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SERIES

SEISMIC ENGINEERING RESEARCH INFRASTRUCTURES FOR EUROPEAN SYNERGIES

Work package [WP9 – TA5 LNEC]

THE LNEC EARTHQUAKE ENGINEERING TESTING FACILITY
Background information: LNEC testing facility, testing setup and protocol and data processing

July, 2013

ABSTRACT

The TIMBER BUILDINGS Project, led by the University of Trento, included testing of four full scale multi-story timber houses with a realistic horizontal plan and three types of timber housing systems: platform frame system (PFS), log house system (LHS) and cross laminated timber (CLT). The tests were carried in the LNEC-3D shake table under different levels of excitation and different conditions of the structure.

The tests were carried with the goal of assessing the seismic performance of the buildings, panel elements and steel connectors, defined in terms of relative displacements and hold-down forces. The results were presented in separate reports, one for each building. This document contains information common to the remaining four reports.

Keywords: Timber buildings, Shaking Table, Equipment

ACKNOWLEDGMENTS

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1 Introduction

The main scope of the SERIES project is bridging gaps in seismic research between different Countries and Research Communities. The Series consortium of 23 European Institutions involved in seismic engineering research provides different aspects of seismic engineering testing: reaction wall pseudo-dynamic (PsD), shaking tables, centrifuges and instrumented sites for wave propagation studies. Transnational Access (TA) to this portfolio of excellent research complementary infrastructures is offered to European researchers groups, selected after specific applications. Users are given access to the infrastructures for the design of specimens and test setups, for the execution of tests and post-processing and interpretation of results. Generally, the lead institution and the majority of the users in a team work in an Institution of a European Union Member State or an EU Associated country. In this context, a research program focused on the timber structures has been activated. Within the transnational access (TA) sponsored by SERIES, three university Institutions, one research Institution within SERIES and several industrial partners have been involved in this research. The research activities involved University of Trento (Italy) as Lead User of Transnational Access, University of Minho (Portugal) and University of Graz (Austria). Table 1.1 presents the TA project factsheet.

Under this TA project three types of timber housing systems were taken into account: platform frame system (PFS), log house system (LHS) and cross laminated timber (CLT). All in all, a total of four full scale multi-story timber houses with a realistic horizontal plan were provided by the User industrial partners for testing in the LNEC-3D shake table under different levels of excitation and different conditions of the structure.

Table 1.1 – TA project factsheet

Title: **Timber buildings: Seismic performance of multi-storey timber buildings**
TA Agreement between Users and Facility: signed on 15th January 2010
Starting date: 16th July 2011
Estimated number of access days: 15 (40 delivered)
Number of users: 11
Lead User Maurizio Piazza – University of Trento (IT) *Additional Users (Institutions)* Graz University of Technology (AT) University of Minho (PT) RUSTICASA, Construções Lda (PT) Rubner Haus AG (IT) Vinzenz Harrer GmbH (AT) Mayr-Melnhof Kaufmann Gaishorn GmbH (AT) Rothoblaas (IT)

The buildings were prefabricated in manufacturing plants and transported to the LNEC Earthquake Engineering Facility by truck. Upon arrival they had to be assembled directly on the LNEC 3D shake table because they were very large and it was not possible either to house them inside the testing room after being assembled or to move them inside the testing room.

The testing setup and instrumentation plan for all buildings was similar, the differences being mainly associated to the number of stories, two in the first one and three in the others. Additional steel masses were placed on the floor and fastened to the planks to account for the live loads and induce the corresponding inertia forces. In the buildings where the roof tiles were not placed, they were replaced by additional steel masses.

After the buildings were set up the instrumentation plan including several types of sensors was implemented. In some particular cases, the instrumentation plan was adjusted during the tests depending on the building seismic response.

The test procedure consisted in a combination of dynamic and seismic tests, the former to identify the dynamic properties of the buildings and the latter to assess their seismic performance. Two different sets of records were used in the seismic tests, the 1979 Montenegro earthquake (Ulcinj, Hotel Albatros record), which was the reference one for all buildings, and the 2011 Tohoku earthquake (Sendai Office Building #2, B2F record), which was used in only two of the four buildings. Additionally, two of the buildings were weakened during the tests in order to simulate some structural damage. In those cases the test procedure was extended and several test stages were repeated.

After the conclusion of the tests the buildings were disassembled and sent back to the suppliers. Teams of specialized workers carried out the assembly/disassembly of the buildings, tasks that took a few days given the size of the buildings.

Since the buildings were larger than the LNEC-3D shaking table, a special steel foundation was purposefully designed and built to increase the platen surface and fix the buildings to the shake table.

In this report is described the LNEC Earthquake Engineering testing facility in chapter 2. The technical data of the sensors used in the tests is presented in chapter 3. The two seismic input signals, the 1979 Montenegro earthquake and the 2011 Tohoku earthquake, as well as the signal generation procedure for the shaking table tests are presented in chapter 4. In chapter 5 is presented the testing setup and in the chapter 6 is described the seismic testing protocol. Finally in the chapter 7 is presented the identification techniques to estimate the dynamic parameters of the structure (modal frequencies, modal damping and modal configurations). The references are presented at the end of this report.

2 The LNEC Earthquake Engineering testing facility

LNEC owns a large scale experimental facility for seismic testing of structures which is part of the European Seismic Engineering Research Infrastructures and whose construction was partially financed by the European Union. The Earthquake Engineering and Structural Dynamics Division operates this facility, pictured in Figure 2.1, and develops R&D activity in the fields of Earthquake Engineering and Structural Dynamics.

Figure 2.1: LNEC Earthquake Engineering testing facility (Ferry Borges building)

The experimental activity carried out in the LNEC earthquake engineering testing facility, and related research, aims at assessing the performance of structures subjected to dynamic and seismic loadings. The tests are carefully setup in order to simulate on the models the same conditions as in the real prototypes and measure all the relevant effects necessary for the performance assessment. The instrumentation is calibrated and a record is made of all the maintenance and interventions made. The preparation and operation of the shaking tables follows standard protocols to achieve the targets proposed. The analysis process uses the most advanced techniques in the fields of signal processing, dynamics of structures and earthquake engineering to achieve optimum results. All these aspects contribute to guarantee that the tests carried out meet the highest quality standards.

2.1 GENERAL INFORMATION ON THE LABORATORY

Table 2.1 – Name and location of the Laboratory

Full Name of the Laboratory	**Núcleo de Engenharia Sísmica e Dinâmica de Estruturas**
Abbreviated Name	**NESDE/LNEC**
Address	**Av. Brasil, 101 1700-066 Lisbon**
Location	**Lisbon**
Country	**Portugal**
Telephone	**+351218443824/3307**
Telefax	**+351218443035**
E-mail/www	http://www.lnec.pt/LNEC/DE/NESDE/

Table 2.2 – Name and location of the parent organization

Full Name of the Parent Organization	**Laboratório Nacional de Engenharia Civil**
Address	**Av. Brasil, 101 1700-066 Lisbon**
Location	**Lisbon**
Country	**Portugal**
Telephone	**+351218443000**
Telefax	
E-mail	lnec@lnec.pt

2.2 THE FACILITY: LNEC-3D SHAKING TABLE

The facility has a large testing room, shown in Figure 2.2, and includes two shaking tables, one large triaxial and another one smaller uniaxial, and various other equipment for seismic testing of structures. The triaxial shaking table, pictured in Figure 2.3, is capable of testing large civil engineering structures subjected to earthquake motions up to collapse.

Figure 2.2: LNEC earthquake engineering testing room

Figure 2.3: LNEC-3D shaking table

2.3 GENERAL INFORMATION ON THE SHAKING TABLE

Table 2.3 – Name of the LNEC-3D shaking table

Full Name of the Shaking Table	LNEC TRIAXIAL SHAKING TABLE
Abbreviated Name	LNEC-3D
Designer/Manufacturer	LNEC and INSTRON
Year of Installation	1995

2.4 SHAKING TABLE DESCRIPTION

Table 2.4 – Type of shaking table

	Longitudinal X	Transverse Y	Vertical Z	Pitch	Roll	Yaw
Uniaxial	-	-	-	-	-	-
Biaxial	-	-	-	-	-	-
Multiaxial	Y	Y	Y	N/A	N/A	N/A

Table 2.5 – Characteristics of the Platform

Size (m×m)	Weight (kN)	Material
4.6 x 5.6	392	Steel

Type of Actuation	***Hydraulic***

Table 2.6 – Characteristics of the Actuators

	Manufacturer	Total Force (kN)	Number of units/axis
Longitudinal	**INSTRON**	**1250**	**1**
Transverse	**INSTRON**	**750**	**2**
Vertical	**INSTRON**	**375**	**1**

Table 2.7 – Shaking table performances

Frequency Range			Hz	**0.1 – 40.0**
Stroke (effective/maximum)	Horizontal		mm_{pp}	**290/400**
	Vertical		mm_{pp}	**290/400**
Max Velocity (nominal/limit)	Horizontal	Transverse	cm/s	**70.1/121.5**
		Longitudinal	cm/s	**42.4/73.5**
	Vertical		cm/s	**41.9/72.6**
Max Acceleration at bare table	Horizontal	Transverse	m/s²	**18.75 (*)**
		Longitudinal	m/s²	**31.25 (*)**
	Vertical		m/s²	**9.38**
Yaw	Rotation degrees		°	**N/A**
	Velocity		rad/s	**N/A**
Pitch/Roll	Rotation degrees		°	**N/A**
	Velocity		rad/s	**N/A**
Max Overturning Moment			kN×m	**N/A**
Max Specimen Dead Weight			kN	**392**
Max Compensated Dead Weight			kN	**392**

(*) Bare table (**) Maximum payload

2.5 CHARACTERISTICS OF THE CONTROL SYSTEM

Type of Control	Analogue	**Digital**	Mixed

Table 2.8 – Characteristics of the analogue part

Manufacturer	**LNEC**
Type	***LNEC-CTL***

Table 2.9 – Characteristics of the digital part

Hardware	Computer	**Host PC+NI PXI Real Time Controller+4 RIO FPGA Virtex-5**
	D/A Channels	**8 ADC channels, 16 bit 96 configurable digital channels**
	A/D Channels	
Software	Designer	**LNEC**

Controlled motions	***Sinusoidal***	***Random***	***Shock***	***Seismic***
No. of Controlled Channels	**3**	**3**	**3**	**3**
No. of Acquisition Channels	**6**	**6**	**6**	**6**

2.6 COMPLEMENTARY FACILITIES

Floating Foundation

Dimensions (m×m)	-
Weight (kN)	-
Natural Freq. (Hz)	-

Hydraulic System

Electric Power (kW)	**330**
Flow Rate (l/min)	**690**
Pressure (MPa)	**20.7**

Bridge Cranes Capacity

No. of Cranes	**2**
Max Load (kN)	**392**
Useful Height (m)	**8**

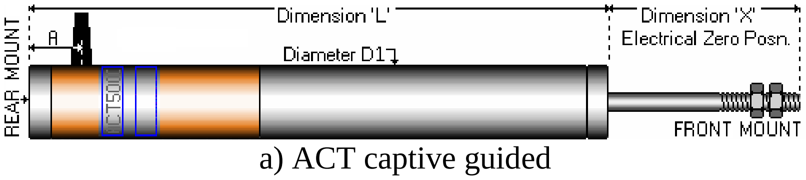
3 Sensors technical data

The experimental assessment of a model performance under seismic actions imposed on the shaking table requires the measurement of several different types of physical quantities like displacements, accelerations, strains and forces. The sensors necessary for this includes displacement transducers, accelerometers, strain gauges and cell forces, all of them available at the LNEC Earthquake Engineering and Structural Dynamics Division. Below is listed only the subset of the existing instrumentation that is relevant for the tests carried out in the scope of the present study.

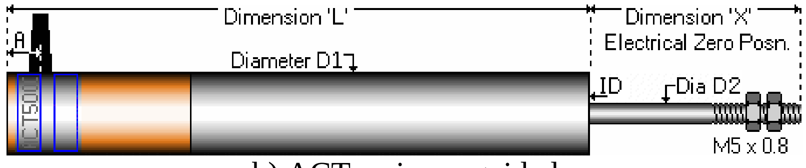
3.1 DISPLACEMENT TRANSDUCERS

3.1.1 LVDT displacement transducers

RDP Electronics ACT2000C, ACT4000C and ACT6000 inductive displacement transducers, having work strokes of +/-50mm, +/-100mm and +/-150mm, respectively, can be used for measuring displacements. Figure 3.1 shows the general aspect of the inductive displacement transducers available in the LNEC Engineering and Structural Dynamics Division while Table 3.1 shows some of its main characteristics.



a) ACT captive guided



b) ACT series unguided

Figure 3.1: LVDT displacement transducers (source: RDP)

Table 3.1 – Characteristics of the RDP displacement transducers

Manufacturer	RDP ELECTRONICS (www.rdpe.com)
Models available	ACT2000, ACT4000, ACT6000
Stroke	+/-50mm (ACT2000), +/-100mm (ACT4000), +/-150mm (ACT6000)
Sensitivity	15mV/V/mm (ACT6000) to 30mV/V/mm (ACT2000)
Energising supply	5Vrms, 5kHz
Linearity deviation	0.08% (ACT2000) to 0.3% (ACT6000)

3.1.2 Hamamatsu optical system

Optical displacement transducers HAMAMATSU C5949 (comprising F50mm lens, sensor head and LED target) and HAMAMATSU conditioning PSH controllers C2399 (see Figure 3.2) can be used for measuring 2D displacements on a plane perpendicular to the line of sight (typically either on a horizontal or vertical plane). Table 3.2 shows some of the main characteristics of the HAMAMATSU displacement transducers.

Figure 3.2: HAMAMATSU optical 2D displacement transducer

Table 3.2 – Characteristics of the HAMAMATSU displacement transducers

Type	Spectral Response [nm]	Measurement Points [-]	Sampling Frequency [Hz]	Position Detecting Error [%]	Resolution [-]	Error due to light [%]
C2399-00		1	300			
C5949	700 to 1150	1 to 7	300	±1	1/5000	±1

The cameras used detect the positions of the points concerned along the x- and y- axes with respect to their absolute reference system [1]. Figure 3.3 shows a typical Hamamatsu system configuration.

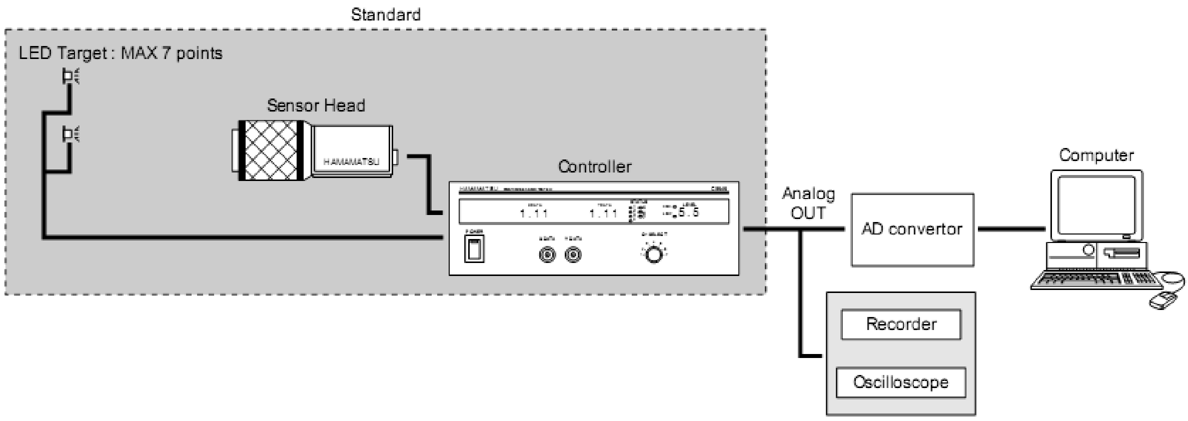


Figure 3.3: Hamamatsu system configuration [1]

3.1.3 Krypton K600 camera

The K600 camera system takes measurements in 3D and consists of three linear CCD cameras. While two external cameras, present inside the instrument, detect the position y- and z- coordinates of the point concerned, the central one calculates the x-coordinate. Thus the position of an infrared LED is calculated by triangulation [2]. Figure 3.4 shows the Krypton K600 camera mounted on a tripod.

Figure 3.4: The Krypton K600 camera [2]

The overlap area of the three linear CCD-cameras in the camera unit, results in an overlapping pyramidal volume as shown in Figure 3.5. The top angle of the pyramid is 34° (+17° / -17°).

The K600 Krypton Camera offers a $17m^3$ field of view volume with accuracies up to ±0.1mm for static and dynamic LED position measurements. According to the rule-of-thumb, the lateral visibility limit (measured from the symmetry plane of the camera) is half the distance from the camera [2].

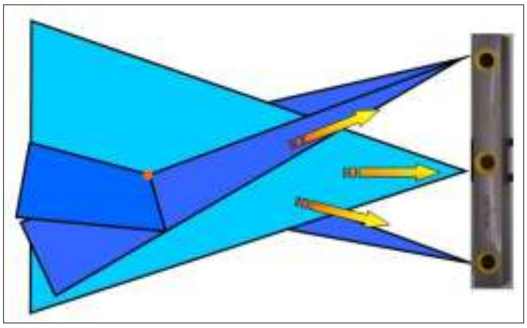


Figure 3.5: Representative measurement volume of a Krypton K600 camera [2]

The field of view is divided into three accuracy zones which are determined based on the distance from the camera as seen in Figure 3.6. Accuracy of LED dynamic measurements has been observed to be higher for motions in the X-Y plane of the viewing volume.

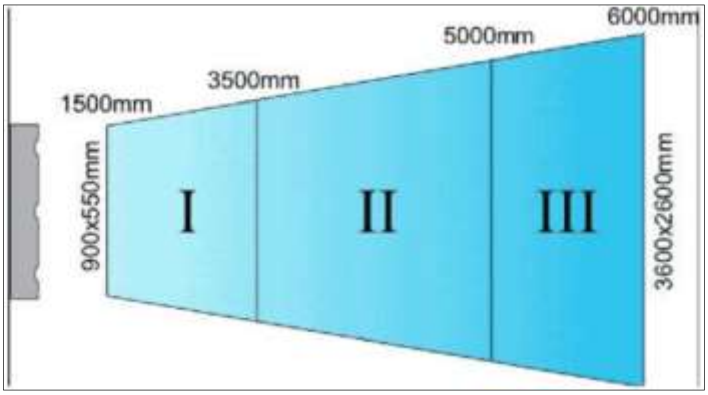


Figure 3.6: Accuracy zones of the Krypton K600 camera system [2]

The acquisition laptop communicates with the camera controller to acquire the 3D position data of the individual LEDs. The camera control unit synchronizes the LEDs with the acquisition of the camera and serves as an interface between the laptop and the camera unit. The strober distributes the control signals from the controller to individual LEDs and translates them into pulse trains causing the infrared LEDs to flash. The strober can be connected to the strober port of the controller or can be daisy-chained to another strober. The LED’s are plugged into a strober and then attached to the object that the user wants to measure. The best results are achieved if they are placed at large distances forming large triangles as seen by the camera.

3.2 FIBRE-OPTICAL STRAIN SENSORS

FBG-Scan 700 and 800 are dynamic, high precision measurement devices for Fiber Bragg Grating (FBG) sensors [3]. The system can measure up to 40 FBG sensors using 2 input channels. Both input channels are simultaneously monitored using an optical coupler at a scan rate up to 2000Hz. The sampling is done using the internal clock or can be controlled by an external trigger signal to synchronize the measurements with other devices. The main characteristics are summarised in Table 3.3.

Figure 3.7: Fiber Bragg Grating (FBG) sensors

Table 3.3 – FBG-Scan 700 and 800 technical characteristics

Parameter	FBG-Scan	
	700	800
Optical		
Wavelength range	1525-1565 nm	1510-1590 nm
Number of optical lines	0.4 nm	0.8 nm
Wavelength precision	± 1 pm	
Dynamic range	30 dB with user selectable control	
Scan and report rate	2000Hz	
Optical connector	FC/APC	
Laser class (IEC 60825-1)	1	
Electrical		
Communication	USB 2.0	
Trigger signal	TTL signal (3.3 V), SMA connector	
Power supply	5 VDC	

3.3 ACCELEROMETERS

Two main types of accelerometers are used in the LNEC Engineering and Structural Dynamics Division: ENDEVCO, model 7290-A with variable capacitance (Figure 3.8), and PCB Piezotronics, model 337A26 (Figure 3.9). The first type is mainly used on the shaking table while the second one is mainly used on the mock ups. Both are high frequency accelerometers adequate for the measurement of accelerations in dynamic and seismic tests; their main characteristics are summarised in Table 3.4 and Table 3.5.

Figure 3.8: ENDEVCO accelerometers

Figure 3.9: PCB Piezotronics accelerometers

Table 3.4 – Characteristics of the ENDEVCO accelerometers

Manufacturer	MEGGITT SENSORS (www.endevco.com)
Model	7290A-2 and 7290A-10
Sensitivity (at 100Hz) [mV/g]	1000+/-20 and 200+/-10
Measurement range [g peak]	+/-2 and +/-10
Amplitude response at +/-5% [Hz]	0 to 15 and 0 to 500
Transverse sensitivity [% max]	2

Table 3.5 – Characteristics of the PCB accelerometers

Manufacturer	PCB Piezotronics (www.pcb.com)
Model	337A26
Sensitivity [mV/g]	100
Measurement range [g peak]	100
Broadband resolution [g rms]	0.0001
Frequency range [Hz]	0.5 to 5000

3.4 LOAD CELLS

The load cells used to measure the hold-down forces have been developed and calibrated by LNEC. The load cell is an electric transducer used to measure a force applied on a mechanical or structural component, through the measurement of an electrical signal that varies due to the deformation that produces such a force on the component itself. The relief of the mechanical deformation takes place in an indirect manner, via a reading in mV or V, and subsequently transformed into the correct unit of measurement.

An individual load cell is constituted of a hollow steel cylinder. Six strain gauges are connected to the body of the load cell – four in the longitudinal direction and two in the transverse direction relative to the axis of the cylinder. The strain gauges are all connected in a full-bridge configuration to amplify the magnitude of the signal. Figure 3.10 shows a typical load cell.

Figure 3.10: Typical load cell

3.5 ACQUISITION SYSTEM

The acquisition system available at the LNEC Earthquake Engineering Research Centre comprises the following components:

Table 3.6 – NI PXI controller

NI PXI-8106 CONTROLLER	
	2.16 GHz Intel Core 2 Duo T7400 dual-core processor Up to 46% higher performance than the PXI-8105 512 MB (1 x 512 MB DIMM) dual-channel 667 MHz DDR2 RAM standard, 4 GB maximum 10/100/1000 BaseTX (Gigabit) Ethernet, ExpressCard/34 slot, and 4 Hi-Speed USB ports Integrated hard drive, GPIB, serial, and other peripheral I/O Windows OS and drivers already installed; hard-drive-based recovery

Table 3.7 – NI PXI chassis

NI PXI-1052 CHASSIS

- 4 slots for 3U PXI modules and 8 slots for SCXI modules
- Latest chassis technology
- AUTO/HIGH fan-speed selector to optimize cooling and acoustics
- 0 to 55 °C temperature range
- 42 dBA acoustic emissions
- Multiplexed operating mode for SCXI
- SCXI high-voltage analog backplane integrated internally

Model	Slots PXI	Slots SCXI	SCXI Operation Mode	High-Voltage Analog Backplane
PXI-1050	8	4	Multiplexed and Parallel	–
PXI-1052	4	8	Multiplexed	✓

PXI-1052 Acoustic Emissions	
Sound Pressure Level[1] (measured at operator position)	dBA
Auto Fan (25 °C ambient)	41.6
High Fan	51.5
Sound Power[1]	
Auto Fan (25 °C ambient)	51.9
High Fan	60.0

[1]Tested in accordance with ISO 7779

Form Factor PXI Platform, SCXI **PXI Bus Type** PXI Hybrid Compatible **Operating System / Target** Windows, Real-Time **LabVIEW RT Support** Yes **Power Supply** AC	**Number of Slots**12 **Number of PXI Peripheral Slots**4 **Maximum System Bandwidth**132 MB/s **Accepts both 3U PXI and CompactPCI Modules**Yes **Optional Front or Rear Rack Mountable** Yes **Integrated Controller**No	**Remote Power-inhibit Control and Voltage Monitoring** Yes **Total Available Power** 450 W **Input Voltage Range** 100..240 V **Input Frequency Range** 50/60 Hz **Field-replaceable Power Supply** No

4 Seismic input signals

Two different sets of records were used in the seismic tests: the 1979 Montenegro earthquake (Ulcinj, Hotel Albatros record), which was the reference one, and the 2011 Tohoku earthquake (Sendai Office Building #2, B2F record). These records are presented next and afterwards the signal generation procedure for the shaking table tests is described.

4.1 1979 MONTENEGRO EARTHQUAKE

This bidirectional signal was recorded during the 1979 Montenegro earthquake (Mw 6.9 – 15th April 1979) at Ulcinj – Hotel Albatros station, [11] and [12]. The earthquake is considered similar to the ones that can occur in the North of Italy. Table 4.1 presents the 1979 Montenegro earthquake main data.

Table 4.1 – 1979 Montenegro earthquake main data

Waveform ID	198	Epicentral Distance (km)	21
Earthquake ID	93	PGA_X (m/s^2)	1.774
Station ID	ST64	PGA_Y (m/s^2)	2.199
Earthquake Name	Montenegro	PGA_Z (m/s^2)	2.076
Date	15/04/1979	PGV_X (m/s)	0.171
Time (UTC)	06:19:41	PGV_Y (m/s)	0.259
M_w	6.9	PGV_Z(m/s)	0.117
Fault Mechanism	Thrust	ID_X	13.043
Building Type	Structure related free-field	ID_Y	8.157
Instrument Location	ground level	ID_Z	12.301
Vs_{30}(m/s)	1083	Site class	A

Figure 4.1 shows the acceleration time series for the two horizontal components and Figure 4.2 the pseudo velocity response spectra.

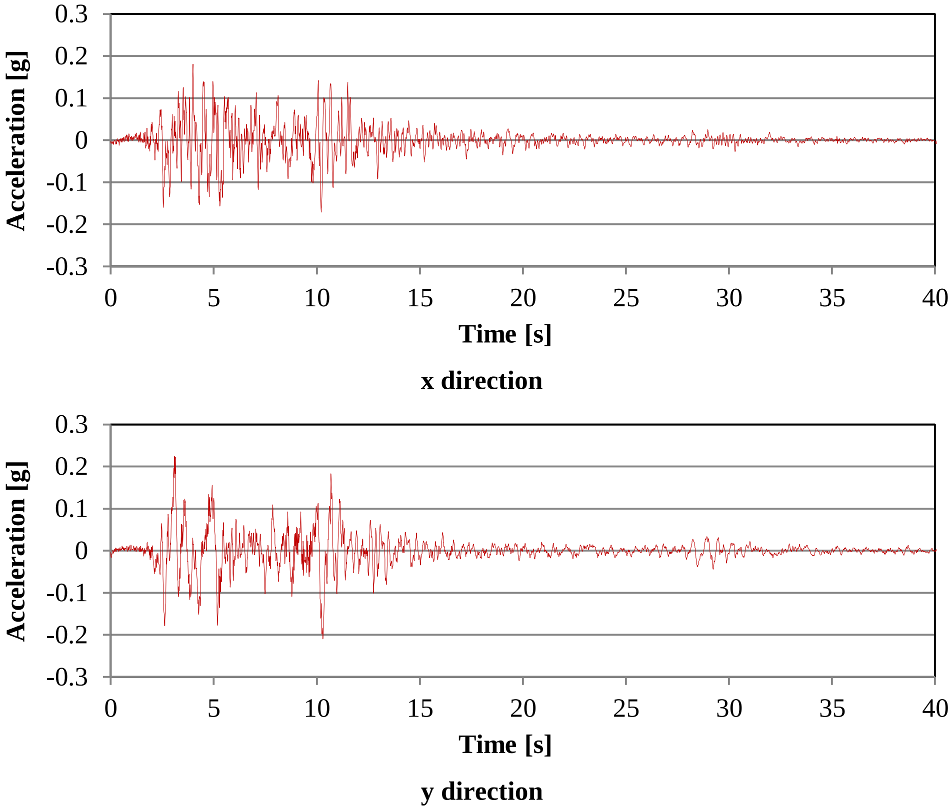


Figure 4.1: 1979 Montenegro earthquake acceleration time series, "Ulcinj - Hotel Albatros" station

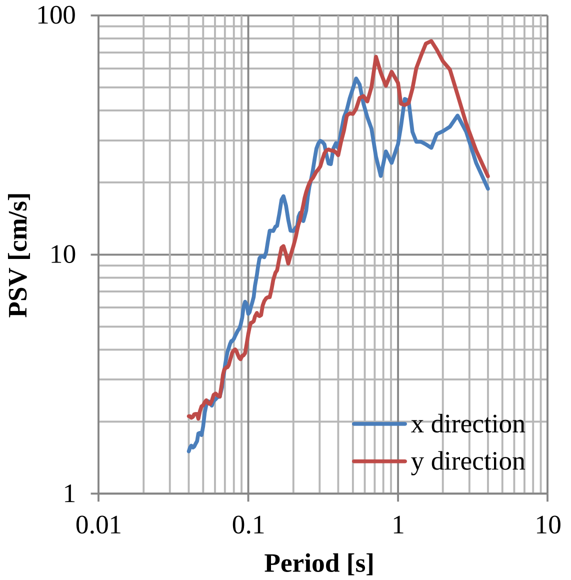


Figure 4.2: 1979 Montenegro earthquake pseudo velocity response spectra of the "Ulcinj - Hotel Albatros" station

The estimated fundamental period of the buildings is expected to be in the maximum acceleration plateau of the response spectrum. Moreover, choosing this signal, the amplitude of the amplification zone (portion corresponding to constant energy on the response spectrum) is large enough to anticipate that the most severe effects will happen in the structure even if its period is different from the design value or if damage occurs during the tests.

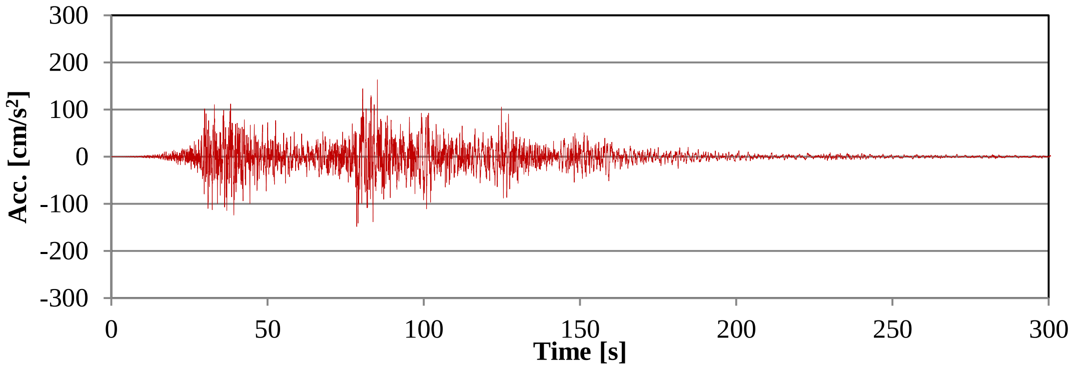
4.2 2011 TOHOKU EARTHQUAKE

The second input signal selected for the 2-D seismic tests was the magnitude 9.0 Tohoku earthquake recorded March 11, 2011, in the Sendai Government Office Bldg. #2 station, [13] and [14]. The main data about the 2011 Tohoku earthquake is shown in Table 4.2.

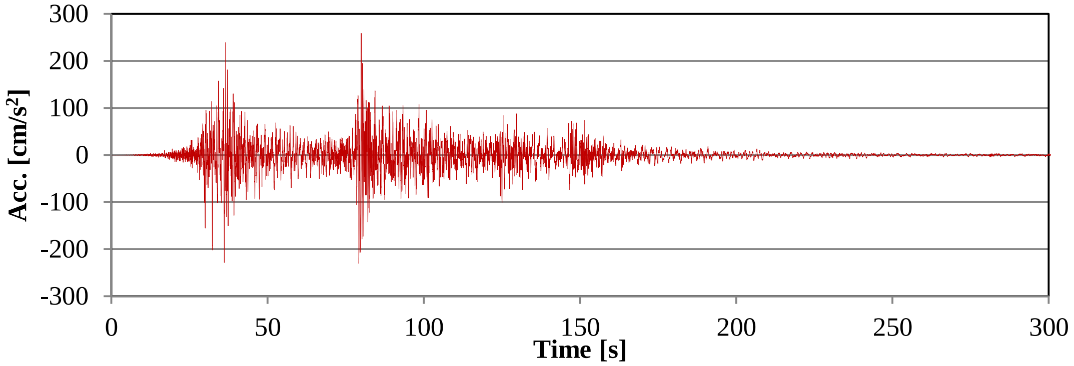
Table 4.2 – 2011 Tohoku earthquake main data

Event	2011/03/11 14:46 Off Sanriku (M=9, h=24 km
Station	Sendai Government Office Bldg. #2 (SND
Instrument	SMAC-MD
Sensor places	B2F, 15F, G40
Epicentral distance	174 km
Peak acceleration	259.0 cm/s2 (at B2F)
Seismic intensity	5.2 (at B2F)
Record length	301 sec

Figure 4.3 shows the acceleration time series for the two horizontal components and Figure 4.4 the correspondent pseudo velocity response spectra.



Transverse direction (074-B2F)



Longitudinal direction (164-B2F)

Figure 4.3: 2011 Tohoku earthquake acceleration time series, "Sendai Government Office Bldg. #2" station

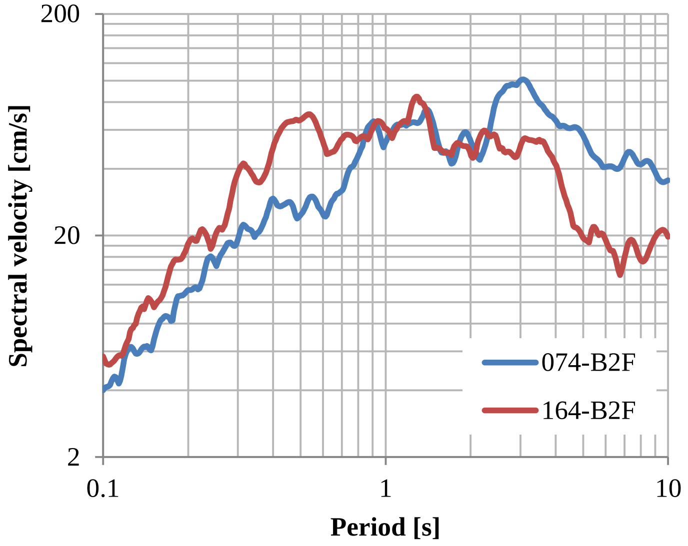
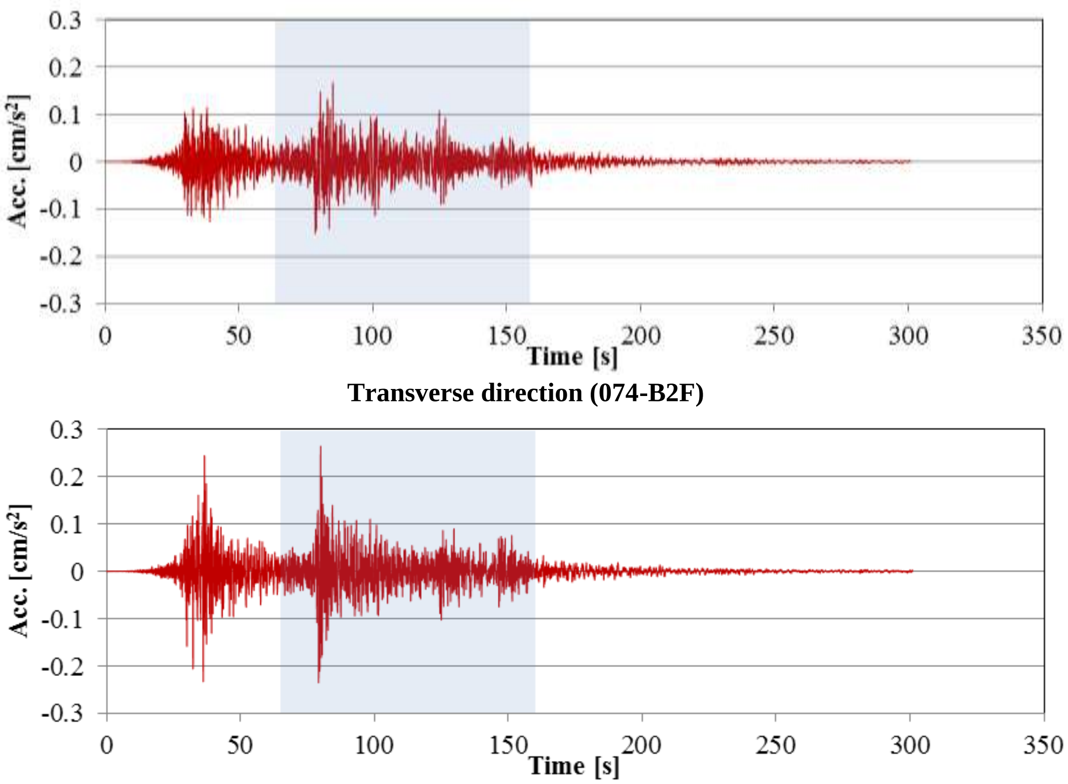


Figure 4.4: 2011 Tohoku earthquake pseudo velocity response spectra, "Sendai Government Office Bldg. #2" station

The target motion results from the selection of a time segment (from 62.94 seconds to 147.94 seconds) of the two horizontal orthogonal components with a total duration of 75 seconds. Figure 4.5 shows the full acceleration record and the time segment selected.



Longitudinal direction (164-B2F)

Figure 4.5: Full acceleration record and time segment used in the artificial generation process

4.3 SIGNAL GENERATION PROCEDURE FOR THE SHAKING TABLE TESTS

In general terms the method of generation of a time series of acceleration, compatible with a target Response Spectra, is done by an iterative process in which the amplitudes of the Discrete Fourier Transform (DFT) of the acceleration time series, computed in a given iteration (*i*), are corrected by the square root of the quotient between the ordinates of the Target Response Spectra and the ordinates of the Response Spectra computed from the previous iteration (*i-1*) acceleration time series.

The initial acceleration time series can be any random time series (modulated by an envelope function) or any particular record from a real earthquake. In the first case the phases are random and uniformly distributed, whereas in the second case the phase for each particular frequency is equal to the phase of the real record (same Fourier Phase Spectrum). In this second case the envelope and non-stationary contents of the real record are retained in the synthetic signal. Furthermore if two orthogonal components of a real earthquake are used in the generation process the Coherence Spectrum between the two components is the same as the one present in selected time window of the two records.

For the control of the LNEC 3D shake table it is necessary to have compatible displacement and acceleration time series, both sampled at 200Hz. Fourier filters, both low and high pass, integration, differentiation and detrending are used to achieve this. This digital signal processing, in both time and frequency domains, is carried out using the LNEC-SPA software developed at LNEC [4].

In the end were obtained the pairs of displacement and acceleration signals as well as the pseudo velocity response spectra presented in Figure 4.6 to Figure 4.11. The seismic input motions for the each test stage are scaled from these ones by a factor to obtain the desired intensities (PGA).

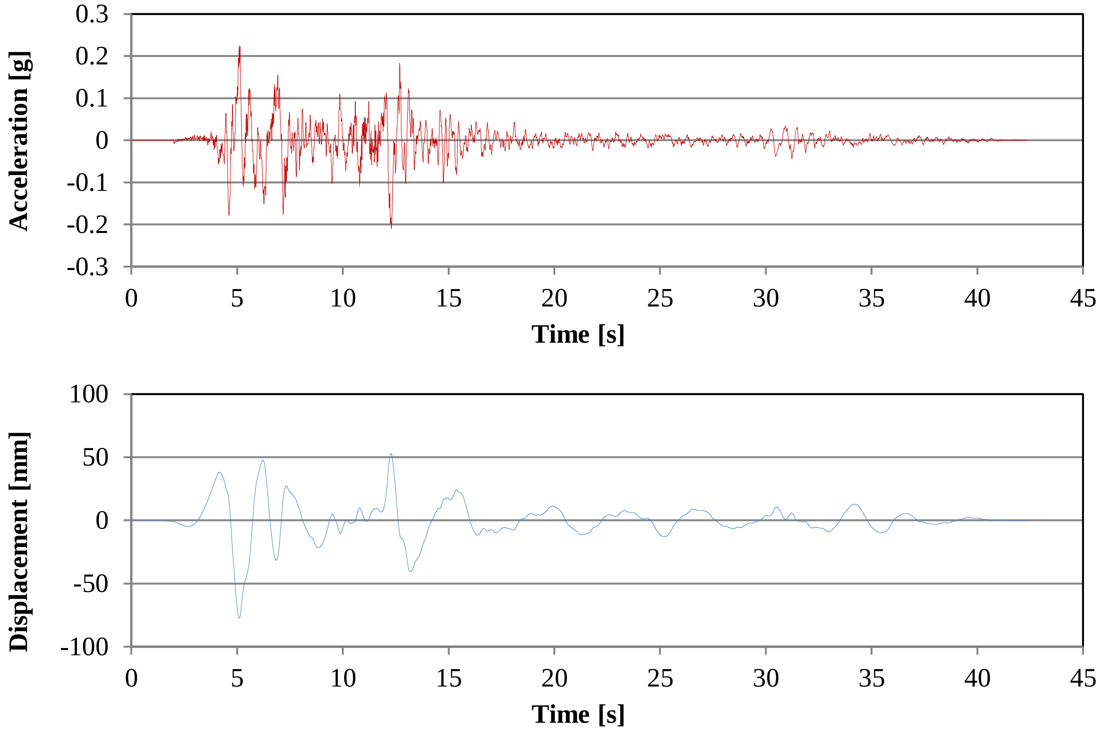


Figure 4.6: Input signal for transverse direction, Montenegro earthquake

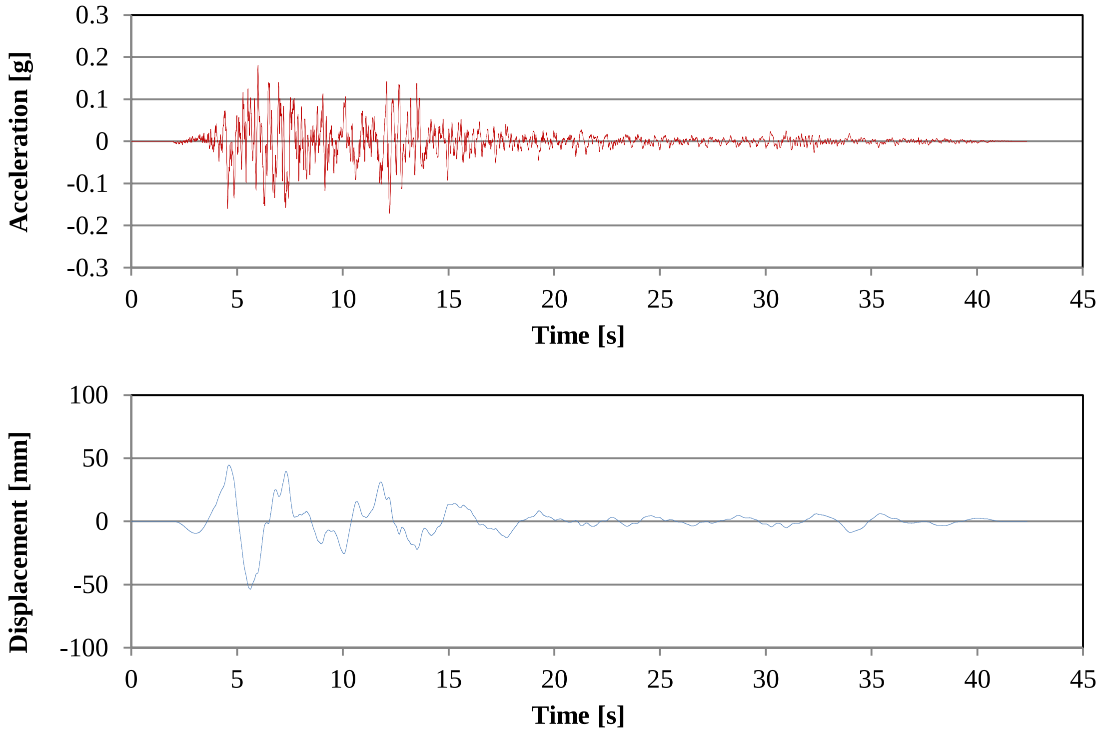


Figure 4.7: Input signal for longitudinal direction, Montenegro earthquake

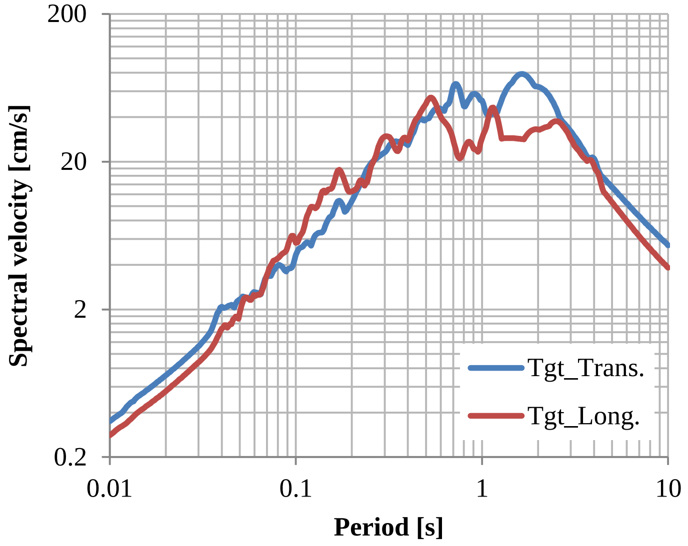


Figure 4.8: Input pseudo velocity response spectra, Montenegro earthquake

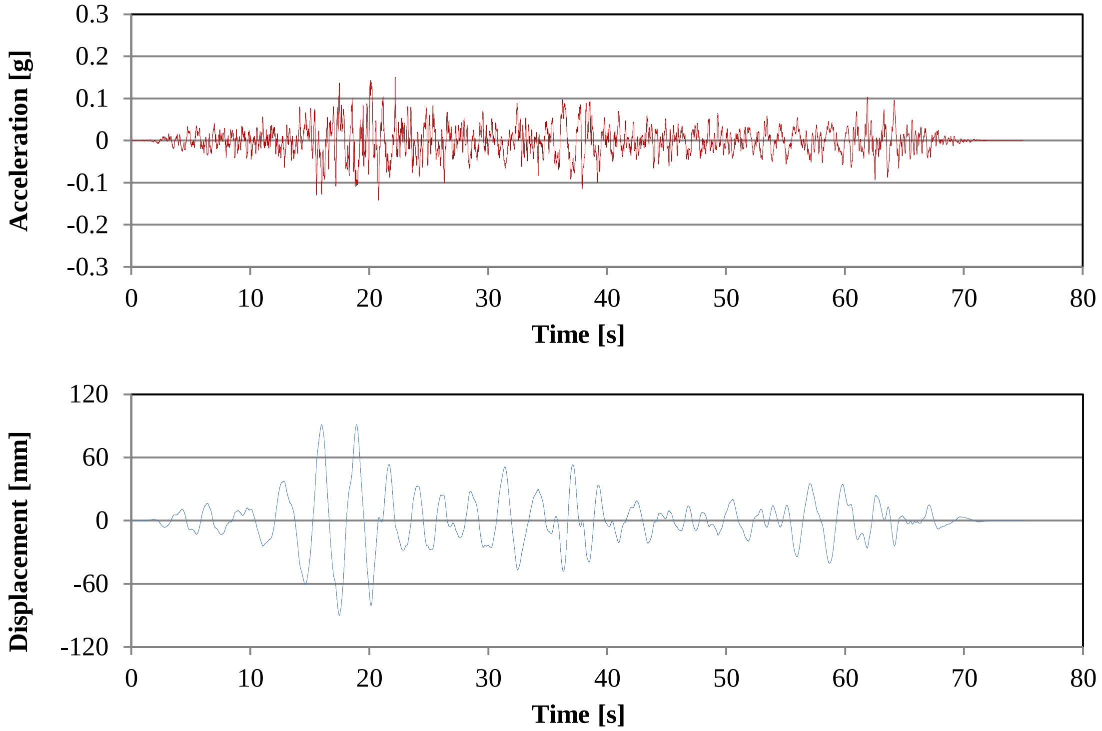


Figure 4.9: Input signal for transverse direction, Tohoku earthquake

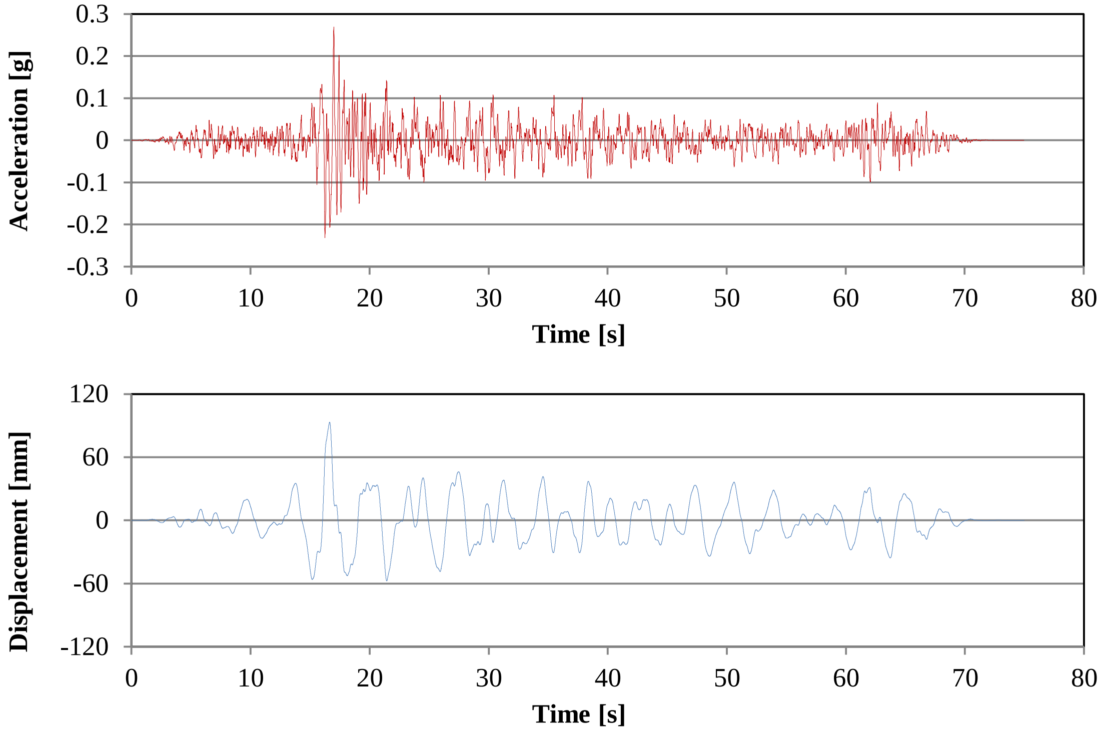


Figure 4.10: Input signal for longitudinal direction, Tohoku earthquake

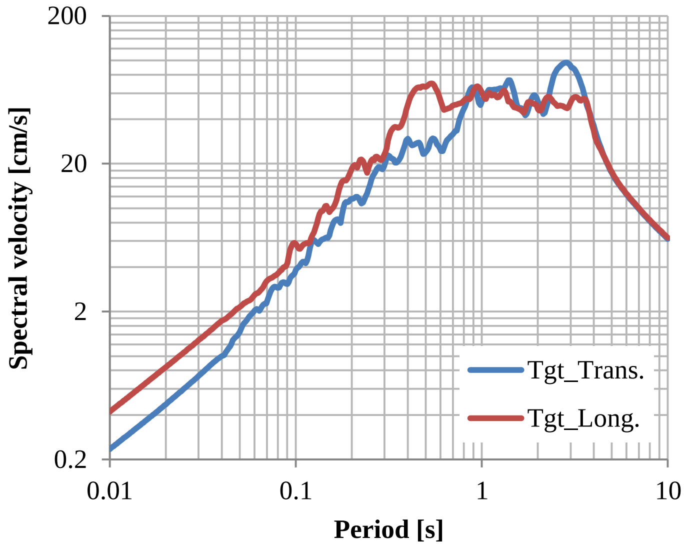


Figure 4.11: Input pseudo velocity response spectra, Tohoku earthquake

5 Testing setup

5.1 ENLARGEMENT OF THE SHAKING TABLE

In order to perform the tests on such large wooden structures a special steel foundation was purposefully designed and built to increase the platen surface and fix the buildings to the shake table. The steel structure (Figure 5.1) is a grid made with HEB400 and IPE400 beams, assembled in two parts to facilitate transport and installation on the shaking table. As seen in Figure 5.2, the anchoring holes for hold-down, angle brackets and sill beam were drilled on the upper flange of the HE profile (the upper flanges of the transversal element were enlarged with steel plates). The same steel structure was used to fix all the tested specimens (one log house, two timber framed and one CLT building).

The beams were reinforced with transverse steel plates (Figure 5.3 and Figure 5.4) to ensure an adequate stiffness of the system. As seen in Figure 5.5, openings were created to allow the fixing of the bolts of the hold down on the joint between the two main elements.

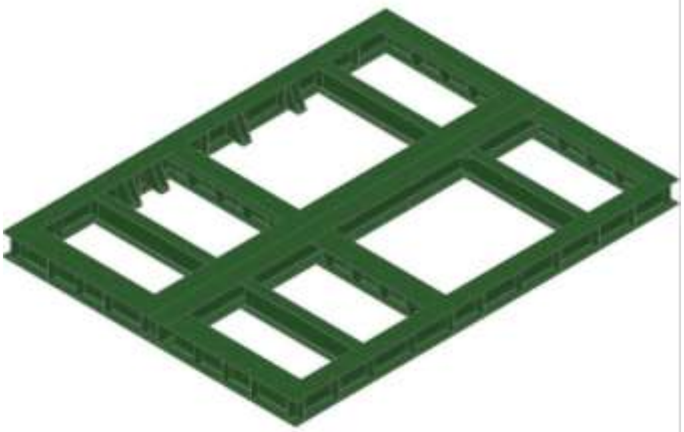


Figure 5.1: 3D model of the steel basement

Figure 5.2: Enlargement beyond the platform

Figure 5.3: Image of the assembly in the factory

Figure 5.4: Reinforcing plates

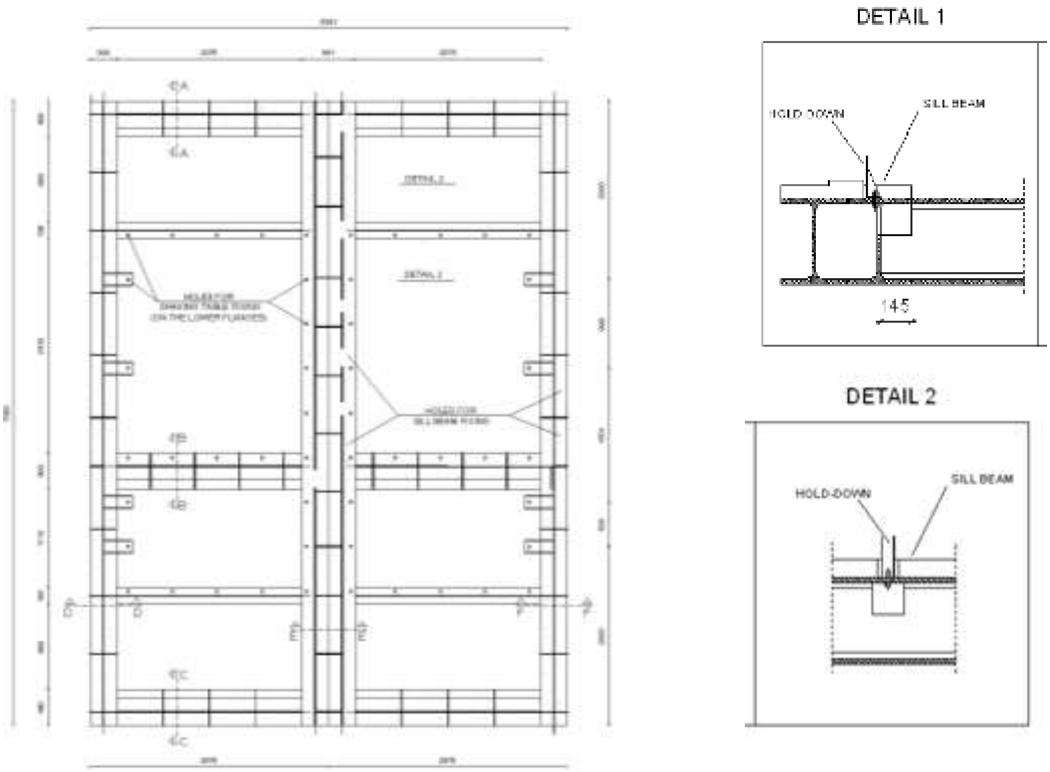


Figure 5.5: Plan of the steel lattice

The assemblage and fixing of this structure to the shake table started in 2012-04-27 (visible in the background in Figure 5.6).

Figure 5.6: General view of the enlargement of the LNEC-3D shaking table platen

5.2 REFERENCE SYSTEM

Different reference systems were adopted during the tests. The first two were adopted by the LNEC laboratory (L – longitudinal, T – transverse and NSEW – North, South, East, West), the last one was used by the TA users (X, Y). Moreover, to identify the intersection between the major axes of the structure, a grid reference system was adopted. The reference systems are reported in Figure 5.7.

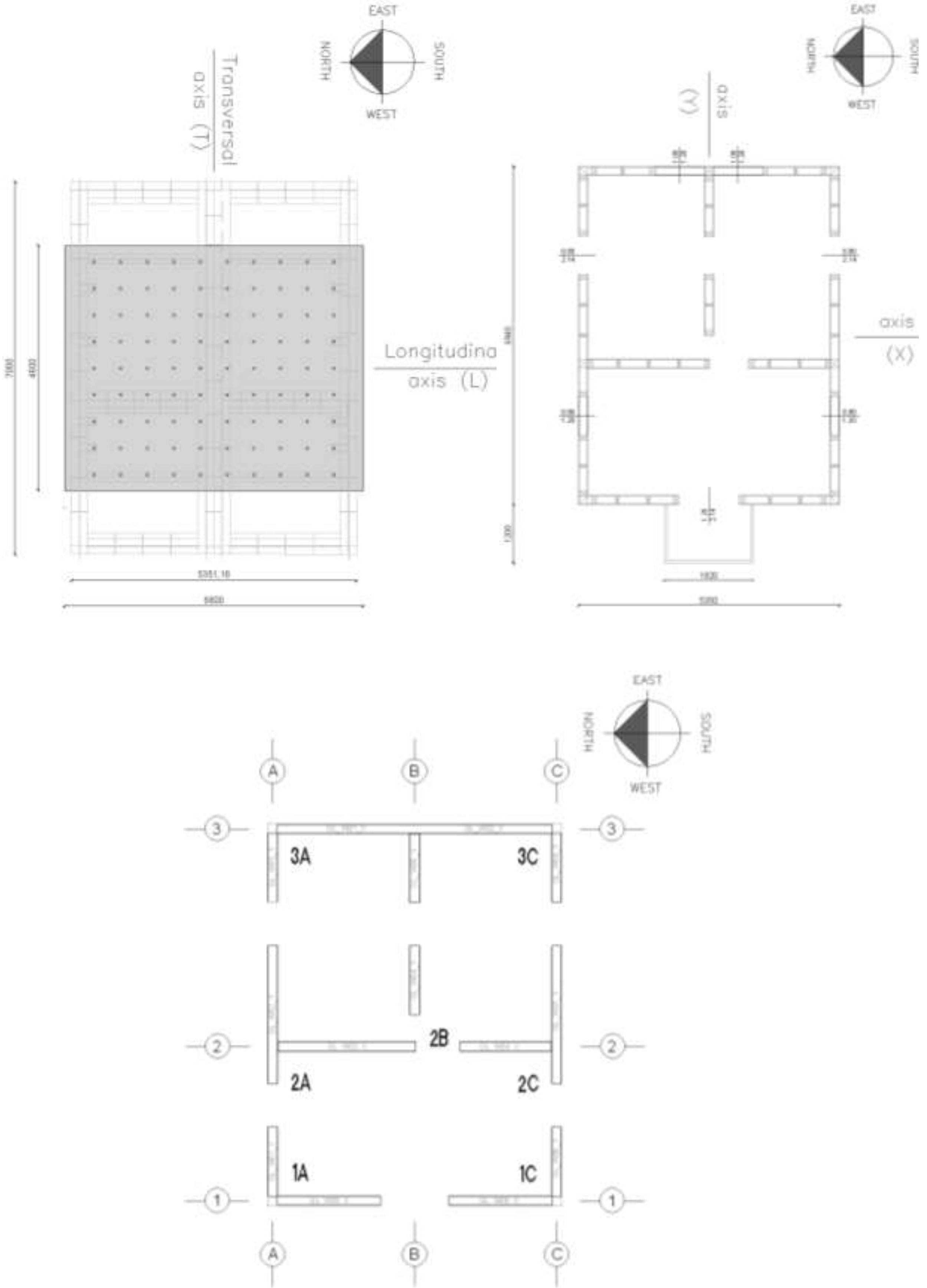


Figure 5.7: Reference system

All the walls of the buildings were tagged with a label that identifies the reference number and the floor. The meaning of the labels is summarized in Table 5.1.

Table 5.1 – Specimen labels

Specimen label **XX_WYY_Z**		
XX (Level) GL – ground level 1L – first level 2L – second level	YY (ID number) From 1 to 6 in X From 1 to 8 in Y	Z (Orientation) X – corresponding to the (L) direction of the table Y – corresponding to the (T) direction of the table

5.3 INSTRUMENTATION PLAN

Different instruments were installed for recording displacements, both absolute and relative, and accelerations; also the forces on anchor elements were monitored with load cells. The instrumentation plan was adjusted during the tests depending on the building seismic response therefore the number of channels simultaneously acquired during tests was a little different, but in all of them 5 additional accelerometers were placed on the steel basement, 4 sensors were placed on the LNEC-3D shaking table to measure the displacements and accelerations. Table 5.2 shows the type of sensors used and the measure.

Table 5.2 – Measurement's instruments

Transducer type	**Measure**
Linear Variable Displacement Transducer (LVDT)	Inter-storey drift, Wall sliding and Wall uplift
Accelerometers on structure	Accelerations at different levels
Accelerometers on steel basement	Accelerations at the shaking table level positions
Load cell	Forces on hold down anchoring elements
Hamamatsu optical 2D system	Point absolute displacements
Krypton optical 3D system	Point absolute displacements

6 Seismic testing protocol

6.1 TESTING PROCEDURE

The test procedure consisted in a combination of dynamic and seismic tests, the former to identify the dynamic properties of the buildings and the latter to assess their seismic performance.

6.2 SHAKING TABLE TUNING

Before conducting a seismic test the shaking table has to be tuned. The tuning procedure is carried out in an iterative adaptive process starting with a low level intensity and progressing in several iterations to the final required signals. The procedure follows a sequence of steps:

- Dynamic identification of the whole system (ST+model) using a low amplitude “pink” noise in acceleration to obtain a frequency response function (FRF);
- Start with a low amplitude displacement signal input;
- Measure displacements and accelerations as output;
- Obtain a feedback synthesized displacement signal using a selected cross over frequency between measured displacements and accelerations;
- Deconvolution of the feedback signal through the system FRF;
- Obtain the new “error” signal to use as input signal to the shaking table;
- Iterate until input signal is tuned for shaking table;
- Increase the input signal and repeat the process for the next stage.

Figure 6.1 shows an example of the definition of the parameters to compute the system (ST+model) FRF for the shaking table tuning process for the hands on application.

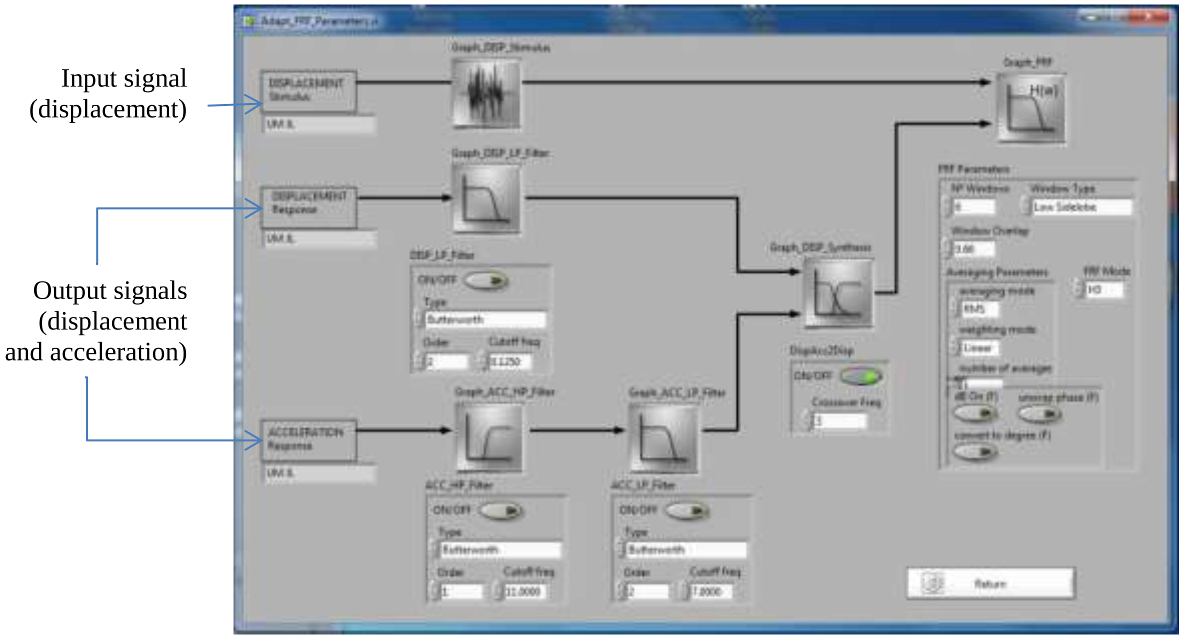


Figure 6.1: Shaking table tuning application: definition of parameters

Figure 6.2 shows an example of the system (ST+model) FRF obtained with the “pink” noise excitation. An example of the signal tuning process is shown in Figure 6.3.

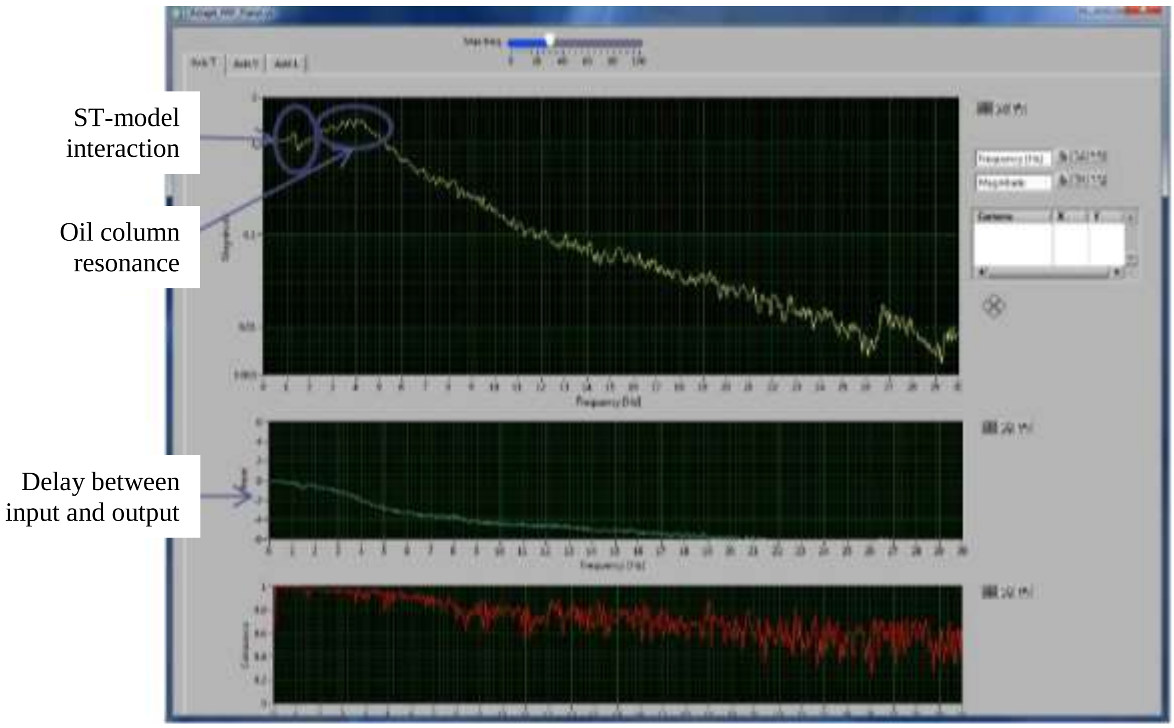


Figure 6.2: Shaking table tuning application: FRF obtained

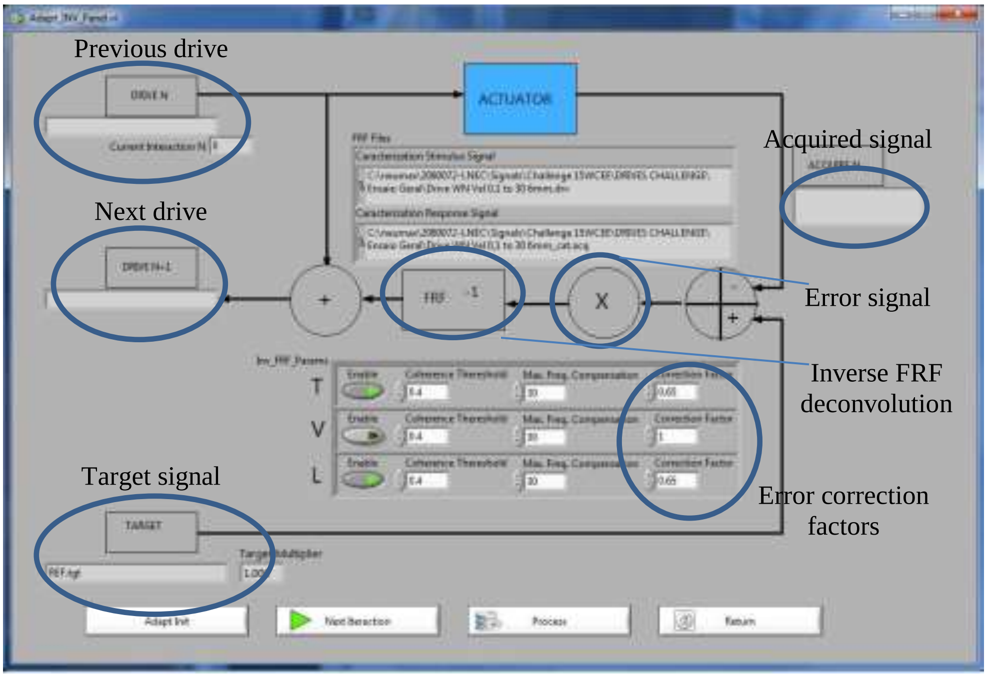


Figure 6.3: Signal tuning iterative process

6.3 SEISMIC TEST SEQUENCE

The test sequence is obtained applying different scaling to the Montenegro earthquake accelerograms (section 4.1). The reference direction for the signal scaling was the transverse while in the longitudinal direction the scaling factor is the same. Table 6.1 shows the different steps of the test procedure.

Table 6.1 – Steps of the testing procedure

Seismic test level	Longitudinal (Shake table direction)		Transversal (Shake table direction)		Scaling	Motion
1	Montenegro X	0.06g	Montenegro Y	0.07g	0.31	2D
2	Montenegro X	0.12g	Montenegro Y	0.15g	0.67	2D
3	Montenegro X	0.23g	Montenegro Y	0.28g	1.25	2D
4	Montenegro X	0.4g	Montenegro Y	0.50g	2.23	2D

7 Identification technique

The dynamic parameters of the structure (modal frequencies, modal damping and modal configurations) in the seismic tests are usually obtained by the modal analysis. For this purpose a white-noise time history with low amplitude or impulse signal are required.

7.1 WHITE NOISE

Before the first stage and after each test stage, the building model is subjected to two inputs, again orthogonally horizontal and uncorrelated, specially generated with the purpose of obtaining the dynamic properties of the model (natural frequencies, mode shapes and critical damping ratios) and their evolution along the experimental test. As these properties are directly related to the stiffness, the damage state of the structure can be characterized.

Dynamic identification tests under these conditions are normally referred to as forced vibration tests, in opposition to the usual ambient vibration tests. When compared to the seismic tests, these accelerograms have lower accelerations and higher frequency range and duration, see Figure 7.1.

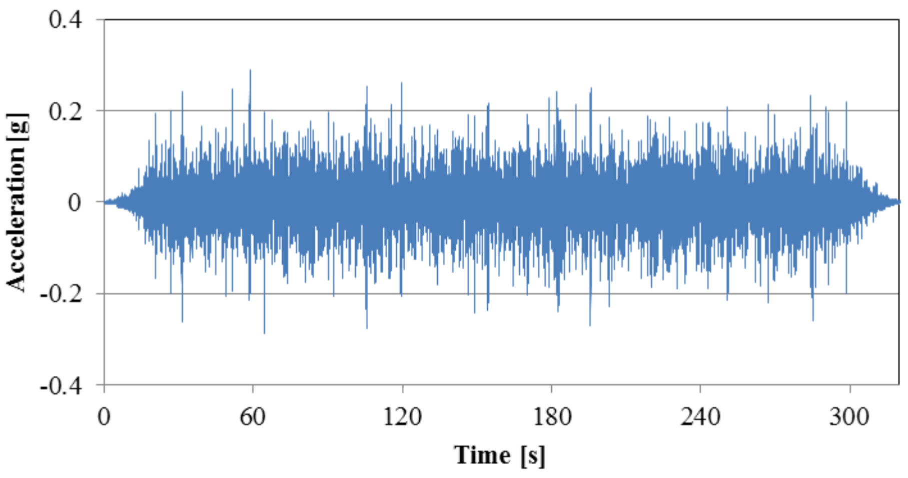


Figure 7.1: White noise signal for dynamic identification tests

These signals are not adapted to a particular response spectrum but generated as a low amplitude white noise. Obviously, the dynamic identifications should not introduce additional damage to the structure, reason why the maximum amplitude is relatively low.

7.2 IMPULSE SIGNAL

The frequency response gain $\left|H\left(f_k\right)\right|$ and phase $\theta\left(f_k\right)$ spectra, as well as the coherence function $\gamma^2\left(f_k\right)$ are calculated taking into account the following approach.

Sequences of data sampled in a time resolution *h*, are divided into *q* frames of *n* points with the total duration of the sequence given by $(n-1)\cdot h\cdot q$ is then applied.

With the FFT procedure, estimates of one-sided power spectral density functions (psdf) for the input, output and cross-spectral can be evaluated using the following expressions:

$$\tilde{G}^{x}_{k,i} = \frac{2\cdot h}{N}\cdot\left|X_{k,i}\right|^2 \qquad \text{for the input psdf}$$

$$\tilde{G}^{y}_{k,i} = \frac{2\cdot h}{N}\cdot\left|Y_{k,i}\right|^2 \qquad \text{for the output psdf}$$

$$\tilde{G}^{x,y}_{k,i} = \frac{2\cdot h}{N}\cdot\left|X^{*}_{k,i}\cdot Y_{k,i}\right| \qquad \text{for the cross psdf between input and output}$$

where $\left|X_{k,i}\right|^2$ and $\left|Y_{k,i}\right|^2$ is the squared modulus of FFT components, at frequency f_k, for the input and output respectively and for frame *i*. The complex conjugate of $X_{k,i}$ is expressed by $X^{*}_{k,i}$.

Taking into account the averaging process over all the *q* frames, the expected power spectra estimates, at frequency f_k, for the total duration of the sequences are evaluated by:

$$\hat{G}^{x}_{k} = \frac{1}{q}\cdot\left[\tilde{G}^{x}_{k,1} + \tilde{G}^{x}_{k,2} + \cdots + \tilde{G}^{x}_{k,q}\right]$$

$$\hat{G}^{y}_{k} = \frac{1}{q}\cdot\left[\tilde{G}^{y}_{k,1} + \tilde{G}^{y}_{k,2} + \cdots + \tilde{G}^{y}_{k,q}\right]$$

$$\hat{G}^{x,y}_{k} = \frac{1}{q}\cdot\left[\tilde{G}^{x,y}_{k,1} + \tilde{G}^{x,y}_{k,2} + \cdots + \tilde{G}^{x,y}_{k,q}\right]$$

The gain factor and the phase factor of the FRF between input *x* and output *y* can now be carried out using:

$$\left|H(f_k)\right| = \frac{\left|\hat{G}_k^{x,y}\right|}{\hat{G}_k^{x}} \qquad \theta(f_k) = \tan^{-1}\left(\frac{\mathrm{Im}\left(\hat{G}_k^{x,y}\right)}{\mathrm{Re}\left(\hat{G}_k^{x,y}\right)}\right)$$

Finally, coherence estimates are evaluated by:

$$\gamma^2(f_k) = \frac{\left|\hat{G}_k^{x,y}\right|^2}{\hat{G}_k^{x} \cdot \hat{G}_k^{y}}$$

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