with distant geographically distributed testing: the local time in Japan is 15 or 16 hours ahead with respect to California: one installation should by force be operated during the night.

The performance issues are more and more taken into account in the current development and use even if it seems difficult to extrapolate the results to geographically distributed testing. Examples are the evaluation of OpenFresco and SIMCOR for fast hybrid single site simulation [Haussmann 2007] and the development of the new MERCURY platform for slow, fast and hard real time hybrid simulation [Kang & Saouma 2008].

It is finally worth noting the latest developments performed by the laboratories part of UK-NEES (Oxford, Bristol & Cambridge) in the field of real-time geographically distributed testing. By using a PSD approach & optimizing the implementation at every levels (communication, computations and control), it is demonstrated that real-time testing is attainable [Blakeborough & Williams 2009]. Clearly these results are obtained at the very limit of what is achievable, and rely on ad-hoc software implementations, use of dSspace boards and high speed networks, control of reduce capacity actuators (10T) with systematic use of delay compensation techniques, 50 time steps par second and are still limited to the study of simple cases. However this could be the starting point of a European network of facilities for fast to real-time hybrid testing.

3.7.2 State of the art of geographically distributed testing

3.7.2.1 *Background*

As shortly outlined in the introduction, the current implementations of geographically distributed testing rely mostly on the classical PSD method where the performances in term of time-step uniformity and trajectory continuity are not considered as of primary importance. It allows a high level of modularity and in particular the complete software separation between time integration algorithms and communication management and control of the experiment. In the monolithic implementation, the experimental parts can be considered as a collection of special elements: it is thus possible to talk of hybrid *simulation* as systematically used in the NEES (Network for Earthquake Engineering *Simulation*) community in the US.

The interest of such an approach is that it allows standardization. As a matter of fact, some software environments have been already developed in order to perform distributed tests. These environments usually encapsulate a finite element code and a communication layer with the experiment(s). The performance of such tools is closely linked to the performance of the communication protocol used underneath.

The next section will shortly introduce these tools.

3.7.2.2 *Available tools & performance*

OpenFresco. This Open-source Framework for experimental setup and control is a C++ object-oriented software developed at UC-Berkeley [Takahashi & Fenves 2006]. It is to be considered as a middleware, and provides services needed to carry out hybrid simulations locally or on a local or wide area network. It has been designed to easily integrate with OpenSEES. In fact, it uses the same scripting language (TCL) and object design. Many of the data structures and architectural concepts are derived from OpenSEES (Nodes, Elements, Integrator objects, etc…), although for release 2.5 OpenFresco can be downloaded at http://neesforge.nees.org/projects/openfresco/ completely independently from OpenSEES.

OpenFresco performs the interface to some FE-software (OpenSees, LS-Dyna & Matlab for release 2.5) and the control systems at the laboratory(ies) (dSpace, LabVIEW, MTS Computer Simulation Interface, and various combinations between xPC-Target, SCRAMNet & Simulink for release 2.5). The various software framework components are indicated in Figure 1.52.

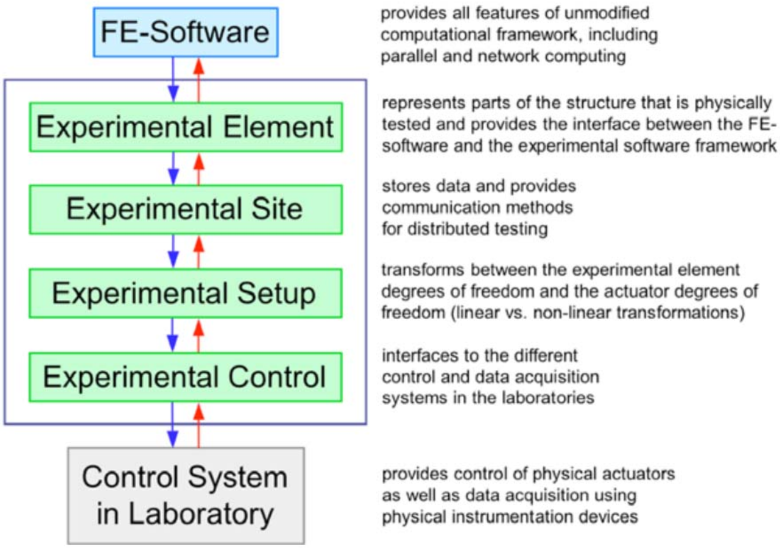

Figure 1.52. OpenFresco software components (from Schellenberg *et al.* [2007])

According to [Schellenberg *et al.* 2007], OpenFresco handles three common, repetitively imposed sets of tasks needed to implement computer-controlled tests. The first involves transforming actions at the boundary nodes for the experimental elements (e.g. displacement, velocity, acceleration or force) from the coordinate system used by the elements of the FE software to those used in the laboratory. Objects implemented within the ExperimentalSetup class are thus responsible for transforming the degrees-of-freedom for each ExperimentalElement into actuator degrees-of-freedom, utilizing the geometry and the kinematics of the loading and instrumentation system, and back again. These transformations can be implemented either as simple linear transformation matrices (small displacements) or they can be implemented as complex algebraic transformations taking large displacement effects into account. The second basic task involves communicating with the laboratory control and data acquisition systems so that the command actions in the actuator coordinate system are imposed and measured ones are returned to the finite element program. The OpenFresco ExperimentalControl class is responsible for interfacing with specific laboratory control and data acquisition systems and performing these functions. The advantage of this abstraction and the encapsulation of these operations is that the ExperimentalSetup class separates the details of the loading system configuration from the ExperimentalControl class. Thus, those responsible for the IT aspects of the control and data acquisition systems need only be concerned with the ExperimentalControl class; while those configuring the actuators and sensors can focus on the ExperimentalSetup class. To enable geographically distributed testing, the ExperimentalSite class provides the services for communicating between the experimental site (as a server) and the computational software (as a client). Other classes are available for utilizing communication protocols between the two.

The source software is served with a rich documentation. Earlier versions of OpenFresco used the NEES Telecontrol Protocol (NTCP) to exchange data. In version 2.5, geographically distributed tests are run using secure communication channels (OpenSSL) and the specialized class pair RemoteExpSite/ActorExpSite pair has been thoroughly changed to increase efficiency and includes NHCP, the secure NEES Hybrid Communication Protocol.

UI-SIMCOR. UI-SIMCOR is the hybrid simulation framework developed at the University of Illinois at Urbana-Champaign [Kwon *et al.*, 2005]. It is a "coordinator" software product built on MATLAB which provides no inherent modelling or testing capability. It provides slots for modules, which communicate through the coordinator (a bus-like architecture). Modules can provide modelling/simulation, or connect to physical instruments (see Figure 1.53). UI-SIMCOR can be downloaded at http://neesforge.nees.org/projects/simcor/.

Following [Kwon *et al.* 2007], the basic concept of the framework is that analytical models associated with various platforms or experimental specimens are considered as a superelement with many DOFs. Each of these elements are solved on a single computer or on different computers connected through the network. The main routine shown in Figure 1.53 enforces equilibrium and conducts dynamic time integration. In this process, the structural model is fully encapsulated as objects of a class. Hence it is straightforward

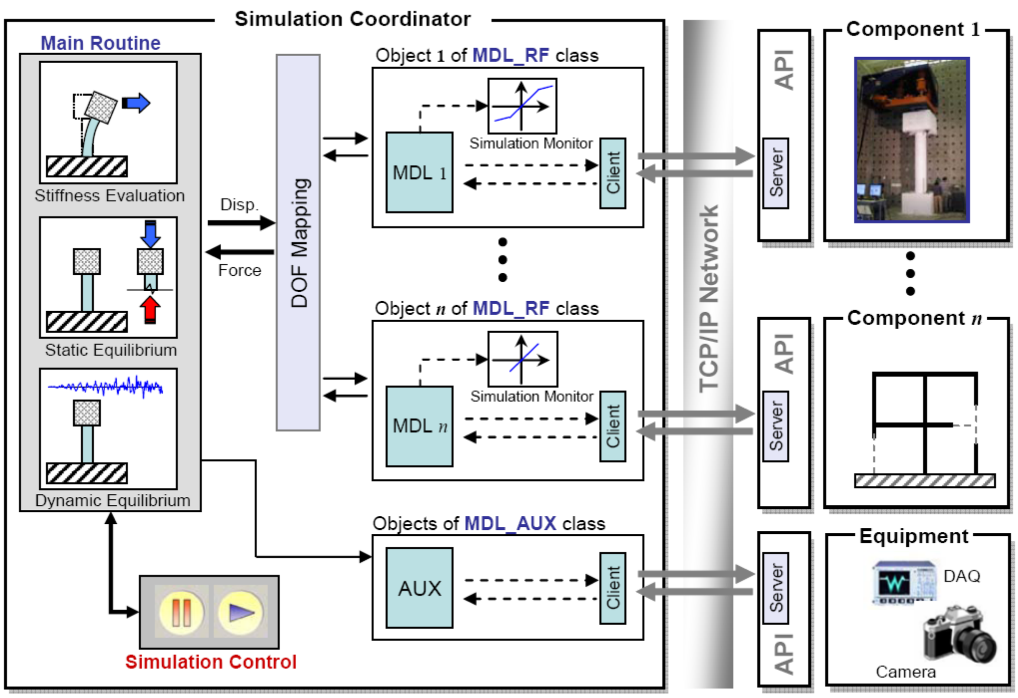

Figure 1.53 Architecture of UI-SIMCOR (from [Kwon *et al.*, 2007])

to add new time integration or methods to enforce static equilibrium.

There are two classes in UI-SIMCOR: MDL_RF (restoring force module) and MDL_AUX (auxiliary module). The objects of MDL_RF class represent structural components. The main functionality of this class is abstraction of the structural components at remote sites. The main routines such as dynamic integration schemes impose displacement onto the structural components and retrieve restoring forces without consideration of communication with remote sites regardless of whether the components are experimental specimens or analytical models. This abstraction allows exceptionally easy implementation of new simulation tools and components.

Another important functionality of the MDL_RF class is communication. When the main analysis routines impose a displacement on a structural component represented by an object of MDL_RF class, the object reformats the data for the pre-specified protocol, opens connections to the remote sites, and sends the reformatted data. These are introduced in the following section. MDL_RF class includes other functionalities such as checking force and displacement capacities at every time step. In addition, the object of MDL_RF class shows the communication status and monitors communicated values at each time step. MDL_AUX class is used to control experimental hardware other than actuators. The object of this class has the function to send out pre-specified commands to remote sites. Upon reception of the command, the remote sites can take actions such as taking pictures or triggering data acquisition.

At remote sites, it is necessary to have an Application Program Interface (API) which opens ports for connection from main framework, impose displacements to analytical model or experimental specimen, and send measured data. The APIs for analytical platforms have been developed for Zeus-NL, OpenSEES, FedeasLab and ABAQUS.

The communication through the network following standard protocol is one of the most important requirements for geographically distributed hybrid simulations. In EU-SIMCOR, six communication protocols are implemented including NTCP, the new NEES Hybrid Simulation Communications Protocol (NHCP), and a protocol for OpenFresco.

The generic module-based approach is very powerful, since each module can be any type of simulation software or any type of experimental interface. Thus, using SIMCOR it would be possible to divide a problem into separate parts, with each part simulated using different software. The separate parts can communicate with each other via SIMCOR to provide a combined simulation/experiment, all with minimal modification and customization. In theory tools such as OpenFresco could provide similar functionality, by putting simulation software in the SiteServer objects, but in reality OpenFresco was generally intended to have a central modelling/simulation program driving multiple "sites" consisting of experimental elements.

The software is also served with a rich documentation. From the User Manual and Examples for UI-SIMCOR v2.6, the examples show an elapse experimental time per PSD time step ranging from 0.4 to 6.5s.

ISEE/PNSE. The platform for collaborative experiments for earthquake engineering ISEE has been developed at NCREE (Taiwan), and developed two different approaches: the database and the application protocol approach. The database approach is interesting for low-speed pseudo-dynamic simulation tests. In fact the network and data processing time cost per step is about 0.2 seconds for networked domestic experiments and is about 2 seconds for transnational experiments [Yang *et al.*, 2004]. More network efficiency is given in the application protocol approach whose architecture is given in Figure 1.54. NCREE is opened for collaboration but the software is not as easily accessible as

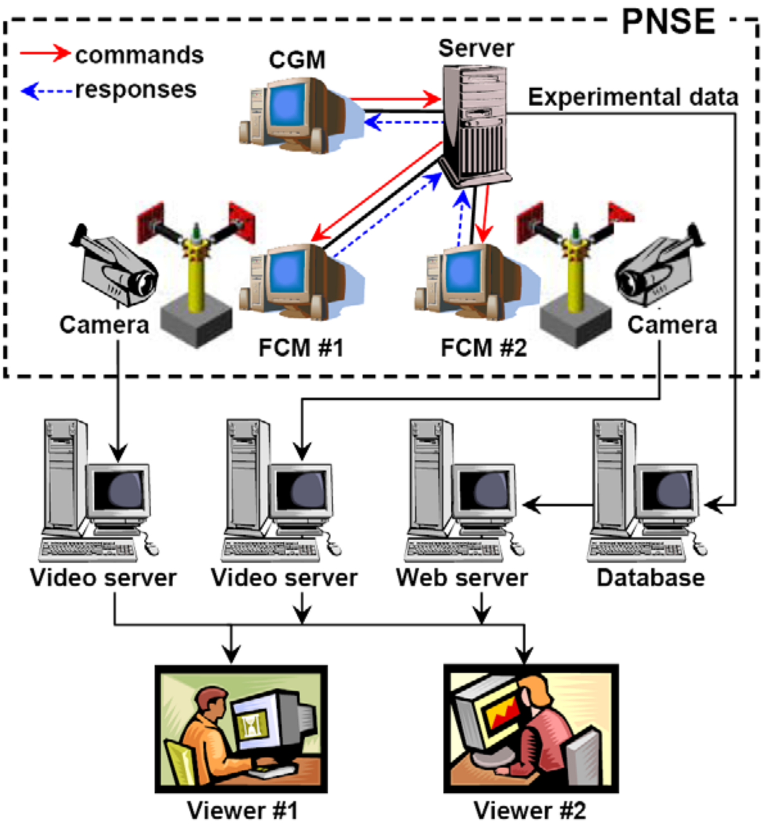

Figure 1.54 Architecture of PNSE (from Tsai *et al.* [2003])

OpenFresco and UI-SIMCOR.

Following [Wang *et al.*, 2004], three types of modules on PNSE, the PNSE server, Command Generation Module (CGM), and Facility Control Modules (FCM) are connected by employing socket operations to utilize the TCP/IP suite to ensure high interoperability between heterogeneous networks and working environments.

- The PNSE server is essentially the information centre of the platform. It provides services of message dispatch and data delivery for clients. Conceptually it is the centre of the network topology, but here it is not the "processing centre" which determines and controls the sequence of the work. The server also takes the responsibility of data storage and manages a simple login process for any connection attempt for security concern. The server can be connected with a FE code (OpenSEES) in case of complex numerical structure.
- The CGM calculates or prepares the commands to be imposed on the specimen. The module that generates commands can be a numerical integration algorithm in pseudo dynamic testing, an input module that queues predefined command profile in quasi-static testing, or simply a remote control application with an user interface that allows its user to enter commands dynamically. The CGM prepares commands for all FCMs and integrates them into a single packet (composite command) to send to the server for parsing and dispatching. It then waits for a data packet (critical response) sent by all FCMs and dispatched by the server as an indication of the completion of the command execution.
- The FCM receives the parsed commands from the PNSE server and controls the actuators to impose the commands on the specimen, then measures or calculates the critical responses and sends them back to the server as a notification of the completion of command execution. When all FCMs complete execution of their own commands, the server notifies the CGM of this event and the CGM can then send the commands for the next step. The FCM on PNSE is quite the same as the traditional facility control program in a structural laboratory. It still controls the actuator motion, performs the data acquisition, alters the test running state if necessary, and displays the real time test results to its operator. One difference is that the FCM on PNSE executes the commands received from the PNSE server, instead of the commands generated by FCM. Another difference is that it is obligated to send the notification to the server when the command execution is completed.Enhances range of applications.

Note finally that PNSE uses its own application protocol called NSEP. It does not seem that NCREE is about to integrate the NEES standards (NTCP or NHCP). The preferred approach is to develop interfaces with UI-SIMCOR or OpenFresco by means of an additional translation software layer.

NTCP. To promote collaboration of equipment sites across the USA, NEES consortium has developed a standard communication protocol, NTCP (NEESgrid Teleoperation Control Protocol [Pearlman *et al.* 2004]). NTCP allows secure communications between remote sites through the NTCP server.

NTCP places a strong emphasis on security, using Globus tools to authenticate and authorize users, with optional message integrity. However, according to Spencer *et al.* 2006, none of the users had mad use of these features in real tests. The findings were as follows.

- Security must be optional, so that it can be disabled if not needed.
- The main risk is programmatic or user error.
- Host-based security for TCP/IP will cover the majority of cases.
- Must be as resistant as possible to worms and denial-of service attacks that might happen.
- Port numbers for servers should be changeable.Enhances range of applications.
- SSH tunnels or VPN routers are also possible solutions.

NTCP is available for Matlab at the following link http://www.nees.org/it/software/ntcp/. It is included in OpenFresco and UI-SIMCOR.

3.7.2.3 *Improving performance*

NHCP (NEES Hybrid-simulation Control Protocol) is a reworking of NTCP such that it can be used for fast, distributed testing [Cowart *et al.*, 2007]. Researchers proposed as a design goal, the ability to perform an experiment in soft-realtime (approximately 50-75 steps per second) over a 500-kilometer link. NTCP in contrast, has a limit of roughly 5-10 steps per second over much smaller distances.

Thus, NHCP is an attempt to become the successor to NTCP, and bridge the technology gap between slow experiments using NTCP and experiments using SCRAMnet, an expensive technology requiring specialized hardware. SCRAMnet can operate at 1024 steps per second and can create a hard-real-time network, but is not based on commodity networking and is therefore quite expensive. Moreover, its physical limitation of having a two to ten kilometer range prohibits the exploration of distributed testing.

NHCP chose to enable a simple system based on incorporating OpenSSL into its architecture. OpenSSL is an Internet standard used in numerous areas, not the least of which is online commerce. This allows NHCP to leverage considerable investments in infrastructure that others have made, with confidence that the underlying code is reliable and well tested.

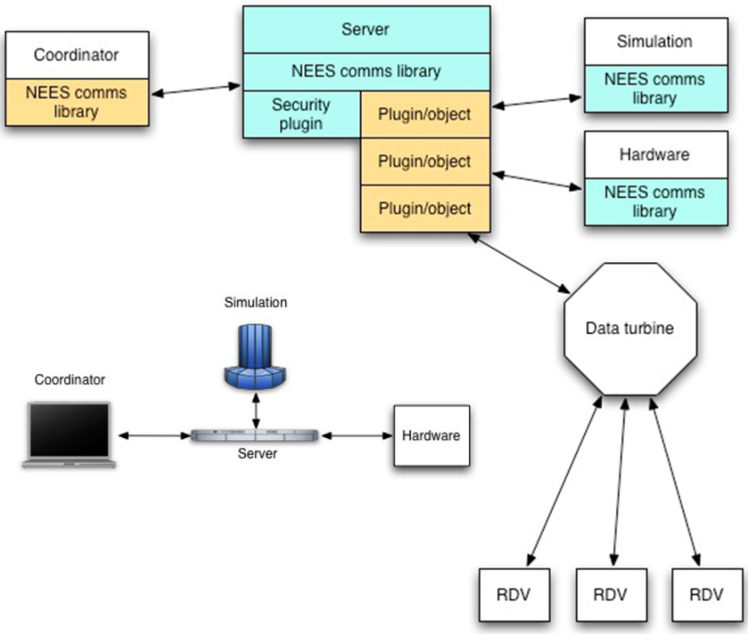

Figure 1.55 NHCP system architecture (from [Spencer *et al.*, 2006])

As depicted on Figure 1.55, NHCP implements a *coordinator/server/simulation* and/or *hardware* paradigm. The coordinator has the central concept of the overall experiment.

- The coordinator has the central concept of the experiment. It knows what is to be tested, units, geometry, username/password, and is generally where the experimenter is monitoring.
- The server runs a process that centralizes communications. It has plugins/code to handle different control systems, communications channels, logging, hooks into the authentication/authorization and streaming data. When the coordinator sends out a new set of commands, the server is responsible for directing messages to the correct destination, routing responses back to the coordinator. A coordinator can and will talk to multiple servers (one per site, probably) but each server will load and run multiple plugins.
- The simulation and hardware look alike to the coordinator; in other words the coordinator's interface to both is the same. This allows the simulation to replace

hardware, both for experiments and algorithmic validation. The server will have dynamically loadable drivers/plugins to allow for different communications channels, protocols and interface.

NHCP is available for download at http://www.nees.org/it/software/nhcp/. It is not served with many documents and the demo applications are not running correctly without interventions in the source code. As far as it is declared, NHCP is implemented in OpenFresco & UI-SIMCOR.

The experience of UK-NEES tends to demonstrate that the declared performance of NHCP may be difficult to reach. The real-time distributed tests [Blakeborough & Williams, 2009] are performed with 50 time integration steps per second over a distance of 300km, but necessitate high optimization of the processes involved which is in contrast with the generality of NHCP.

3.7.2.4 *Challenges of geographically distributed testing and consequences for EFAST*

Whatever is the nature of the connection between 2 laboratories, the maximum speed of transfer of information is the light velocity. To put numbers, a round trip (back and forth) of photon take 2ms for points distant of 300km, 6.6ms for 1000km and 66.6ms for 10000km.

As a consequence, it is a priori impossible to run distributed test involving strong coupling of 2 (or more) shaking tables (or dynamic physical substructures) located on different continent. Only closely located installations (<300km) would be eligible for such tests, providing that the most advanced communication technology is available. At software level, it can be seen that 100 steps/s (10ms/step) is the maximum current expected performance (not yet reached), which is already too large to couple shaking tables if sudden events are expected during the test.

Then, for tests that do not require hard real time (laboratory time equal to prototype/accelerogram time in a guarantied uniform manner), and using procedures [Mosqueda et al., 2005] or algorithm [Pegon, 2008] leading to smooth trajectory of the actuators, it seems to be possible to reach in a future fast test speed (10 times to 3 times slower than the real time). However, for the time being, 10 to 20 prototype time steps per second seem to be what is reachable while maintaining a certain generality of the approach. The demonstration test to be performed in Task 3.3 of EFAST should take into account this fact.

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3.8 INSTRUMENTATION AND DATA ACQUISITION

Alain Le Maoult, CEA

3.8.1 Introduction

Efficiency of experimental research studies is generated by the confrontation between tests and models. But researchers can only compare tests and models if physical time varying phenomena are measured during the test and converted into useful data (numerical data now days). That is what instrumentation has to do: measure with sensors and convert with signal-conditioning equipment (recording and processing).

Instrumentation and data acquisition is a major and huge experimental subject. The objective of eFast study is to design the possible future European facility. This part of the state of the art will then focus on aspects that have to be taken under account to design the instrumentation of eFast facility.

In seismic facilities, there are 2 main uses of measurements in testing and simulation. The first one is for closed-loop control of actuators; the second one is for data analyses (seismic tests or modal analyses).

Moreover, in eFast facility, two kinds of tests will probably be performed:

- "Standard tests" with "standard instrumentation" that is currently used in shaking table and reaction wall facilities,
- "Real time hybrid tests" with a more specific instrumentation (numerical data are integrated in real time to a model…).

Then, for control and data analyses of standard tests and hybrid tests, we will try to answer to following questions:

- What instrumentation will be needed in eFast facility?
- Which studies have to be done during eFast study to better design the instrumentation of eFast facility?

To answer to those questions, we will present and discuss instrumentation that is currently used in shaking table and reaction wall facilities for control and data analyses.

The first part will introduce general concepts of instrumentation, the second will present some interesting kind of sensors and cables, the third one will deal with signal-conditioning equipment.

3.8.2 General concepts of instrumentation

There are many references in the literature describing sensors types, amplification and filtering. For example, topics of instrumentation and data analysis have been well covered by ASME [1975]. Nevertheless, during the last 30 years, electronic improvements generated many changes and innovations in instrumentation and conditioning: digitalization of data, computers (to manage calibration, conditioning, storage, analyses…), embedded conditioning systems… Then, it is preferable to refer to quite recent references. For example, it is possible to find much information presented below in [Kleman, 1989, Norvelle 2000, Boyes, 2002, K. G. McConnell, 2008, Bolton, 2008].

3.8.3 What is instrumentation?

Instrumentation is now days necessary to most of machines. The information created by instrumentation can be used inside the system, to make it better work (regulation and control for cars, actuators…) or transmitted outside the system (phones, telescopes, medical thermometers…) for data storage and analyses. Instrumentation is a very dynamic market field with many companies providing sensors and transducers, research and development activities.

Note: in the following state of the art, no difference will be done between a sensor (sensing part) and a transducer (converting part).

Instrumentation consists in sensors, transducers, signal conditioning, processing and recording. A transducer transforms a physical time varying phenomenon to an electrical voltage. That conversion is done using a mechanical or/and electrical effect. The physical phenomenon is generally named “measurand”. In seismic laboratories, the five following measurand are useful in most applications:

- Displacement (low frequencies),
- Velocity (medium frequencies),
- Acceleration (high frequencies),
- Strain,
- Force.

Displacement and force are major measurements in reaction walls laboratories. In shaking table facilities, major measurements are displacement, force and acceleration.

Major measurement characteristics of transducers are:

i) Static characteristics:

- Noise (electrical or numerical),
- Sensitivity,
- Linearity,
- Operating bandwidths (temperature range, motion cross-sensitivity, frequency range…),
- Stability,
- Repeatability and reproducibility.

ii) Dynamic characteristics:

- Response time: time to have a sensor output value equal to 95% of the input step signal (the physical phenomena),
- Rise time: time to have a sensor output value from 10% to 95% of the steady-state value,
- Settling time: time to have a sensor output value settled within some percentage of the steady-state value,
- Linear phase response.

iii) Other characteristics:

- Interaction with the mock up (sensor size and stiffness…),
- Price,
- Friendliness,
- …

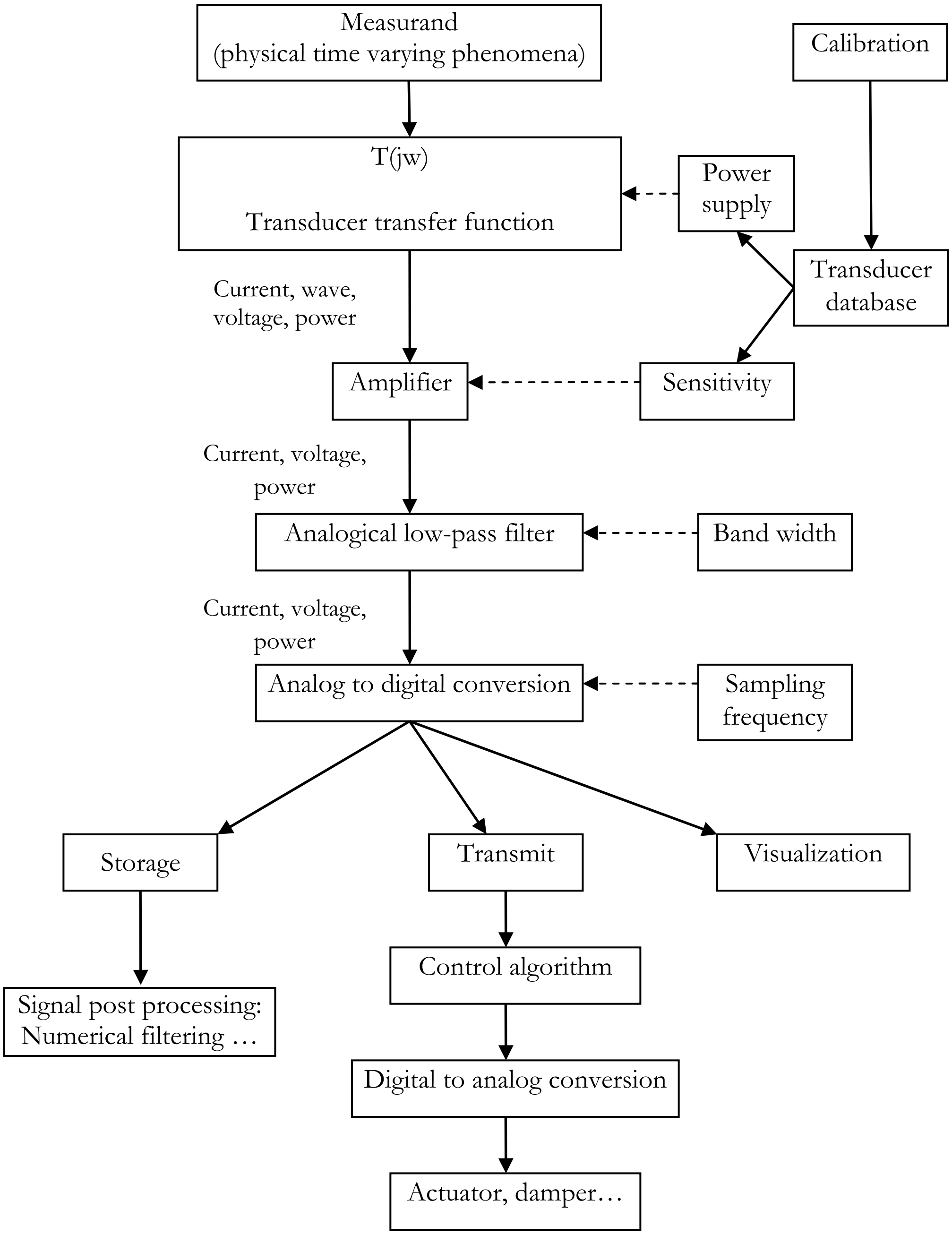

Figure 1.56 A standard measurement process.

Depending of the use, measurement specifications are different: for example, for control, time delay is a main characteristic but friendliness is not so important. For analyses, measurements do not need a short time delay but friendliness can be important.

The measurement process is more or less the same in each laboratory. A standard measurement process is presented in Figure 1.56.

3.8.4 Accuracy

The general term "accuracy" is used to define the ability of the instrument to give results that are "the true value". The difference between the true value and the measured value is due to measurement errors: time delay, noise, calibration… Sources of errors can be random or systematic. Random errors are ones which occurs when reading successively the same quantity. Systematic errors do not vary between one reading to the other. Random errors can be minimized by taking a number of readings and obtaining a mean value. Systematic errors require the use of a different instrument or measurement technique to establish them [Bolton, 2008]. The measurement error is a combination of errors due to temperature, noise, … The basic rules to calculate errors are:

- When we add or we subtract two measured quantities the worst possible error in the calculated quantity is the sum of the errors in the measured quantities.
- The percentage error in the result of the product or the division of two measurements is equal to the sum of the percentage errors in each of the measured quantities.

Accuracy is connected to the dynamic characteristics of the transducer. The "mechanical impedance" of the transducer is the ratio between the measurand and the mechanical effect. The "electrical impedance" is the ratio between the mechanical effect and the electrical voltage. Both mechanical and electrical impedance have to be as larger as possible to have the best accuracy as possible.

Mechanical and electrical characteristics of the sensor have then a major impact on measurement accuracy. It is generally possible to describe transducer behavior with some quite simple models. Some of those models will be presented below.

Accuracy is connected to the environment of the transducer too. The environment can have effect on the measurement errors: temperature, humidity, acceleration, electrical parasites…. In seismic testing, environment is generally ambient temperature and ambient humidity.

Many measurement errors can be corrected using procedures and techniques, for example:

- Time delay is most of the time due to filtering. It can be easily reduced with a higher cutting frequency or with appropriate filter characteristics.
- Electronic noise exists in all circuits and devices as a result of thermal motion of the resistor molecules (linked to temperature, bandwidth and resistance of the transducer). Random noise can be reduced with filters, means, length cable reduction and electrical isolation (twisted pairs of wires, electrostatic screening…).
- Calibration procedures improvement permits better sensitivity evaluation. Look up tables now permit to define sensitivity "by parts" along the measuring bandwidths.

As the measurement of time-varying physical phenomena includes many steps, errors can occur in every step: calibration, amplification, filtering, analogical to numerical conversion, cables and sensor, installation. In the case of hybrid testing for example, propagation of errors will depend on the algorithm stability. Accuracy will be developed along the following chapters.

Future direction: Evaluation of propagation of errors in hybrid algorithms.

3.8.5 Sensors

Basic control of actuator can only be done with displacement feedback but modern dynamic control techniques generally use multiple feedbacks and force feedback is most of the time needed for hybrid testing Dimig J. [1999].

As hydraulic actuators are velocity sources and tested structures are force sources, closed-loop control of hydraulic actuator are using displacement feedback, velocity feedback, acceleration feedback or/and force (or pressure) feedback. Then, displacement sensors, accelerometers, force and pressure sensors can be used for actuator control.

3.8.6 Location and number of sensors

For standard control, almost all sensors are embedded in facilities (actuators, shaking table…). For hybrid testing, many sensors could be used in future tests. Currently, this question of number of sensors is precocious in the development of this control technique.

For data analyses, signal from a single point and a single direction is not sufficient, but sensors are expensive and time consuming (calibration, installation, data storage and data analyze). The number of sensors has to be minimized. The minimization of the number of sensors is a challenge. The minimization can only possible if objectives of the study are well defined and if a model of the structure has been done before tests to optimize sensor operating bandwidths and location.

In seismic laboratories, white noise tests or hammer tests are performed for modal analyses. These tests use standard instrumentation but more transducers are generally needed for higher modes evaluation. In the field of Structural control and health monitoring, some solutions to the optimal sensor location problem have been proposed based on convergence and uniqueness criteria, and on the use of efficient estimators [Shah, 1978, Heredia-Zavoni, 1998]. This kind of optimization has for example been studied on 3 multistory frames by Limongelli [2003].

Large facilities generally use 3 kinds of sensors:

i) Standard sensors: Displacement (LVDT, RVDT), Acceleration (piezoresistive), Force (piezoresistive). They are used in all experimentations.
ii) Specific sensors: facilities provide sensors dedicated to specific experimentations with specific specifications: other technologies (Laser, optical…), measurement of other physical parameters (flow, pressure, velocity …), other dimensions...

The following table gives an idea of the number of most used sensors in some large facilities in Europe and USA:

	Displacement	**Acceleration**	**Force**
France/CEA/Tamaris (shaking tables)	204	105	132
Italy/JRC (reaction wall)			
Italy/Eucenter (shaking table + reaction wall)			

USA/University of Buffalo (Shaking tables)	112	173	-
USA/University of San Diego (Shaking tables)	25	85	-
USA/University of Nevada (Shaking tables)	156	19	24

Table 1.2 Number of standard sensors used in some large facilities in Europe and USA

Datas for US facilities have been collected from NEEScentral web site (https://central.nees.org/?facid=274&action=ListFacilitySensors) that gives an access to all equipment details for NEES facilities (shaking tables, reaction walls…).

3.8.7 Displacement transducers

Displacement transducer is one of the most used in shaking table and reaction walls laboratories. In regard to the reduction of signal to noise ratio reduction, displacement transducers should be used to record signals at low frequencies (< 20 Hz, depending on the used technology).

Much kind of translation displacement sensors technologies exist: LVDT (Linear Variable Differential Transformer), potentiometers, rotary with cables (Rotary Variable Differential Transformer), laser, optical camera (presented in "optical camera" section), optical encoder, optic fibers…

For actuators control, displacement transducers are the most important transducers and basic control of actuator can be done with only displacement feedback. Two LVDT sensors are used in actuators, one in the servovalve (spool of the amplification stage) and the other in the piston. Accuracy and linearity of LVDT is very good for short stroke measurement.

For data analyses, RVDT are frequently used. They do not have high accuracy but they are easy to install, not expensive, robust and they are able to measure relative displacement between 2 points even if a little rotation of the cable occurs (lateral displacement of the structure).

3.8.8 Velocity transducers

Linear and rotational velocity is most of time filtered and deduced from displacement and/or acceleration measurements (cost efficient).

In regard to the reduction of signal to noise ratio reduction, velocity transducers should be used to record signals at medium frequencies (>5 Hz and <50 Hz, depending on the used technology).

Nevertheless, for actuator control, if accuracy is not good enough (errors due to differentiations of displacement measurement), linear velocity can be measured with magnet sensors too (Tachnometers).

For data analyses of rotational velocity, gyrometer transducers are very efficient. Magnetic sensors (Eddy-Current Tachnometers) and optical encoders can be used too.

3.8.9 Acceleration transducers

Acceleration transducer is one of the most used in shaking table laboratories. In dynamic testing applications, typical accelerometers lower limit is 0.01 g and typical higher limit is 20 g. In regard to the reduction of signal to noise ratio reduction, acceleration transducers should be used to record signals at high frequencies (>20 Hz, depending on the used technology).

Accelerometers transducers can be correctly represented with a simple degree of freedom oscillator, a second-order differential equation with constant coefficient of mass, damping and stiffness. 2 forces are exciting the oscillator, one due to gravity and the other to inertial excitation forces. This model permit to better understand that impedance is not the only parameter to build an accurate transducer:

- The mass has to be low, to decrease interaction with the mock up.
- The natural frequency of the transducer has to be higher (at least 5 time higher) than the one of the measured signal to minimize distortion. To have a low mass and a high frequency, stiffness has to be high (reason why piezoelectric material is frequently used in transducers).
- Damping has to be closed high enough (0.7 is perfect) to increase stability but low enough to decrease time delay.

Some technologies and general models (and more specific ones for force, pressure and acceleration) are presented by Walter [2001].

All accelerometers technologies are based on the Newton's second law (Force=Mass x Acceleration). Measuring deformation generated in the support of a mass can then permit to deduce Acceleration. This deformation can be measured with piezoresistive or piezoelectric effect.

Piezoresistive effect describes the changing electrical resistance of a material due to applied mechanical stress. This changing can be generated by a geometrical deformation (strain gage made of constantan for example) or a stress dependent resistivity of the material (germanium, silicon, single crystal silicon). Sensitivity of stress dependent resistivity effect can be several orders of magnitudes larger than the geometrical piezoresistive effect. For acceleration measurement, wire strain gage technology gives a limited frequency range due to the low gage factor (~ 2). The high gage factor of piezoresistive materials permits measurement of large frequency range. For acceleration measurement, Piezoresistive sensors are very much used in seismic studies. Nevertheless, with low frequency measurement, gravity force can generate errors when the accelerometer's sensing axis rotates.

Piezoelectric effect is the ability of a material (crystals in sensors) to generate an electrical potential in response to applied mechanical stress. The crystal in piezoelectric accelerometer acts as an electrical charge generator with a certain capacitance, this produces the voltage output (Charge=capacitance x voltage). Then, this technology is very useful and accurate for high frequencies measurements but do not measure low frequencies, approximately fewer than 6Hz (because of the capacitance discharge). Therefore, piezoelectric accelerometers should not be used for seismic studies. Nevertheless, piezoelectric sensors can be useful for shocks studies.

Another important parameter is the cross sensitivity of the sensor (influence of the acceleration in orthogonal directions) that is mainly induced by the manufacturing quality.

3.8.10 Pressure transducers

Pressure transducers are used in actuators control systems to estimate the force generated by the facility (table plate, mock up …). Transducers are generally strain gauge pressure instruments that are able to measure static pressure and high pressure.

The measured pressure ΔP is the differential pressure of oil between the two cylinder chambers of the actuator. Neglecting the viscous forces in the actuator, we can calculate the force using the piston area.

Supply pressure is also sometime measured in hydraulic systems. Indeed, this pressure can decrease when flow demand is higher than hydraulic pump flow capacity. Supply pressure is a main parameter for actuator motion and control.

Future direction: Internal pressure ΔP of each actuator should be measured. Supply pressure should be measured. As the supply pressure is an important parameter for actuator motion and control, its influence could be numerically evaluated using a standard actuator model like the one described by Merritt [1967]. That relation between supply pressure and actuator performance can be an important parameter for the design of the hydraulic pumps of the eFast facility.

3.8.11 Force transducers

Force transducer is one of the most used in shaking table and reaction walls laboratories.

Force transducers (load cells) are based on strain gage (wire or piezoresistive) or piezoelectric technologies. Efficiency of those technologies has been already described in "accelerometers transducers" section. The main difference between acceleration and force transducers is the strong interaction of force transducers with the structure being measured. Force transducer model have been described by McConnell [1990, 1993] and Han (1986). Force transducers can be well represented by a 2 DOF model: one mass m1 and displacement x1 coming from the seismic mass of transducer and one other mass m2 and displacement x2 coming from the transducer base. This model has to be completed with the external forces: force F1 coming from the structure and force F2 coming from the support of the sensor.

We can study 3 different cases depending on the support:

First, if the mass of the support is infinite. Then x2 is zero and the model can be reduced to a one degree of freedom oscillator (accelerometer transducer model). In that case, the output voltage of the transducer is only linked to the seismic force F1 (and the transducer sensibility):

$$Uf = Sf.Hf(w).F1 \tag{1.29}$$

With:

$$Hf(w) = \left[\frac{j.Tf.w}{1 + j.Tf.w}\right].\left[\frac{1}{1 - r^2 + j.2.\varsigma.r}\right] \tag{1.30}$$

Hf(w): transducer transfer function (Hf(w) = $H_{electrical}$(w) x $H_{mechanical}$(w)).

Sf: voltage sensitivity.

Tf: force transducer's electrical time constant.

$r = w/w_n$ dimensionless frequency ratio.

ζ: damping of the transducer (generally about 0.05).

Second, if the support does not have an infinite mass m2, but the force F2 is zero. m2 and its acceleration have an effect on the output signal of the transducer. The outputs signal will no more be only linked to the seismic force of the structure. An interesting example of this case is the hammer test. In this test, the hammer has a mass m2. Assuming that the hand of the hammers' user does not create any force during the shock (or using a pendulum system to support the hammer), the effective voltage sensitivity Sf' is given by Connel [1993]:

$$Uf = Sf'.Hf(w).F1 \tag{1.31}$$

with:

$$Sf' = \left[\frac{m2}{m1 + m2}\right] Sf \tag{1.32}$$

effective sensibility.

The effective sensibility is clearly influence by m2 mass. Calibration of the sensor should then be done with each m2 masses (generally changed to achieve different contact times and peak impulse force).

The third case of study is the more complex one. In that case, m2 does not have an infinite mass, x2 and F2 are not zero. That can be the case of a force transducer used with actuator and structure in hybrid testing. In that case, the mass m2 may include a part of the actuator (piston for example). The force F2 is the one applied by the oil to the piston. It can be shown S. Han [1986] that the force F1 is clearly dependant on the dynamic characteristics of the force transducer (transducer stiffness).

The output voltage can be written:

$$Uf = Sf.Hf(w).F1 + Sf.Hf(w).F1.m1.\gamma s(w) \tag{1.33}$$

$\gamma s(w)$: Acceleration of the structure.

The second term of the equation is the error. It is linked to the mass m1 and the acceleration $\gamma s(w)$ of the structure. This error has been studied by McConnell [1990]. It has been shown that this error can be significant (~ 25% at the transducer natural frequency) when m1 is very small and the structure is low weight and lightly damped.

In that specific case, some electronic compensation has been developed by D. J. Ewins [1986].

In pseudo dynamic tests and real time hybrid tests, force transducers are necessary in actuator control. In standard shaking table tests, force transducers improve actuator control. Indeed, for a good actuator control, force feedback has to be measured. Pressure transducers (in the two cylinder chambers) or force transducers (mono directional load cells) at the piston rod are currently used. The technical specifications of load cells are quite the same as pressure transducers (strain gauge for static and high forces measurements).

For hybrid testing, force has to be measured at the connections between the real structure and the virtual structure [Mahin *et al.*, 1989, Dimig J, 1999]. Those connections are between the actuator and the tested structure or between a support (a rigid frame or the plate of the shaking table) and the tested structure:

- Between actuators and the tested structure: the force is already measured for actuator control (load cells or pressure transducers).
- Between a support and the structure: load cells have to be included.

Most of time, load cell will have to measure in three directions. For hybrid testing, the force is used in algorithms and measurement errors need to be reduced to increase algorithms stability. Load cells need a good accuracy; the measurement range will depend on the mock up and on the measurement direction: load cells need to have a specific design for each tested structure. To include load cells between the mock up and the support, specific connection are necessary: connections with swivel or pivot, rigid instrumented plates... connections are a major part of boundary conditions, the design of connections have to be very good but connections are time consuming (for the design and manufacturing) and expensive. To reduce this cost, strain gages can be used to measure force in steel mock up U. Dorka [2006].

For data analyses, forces have generally to be measured too. To measure force directly on the mock up, strain gages are commonly used. Strain gauges can be stuck on steel, concrete or mortar. On steel, accuracy is very good for large deformation and strain gauges are not bulky and not expensive.

Future directions:

i) a comparison between pressure and force measurements should be interesting. It could validate the use of pressure measurement to estimate force. Moreover, it should be possible to deduce internal friction forces in the actuator.

ii) a possible solution to measure force between the plate of shaking table and the mock up could be to have instrumentation (strain gages) inside the plate, measuring deformations of the plate during the test. A verification of the performance of that kind of instrumentation could be done: the FE model of an existing shaking table plate should be done, evaluation of table deformations, determination of possible measurements accuracy, and validation with tests.

iii) Development of a sensor model with a simulation software to evaluate measurement errors. Development of electronic compensation of those errors if needed.

3.8.12 Temperature transducers

Temperature transducers are generally thermocouples, thermistors or metal-resistance detectors. Seismic tests are performed in ambient temperature. Temperature transducers have generally no use in data analyses.

Temperature is an important parameter in actuator control because temperature generates main changes on oil characteristics: viscous number (Mac Coull relation) and bulk modulus. Oil temperature has to be measured in the hydraulic circuit. Generally, control tuning is done when temperature is stabilized (generally between 35°C and 40°C).

During the test, with pressure modifications, oil temperature changes. Indeed, a modification of 200 bars (possible supply pressure) will approximately generate a modification of 2.8 °C. This little modification is not significant and doesn't mainly affect oil characteristics.

3.8.13 Optical camera

With recent electronic improvements, optical transducers are now more efficient. Optical transducers can be used for displacement or strain measurements. Optical transducers are composed of cameras, cables, a computer, a lighting system and image processing software. The transducer itself is the camera which is nowadays most of the time a numerical camera. A minimum of 2 cameras are necessary for 3D analyses (stereovision). The choice of the quality of the camera (CCD or CMOS) is important as, obviously, having good pictures analyses is impossible using bad pictures (due to noise and lose of data generally).

The computer permits the conditioning of the camera(s), data acquisition and data analyses (image processing). The major challenge is to manage flow of data for real time tests.

Movies can be acquired and directly analyzed to track the target (displacement measurement). Optical correction of the lens has to be done to ensure precision and lost data have to be avoided.

The lighting system is a key component too. Leds are generally used due to their long life time (100000 hours), easy to design, many colors, large frequency spectrum and possible synchronization with the picture acquisition. Leds have recently increased their power. Multiple lighting sources, directions and filters (monochromatic or polarizing) can be used to improve quality of the system.

The image processing can be done during or after the test (around a crack for example). Many algorithms are developed and available (not presented here). 3D analyses can be done, tracking translations and rotations of objects. The number of possible targets is very high and strain can then be observed for large areas.

Future directions:

Optical sensors should be evaluated for eFast facility.

A comparison between optical sensors efficiency (hardware and software) and standard transducers could be done.

3.8.14 Other transducers

Significant research in the field of transducers for damage detection is currently done on the subject of structural health monitoring van der Auweraer [2003]. In structural health monitoring, modal analyses are combined with FE model of the structure for damage location Friswell [1997].

In seismic laboratories, local measurements are generally realized after the earthquake because they need a priori knowledge of the damage localization. The major technique used in laboratories for local damage detection is visual inspection. If more precision is needed for the quantification of the severity of the damage, local measurements can use acoustic, ultrasonic, magnetic field, X-ray or thermal principles. Nevertheless, the previously presented optical sensors (displacement transducers) can be an interesting solution for damage detection because post test analyses are possible.

Specific displacement or force transducers are frequently built and calibrated in laboratories (generally using strain gages).

Future directions: Optical techniques validation for a damage location during the test.

3.8.15 Link between sensors

The signal transmission component (cable or wireless) is often passed over very lightly. Such treatment can often lead to serious errors (noise, offsets…). Cables are, for example, a major cause of problems but are given little consideration in the design of the experiment. In regard to the high cost of transducers, high quality of cable should be used in experiments. A special documentation has to be available with each kind of sensor, describing details of connections. An ideal system should have only one kind of plug to the conditioning system whatever sensor is used. To avoid cable inversion between channels, systematic operating verifications as to be done.

Cable is an electrical noise source. For noise reduction, cable can be clamped to the vibration surface, length of cable can be reduced and electrical isolation can be made (twisted pairs of wires, electrostatic screening….)

Cable is also a signal attenuator. For resistive and capacitance transducers, output voltage can easily be calculated:

For resistive transducers: $v = \dfrac{Rc}{Rt + Rc} . e$

For capacitance transducers: $v = \dfrac{Ct}{Ct + Cc} . e$

e: voltage source.

v: output voltage.

Rc: cable resistance.

Rt: transducer resistance.

Cc: cable capacitance.

Ct: transducer capacitance.

For resistive transducers, the cable should have the highest resistance (relative to the transducer resistance) as possible to minimize attenuation:

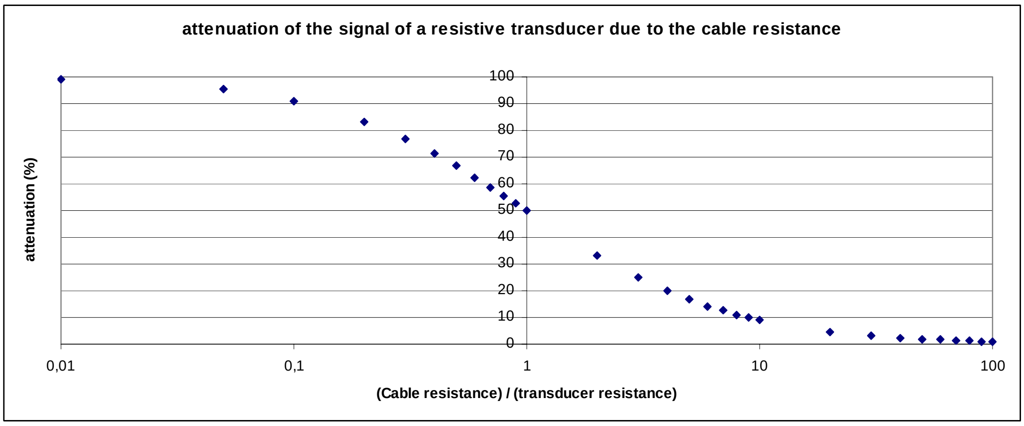

Table 1.3 Attenuation of the signal of resistive transducer due to cable resistance

Therefore, for quite low resistance ratio, the calibration of the transducer has to be done with the same cable than the one used in the experiment. We can then deduce that, for resistive transducers, long cables decrease the attenuation of the signal (but increase the electrical noise).

For capacitance transducers (piezoelectric accelerometers for example), the cable should have the lowest capacitance (relative to the transducer capacitance) as possible to minimize attenuation (see Table 1.4).

That important attenuation is the reason why piezoelectric transducers need very high quality (low capacitance) cables and very short cables. Long cables need intermediate amplification systems or preamplifier with impedance conversion characteristics. Miniature unity gain voltage follower amplifiers are now built inside the transducer's housing (Smart sensors) and the cable capacitance and length have no significant effect on the output. Moreover, with this technology, we obtain high level output voltage signals along with low level noise.

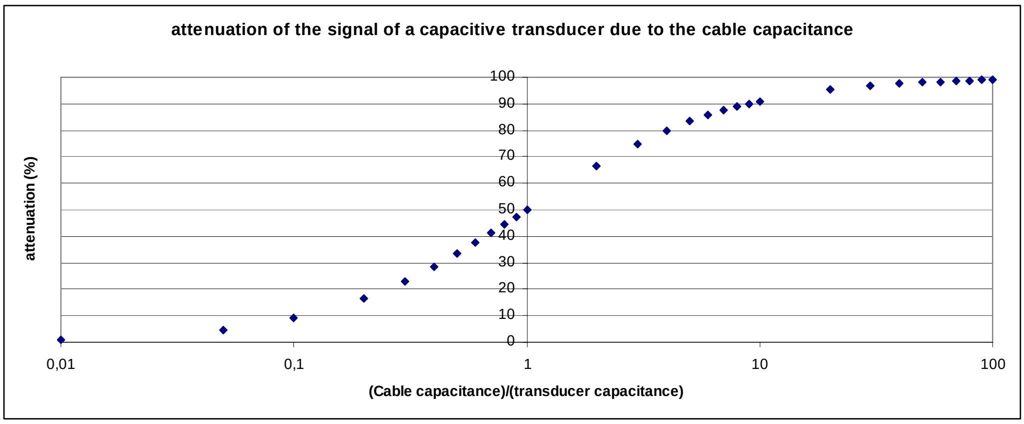

Table 1.4 Attenuation of the signal of capacitance transducer due to the cable resistance

For data analyses, wireless sensors networks have rapidly matured in recent years. They are low cost, easy to install and accurate. Nevertheless, wireless network sensors have low sample rate and communication protocols are complex and still under progress. The operational life of wireless sensor is moreover limited.

For control, one other main problem of wireless sensors is the time delay governed by deterministic and stochastic processes introduced in the network. Wireless sensor networks have recently been studied by J.P Lynch [2008].

3.9 SIGNAL-CONDITIONING

Data acquisition is the process by which data from sensors is transformed into electrical signals that are converted into digital form for processing and analysis by computer. A data acquisition system will include sensors, signal processing, data acquisition hardware and a computer.

Output signals are generally very weak power signals that have to be conditioned in order to transform them into a suitable form for visualization, recording or processing. Then, the signal is first amplified with an external power generator (using the sensitivity of the sensor), filtered and converted to numerical data. Those 3 functionalities are nowadays generally available into only one system. A computer and conditioning software permit to tune conditioning's parameters for each transducer.

The determination of those conditioning's parameters (sensitivity…) has to be made before the test, during tests of calibration.

3.9.1 Amplification, filtering and digitalization

i) Amplification:

Amplification is the process of proportionally increasing the level of the input signal that can be current, voltage or power. Stability is necessary for operation of the amplifier. The main characteristic of the amplification is the gain (output /input).

ii) Filtering:

Filtering is used to extract unwanted frequency components in a signal. The categories of filters are low-pass filters, high-pass filters and band-pass filters. For example, in sine sweep tests (frequently performed in seismic laboratories), a band-pass tracking filter, following the excitation frequency, is generally used to build the transfer function of the mock up.

Filter characteristics are:

- Input and output impedance,
- Cutoff slope (dB/octave),
- Number of frequency bands available for operation and their bandwidths,
- Maximum input voltage amplitude,
- Maximum power of the output signal,
- Linearity over the operating range,
- External power requirement,
- Internal noise,
- Phase response (response delay).

For control use, the phase response is one of the most important parameter because of the direct link to the response delay.

After the analogical to numerical conversion, numerical filters are available in many post-processing software as MATLAB (Mathworks) or LabView (National instruments). They are cost efficient, easy to use and to configure.

Nevertheless, analog filters are necessary to most seismic tests before the analogical to numerical conversion. Low-pass analog filters are used to remove signal components that have a higher frequency than the sampling frequency. This removal is named anti-aliasing. The cutoff frequency of the low-pass filter has to be half the sampling frequency (Shannon theorem).

iii) Digitalization:

Analog to digital conversion (A to D) converts continuous signal to discrete digital numbers. The resolution and the sampling rate are the two main characteristics of A to D. The resolution of the converter indicates the number of discrete values (in bits) it can produce over the range of analog values. For example, 8 bits converters can produce 2^8 = 256 values. In that case, for a displacement sensor with a range of +/- 100 mm, resolution errors are 0.8 mm. This error is the numerical noise. Recent converters are 16 or 24 bits (corresponding to 0.003 mm or 0.01 µm for a range +/- 100 mm).

Sampling frequency has to be chosen in regards to the maximum observed frequency (Shannon theorem). If the sampling frequency is too high, the large quantity of data can complicate analyses.

3.10 CALIBRATION

International agreement defines national standards. There are seven primary standards used to define national standards: Mass, length, time, current, temperature, luminous intensity and amount of substance. Calibration should be carried out using equipment which can be traceable back to national standards with a separate calibration record kept for each measurement instrument.

The system (sensor + cable + conditioning system) response can be described by 2 standard tests. The first one is the variation of amplitude and phase with frequency. The second is the variation of time signal output of the system for a given input such as step function (transient response). In seismic laboratories, calibration is based on these two tests.

As sensor calibration is expensive, for large seismic facilities using many sensors, a calibration room (verification should be the best word) can be cost efficient: an electrodynamic actuator for acceleration (sinus sweep test), displacement bench for displacement transducers and hydraulic actuator for force (variation of time signal output of the system for a triangle function). EMSI laboratory of CEA (France) has for example developed that kind of capability. Verifications are performed by comparison to a reference sensor (previously calibrated in a national standard laboratory). This calibration mainly consists in verifying the sensitivity of the sensor along time and frequency. We can indicate here that look up tables are now available in recent software to define multiple sensitivity values depending on the measurand value. The calibration of sensor should ideally be made after each test to validate measurement data of the test.

After the calibration process, calibration parameters should be included in a transducer database which is useful to increase friendliness, survey ageing (time stability) of parameters, decreases system configuration errors, decrease configuration time and then increase process quality.

A simple verification of the sensor should be made before the test. For accelerometers, this verification can for example be made using the gravity measurement or a little calibrated electrical exciter (one level, one frequency).

Future directions: eFast facility should have a verification (calibration) room that has to be defined in WP4. In that case, calibration procedures have to be defined.

3.11 INSTALLATION, VERIFICATION AND MAINTANANCE

The installation is time consuming but it is important that the transducer moves with the surface being tested. The transducer is fixed with screw, magnetic base, Glue or cement. For displacement sensors, supports are frequently welded and bolted. Those supports have to be stiff enough (for large supports, first frequencies calculation need to be done) when loaded on a shaking table. Supports can then be expensive.

Dynamic interaction between the transducer and the mock up has to be taken under account when choosing the transducer and the support. Therefore, the mass of the sensor should be sufficiently low compared to the dynamic mass of the structure. For displacement transducer with cables, the traction force of the cable has to be high enough to decrease the cable frequency but should not disturb the structure behavior. If such interaction exists, it has to be included in numerical analyses of the mock up.

For control in hybrid tests, this interaction problem will probably appear due to force measurements. Indeed, in hybrid tests, force has to be measured between the structure and actuators or shaking table (representing the calculated substructure) and load cell has to be stiff enough (compared to the structure stiffness).

To increase friendliness, decrease time and errors of installation, recent conditioning systems now offer new capabilities.

First, a sensor data base can simplify organization of sensors (management of supplies) and their parameters. The data base should be filled and modified in the calibration room. During tests, the conditioning system is connected to the data base. The user simply has to indicate to the conditioning system which sensor is plugged to which channel. Manual errors when the user writes conditioning parameters are then mainly retired.

Second, with recent MEMS technologies (Microelectromechanical systems), sometimes called MST (MicroSystem Technology) in Europe, the sensor itself can communicate and interact with conditioning systems. MEMS usually consist of a central unit that can process data, the microprocessor and several components that interact with the outside. MEMS are made up of components between 1 to 100 micrometers in size. A main application example is related to TEDS (transducer electronic data sheets) technologiy. TEDS are “plug and play” sensors with calibration data embedded in an Eeprom memory located in the sensor or the connector. The conditioning system automatically recognizes the connected sensor and uploads conditioning parameters from the Eeprom memory. IEEE 1451 is the international standard used by manufacturers (National instrument for example) to configure TEDS. TEDS are one solution to ensure good cable connection (the right sensor to the right channel).

Another application of MEMS technology is the capability to integrate signal processing (Smart systems or “intelligent” sensors) such as internal analog signal conditioning and A to D conversion. Those sensors are for example able to compensate random errors and make self calibration and non-linearities adjustments.

Future directions: eFast facility should have supports to fix transducers. Some principles of load cells fixation could be defined.

Sensor data base to manage eFast facility supplies. TEDS could be useful too.

3.12 CONCLUSION

The state of the art for instrumentation permit to specify some details for the eFast facility design: internal pressure ΔP of each actuator and supply pressure should be measured, a calibration room should be done…

This state of the art also permits to define the interesting subjects that could be studied during eFast project:

- Numerical evaluation of the relation between supply pressure and actuator performance (can be an important parameter for the design of the hydraulic pumps of the eFast facility).

- Optical sensors: comparison between optical sensors efficiency (hardware and software) and standard transducers, techniques validation for a damage location during the test.
- Comparison between pressure and force measurements in actuators to validate the use of pressure measurement in the force estimation.
- Validation of the efficiency of a force measurement between the plate of shaking table and the mock up (strain gages inside the plate). A FE model of an existing shaking table plate should be done, evaluation of table deformations, determination of possible measurements accuracy.
- Development of a sensor model with a simulation software to evaluate measurement errors and their propagation in hybrid algorithms, development of electronic compensation of those errors if needed.
- Definition of some principles of load cells fixation.
- Definition of calibration procedures.

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4.PRELIMINARY DESIGN OF THE WEB PORTAL (TUIASI)

Gabriela M. Atanasiu, Mihai Horia Zaharia, Florin Leon, Stefan Boronea

4.1 DESIGN SPECIFICATIONS AND IMPLEMENTATION OVERVIEW

The currently presented web site is intended to offer information about the E-Fast project to users in a structured orderly manner. This document proposes an overall website design that has several main features described in the following sections and a technology approach suitable for each problem in particular.

The design focuses on only presenting the most important aspects of the project on the main web page, thus increasing the accessibility of the web site. Figure 4.1 shows the current version of this design (the main web page), while Figure 4.3 represents a normal web page that follows the same design approach.

This document wishes to present some views regarding the E-FAST Web Portal implementation and its uses within the E-FAST project. The document follows a number

Figure 4.1 The EFAST Web Portal main page design

of issues and problems that may occur during the portal's lifetime from a software point of view.

4.1.1 The problems

i) We presume that this portal should be developed based on a custom project solution with general specifications. Will the solution follow this approach or will it take into account some existing software on the market?

ii) Portal should be designed based on a clear definition of users' classes or groups (e.g. professors, researchers, students, administrators, visitors, etc.) which will require the following:

- Specifications of access rights and resource needs. These specifications related to internal classification of the confidentiality level for different categories of information.
- Classifications of offered services (e.g. audio, video, control, access to various data streams) for an experiment conducted on the seismic platform for different categories of users

iii) The need to ensure a secure access from outside the main cluster into the E-FAST information system is raising the problem of using authentication certificates, which are usually granted by an external organization. There are two possibilities or options in our opinion, which shall be taken into account in design:

- At least one of the organizations involved, has its own server that authenticates the certificates, or a PGP solution.

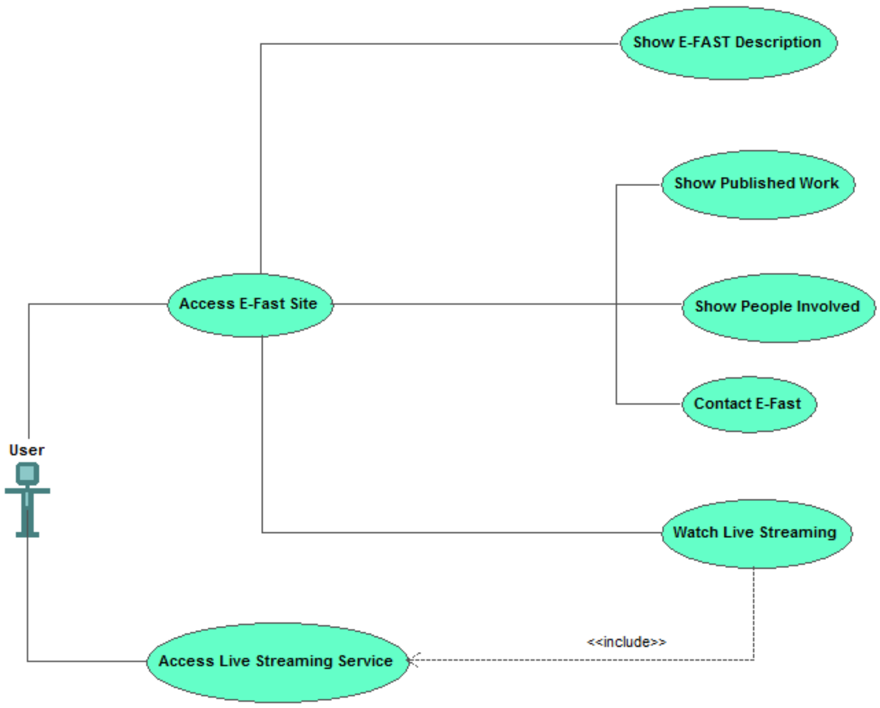
Or:

- The organizations do not have this possibility in which case the design should specify the need of having these certifications and the cost estimates for purchasing them from specialized organizations.

iv) Concerning the video/conference there are some specifications to be taken into account:

- Stream access level (private, semiprivate or open to some categories of public). For example a certain user can be granted access ONLY to some parts of the video streaming
- Streaming can be done online or offline, a specification which should be mentioned

v) Related to the visualization problem, here there are two general possibilities in our opinion: local and long distance visualization. These specifications should state what the system design needs for the data transfer and computing capacity, which all depend on whether the video is streamed to one client, or if it is recorded and processed locally on a cluster and only the generated images are sent to client. Will this document have to specify the software which will be used (existing on the market or not)?



4.1.2 The solutions

Figure 4.2 Accessible sections for users of the EFAST Web Portal

i) In order to achieve the needed features for the web portal, we propose a hybrid structure for this matter so that it will provide users both features from some of the existing features already implemented in various existing projects of its kind but also with custom implemented features that this project wishes to provide to its users.

The existing features could be implemented in the same manner for the E-FAST platform web portal given the required resources. We have based our proposal on the features provided by George E. Brown, Jr. Network for Earthquake Engineering

Simulation (through the NEES Cyberinfrastructure Center at the San Diego Supercomputer Center – see http://it.nees.org), the National Center for Research on Earthquake Engineering in Taiwan (see http://www.ncree.gov.tw/eng) and the Pacific Earthquake Engineering Research Center (see http://peer.berkeley.edu). All of these portals provide methods of presenting the data to the end user, whether it is through video streaming and telepresence systems (http://it.nees.org/software/flextps) with direct control of the viewports or through a database system that allows direct access to the recorded experiments conducted over time (see NEEScentral - http://it.nees.org/software/central). The NEES infrastructure allows a two way communication with the platform where users may upload their own simulations and tests remotely using custom tools (also through NEEScentral). Although some of these solutions are developed and maintained locally, there are cases where a number of tools were developed by third-party companies. The integration with some of the well-known commercial software products (such as MathWorks MATLAB™ - http://www.mathworks.com/products/matlab/ or NI LabView™ - http://www.ni.com/labview) could allow a fast development and adoption of the platform tools. Also these systems have evolved over time mostly because of an active community of software developers that work together with researchers in developing and updating these tools (see http://neesforge.nees.org).

These powerful existing tools allow a secure and reliable communication between the simulation system and the community, also providing a large amount of data stored over time. In order to implement similar tools for the E-FAST platform, the underlying system must be able to store a large amount of data, categorize it and maintain it over time. Also, security is an important issue and thus must be thoroughly discussed. By allowing remote simulations over the E-FAST system, a synchronization method must be designed and a sharing policy must be considered. It is of crucial importance that a community of developers and researchers is maintained and that the means of communication are provided so that slack time is diminished and the inevitable problems are communicated in a structured, punctual and direct manner. Therefore it is our opinion that developing a hybrid system is the best solution for the E-FAST platform web portal, allowing a rich and open view of the developed tools. The existing solutions present on the market can be implemented successfully given the required resources and that the E-FAST platform can provide the data.

ii) The presence of a security system is highly important in the design of the E-FAST platform web portal. This should cover two main components: authentication and authorization. This point discusses the latter. We will first discuss the various features that will be available for a user from the project's point of view:

- **Video streams** – the video streams that will be available to the user.

- **Data streams** – the data regarding a certain experiment. This can include database connections and access to certain web pages. The access to these streams can be specified as read-only or read and write, depending on the user security level.

- **Administrative tools** – the access to the web portal's administration panel which allows complete control over the system. In order to provide a secure system, the access to these tools through administrative accounts should be limited to local access.

- **Community contributors** – a user may be a contributor to the E-FAST community of developers. This should allow him to post updates, download and upload software and communicate with other developers and researchers.

- **News** – the news section.

- **Publications** – a list of publications related to the E-FAST project

- **Conferences** – the ability to participate in conferences with other project users.

In the context of these features, we propose a user group scheme which will include different rights (read / write) for each of the mentioned services:

	Admin	**Professor**	**Researcher**	**Student**	**Guest**	**User**	**Developer**
Video streams	R/W	R/W	R	R	n/a	R	R
Data stream	R/W	R/W	R	n/a	n/a	n/a	R
Administration	R/W	n/a	n/a	n/a	n/a	n/a	
Community	R/W	R/W	R/W	R/W	R	R	R/W
News	R/W	R/W	R	R	R	R	R/W
Publications	R/W	R/W	R/W	R	n/a	R	R
Conferences	R/W	R/W	R/W	n/a	n/a	n/a	n/a

Table 4.1.1 Authorization policy for user categories in the EFAST web portal

Also we believe that every project (simulation / data client) should have its own administrators which may grant the same read / write rights for that project. They will not be allowed to change other project's user rights until specified by a System Administrator.

iii) The authentication process is crucial to a secure information system. We believe that a security certificates authentication would be best in our opinion. This would prove to be a very costly process for the end user and therefore we consider that some user categories should be allowed to access the system even if they don't have issued certificates, through necessary credentials (user & password).

iv) We propose that the users which upload sensitive data should always have a valid security certificate when accessing the E-FAST web portal from a browser or from one of the additional tools that the E-FAST platform will provide. Users which access to a small amount of insensitive data (Student, Guest and User) should be allowed to provide the credentials using an unencrypted channel.

	Admin	**Professor**	**Researcher**	**Student**	**Guest**	**User**	**Developer**
Security Certificate	Required	Possible	Required	n/a	n/a	n/a	Possible
SSH	n/a	Required	n/a	Possible	n/a	n/a	Required
Web auth	n/a	n/a	n/a	Required	n/a	Yes	n/a
No auth	n/a	n/a	n/a	n/a	Yes	n/a	n/a

Table 3. 2 The authentication requirements for user categories in the EFAST web portal

v) The video streaming and telepresence services are very important to the E-FAST platform web portal. In order to solve possible problems such as unauthorized users viewing existing projects and data, we believe that these services should allow a further and more in-depth authorization administration. Thus, the System Administrator or the project administrators may change how the users view the media.

We believe that a system in which videos may be either public or private would suffice, mainly because the projects already have a list of users which may contribute to it. The already authenticated and authorized project users would therefore have access to all the media systems (for viewing purposes) and other users may only access media (for viewing purposes) which was tagged as public by a project or system administrator. In order to solve possible issues regarding multiple users control during an experiment, this will be interdicted by allowing only one user to control the media recording devices at the same time. This will too be specified by the administrators.

When recording the experiment, the remote software could provide a partial or total control for the recording devices, depending on the hardware solutions present. If the hardware supports such actions and an API (Application Programming Interface) is available for it, then this task could be completed. Thus, for a specific experiment, a user would be allowed to set the recording parameters before the experiment or set a recording path that will be executed along with the actual experiment, so that more concluding data is caught.

The stored media can be later viewed through the web portal or a desktop client for the E-FAST information system if a user has access to it. The offline viewing of the data poses some issues in terms of storage space. Video files tend to grow rapidly and would prove very costly. Therefore, a clustering solution should be found or a dedicated storage network for these files that in time would be able to provide a wide history for the conducted experiments. If this solution is too expensive and would require additional resources for maintaining it, a simple purging of the video files and unessential projects could be done by the System Administrator.

vi) In terms of computational power, the E-FAST will require dedicated servers for video processing, synchronization with the other data from various sources (such as measurement devices) and the serving of client users. Therefore, a local cluster of computers would be required and a storage solution found. Depending on the magnitude of projects and data which will be collected from the sources during the experiments we may make an assumption in terms of storage and processing power. Such an estimate could be made also by consulting with the people responsible for similar projects.

For the E-FAST web portal (for news, papers and other information for normal users), the requirements are low and would require only a server and an Internet connection of the expected bandwidth. If additional features are added (such as streaming, live conferences, remote control of the recording devices, and data processing), the storage and computing needs will grow rapidly.

In terms of required software products, both Windows and UNIX solutions are available for some of the tasks. Nevertheless, a UNIX-based approach would prove more prudent because of the HPC (High Performance Computing) capabilities it provides and the long history that these systems have with scientific projects. It is also a better solution in terms of system scalability, performance, security and costs.

4.1.3 Web portal features

Taking into account the possible solutions to the existing problems previously presented

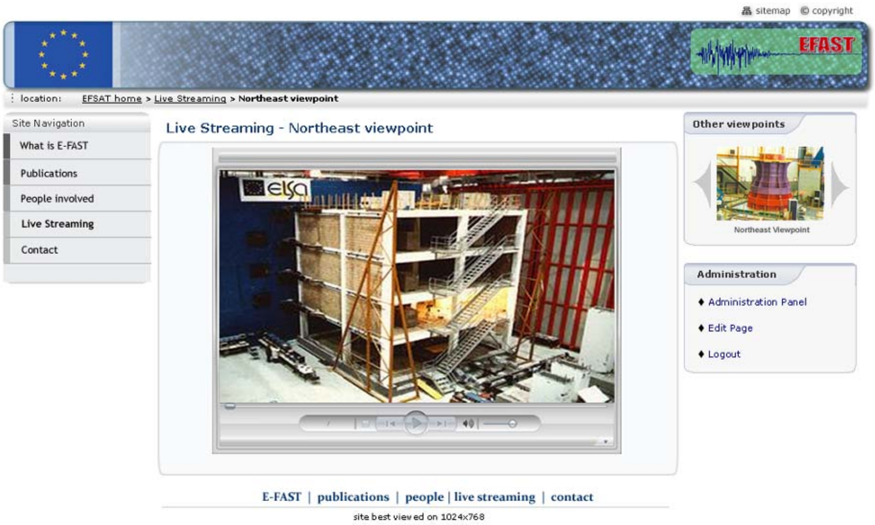


Figure 4.3 The live streaming section design

in this document, we may conclude by presenting the features that will compose the EFAST Platform Web Portal. These features are included as a draft, in addition to the facts already presented in the Web Site Specifications document containing the general project overview.

i) EFAST Information - The EFAST portal will be able to provide general information describing the purpose of the project, its current state and additional information that users may find useful in understanding its value and goals.

ii) Simulations - The simulations section will be able to provide users with the information regarding current and previous projects and tests conducted on the E-FAST Platform. This history will be accessible if the current user will have enough credentials to do so (based on the group membership and the access rights specified by the System Administrators and the project administrators). This section will allow users to view recorded media, access statistics and data from during the tests and see an overview of the simulation project.

iii) News -The users are allowed to view the latest news regarding the E-Fast project using the news section. The news is presented by date and priority according to the System Administrator. He and other administrators that have rights to publish news may add news at any time, set the interval in which the news item will be displayed and add an image and content to it. The news is stored in a database and a search engine may be used if the situation requires so.

iv) Live Streaming Service - In order to allow users to track the evolution of the project in real-time, a live streaming service is proposed. Its main purpose is achieved by using a series of technologies that allow the processing of more video signals from various peripheral devices (video cameras) and their publishing to a service that can be easily accessed through the web site or directly using an application. Of course, this is done in a real-time manner, the system's performances depending on the current number of viewers and server processing power. The web users can access this video service without any other setup by clicking on the desired camera viewpoint from the available cameras list. For this task we propose that the actual signal processing and publishing be done using Windows Media Encoder and Microsoft Expression Encoder 2. The video received from different viewpoints can be published to a Windows Communication Foundation (WCF) service on the local server. In order to access the service from an external application, .NET Framework 3.0 or later is required. The normal website users are required to only have a basic web browser video player plugin installed on their local machine (such as Flash Player or Silverlight). The actual system deployment is presented in Figure 4.4. To allow a better integration of these technologies, an ASP .NET website implementation is advised.

v) Publications, People Involved and Contact - These sections show the lists of publications and people involved in the E-Fast project and allow the user to contact the project members through a dedicated section.

vi) Download - All the additional tools that the project will provide will be downloadable from here.

vii) Community - The developer community forum will be a separate part of the E-FAST portal. Here software projects (tools offered by the E-FAST project) can receive feedbacks, updates and news and discussions on the results and preparing of new tests can be made.

viii) Sitemap

ix) Copyright Information

x) Website Administration - The administration section will allow system administrators and project administrators to change media providers, viewpoints, add news, add projects, manage user rights and groups and delete existing data on the servers.

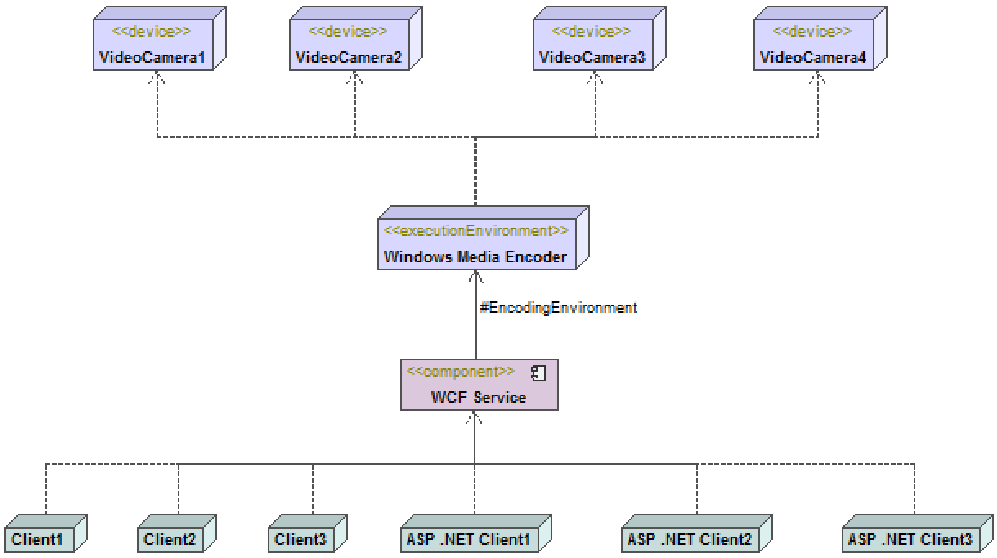


Figure 4.4 The deployment configuration of the telepresence system.

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Abstract
The present report provides information about the activities conducted during the 1st year of the EFAST project. The first chapter is dedicated to describe the inquiries conducted at the beginning of the project and to briefly summarise the main results. The second chapter is dedicated to the first EFAST workshop where some of the leading scientists in the field of earthquake engineering have met to discuss about the need and the technologies related to earthquake engineering. The third chapter contains a state of the art and future direction in seismic testing and simulation. The final chapter is dedicated to describe the preliminary design of the web portal of the future testing facility.

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