Development of a Multi Modular platform for seismic engineering courses and research

DEVELOPMENT OF A MULTI MODULAR PLATFORM FOR SEISMIC ENGINEERING COURSES AND RESEARCH

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ABSTRACT

Dynamics of structures has been deeply investigated in recent years through shaking table tests leading to innovative solutions in structural design, such as active and passive systems to mitigate seismic loads. With the aim of supporting the research in the field of resilience and emergency management after earthquakes, this paper presents the construction of a multi modular platform and its applications in earthquake engineering. The platform has been developed entirely by undergraduate students at Politecnico di Torino in Italy within a specific educational program. The project is aimed at testing scaled models of different structures to highlight specific response characteristics and involve students in proactive learning during dynamics and seismic courses. A specific procedure has been also planned in order to explore human body motions and behavior under real ground motions and floor response records as well as artificial input signals. Virtual reality is then introduced as an additional tool to enrich possible applications in the seismic engineering research field. Indoor and outdoor virtual environments have been generated to replicate a realistic situation of emergency conditions. Results of the first test campaign on people show some patterns of behavior that allow the development of agent based models.

Keywords: Shaking Table; Earthquake Engineering; Experimental Test; Virtual Reality; Human Behavior.

1. INTRODUCTION

In recent years, much efforts have been directed to finding methods that are more efficient to give engineering students the problem-solving skills that they need (Wankat and Oreovicz 2015). Among such techniques, laboratory activities can be useful in teaching and advancing the state of knowledge and education within the earthquake engineering field. Indeed, within a dynamic laboratory, it is possible to do hands-on-experiments to demonstrate the fundamental concepts in structural dynamics and provide undergraduate students with an opportunity to experience a deep understanding of structural response.

This type of course-related learning other than simply students watching, listening and taking notes in a class session is also termed as *active learning*. Indeed, analysis of the literature highlights that students should do more than just listen but be actively involved and engaged in higher-order tasks (Bonwell and Eison 1991).

An effective classification of learning objectives for educational purposes, termed as Bloom's taxonomy, can also be applied to seismic engineering courses. It selects the educational objectives within three domains: the cognitive, the affective and the psychomotor (Bloom et al. 1956). It is most often

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used for designing training and learning processes, in order to promote higher forms of thinking in education, such as analyzing and evaluating concepts, processes, procedures, and principles, rather than just remembering facts.
In the field of civil engineering, effect of earthquakes on structures is one of the main subjects of investigations. Indeed, during an earthquake, the displacements induced by ground vibrations can induce severe damages, injuries and sometimes losses of billions of dollars. All over the world, the educational assets in seismic engineering knowledge are significant and the shaking table is one of the main laboratory platform employed to investigate this field.
At the Disaster Resilience Simulation Laboratory of the Politecnico di Torino, the students themselves with the support of teachers have created an earthquake engineering demonstration laboratory within the *Shaking Table Educational Program*. It consists in the design and the construction of an unidirectional shaking table for educational and research opportunities. Physical testing are intended to be conducted during the earthquake engineering courses in parallel with the theoretical lectures.
The goal of this paper is to illustrate the experiences developed at Politecnico di Torino in the construction and development of a bidirectional shaking table within an educational program and its application for research purposes in earthquake engineering.

2. DESIGN OF THE SHAKING PLATFORM

The first part of the project was aimed at realizing the shaking platform. Despite its main application is related to earthquake engineering, the construction of this kind of systems requires competences coming from different fields. Therefore, students of electronics, computer, mechanic and civil engineering worked in team to achieve the goal of the project.
The preliminary phase consisted in the design and realization of the steel frame supporting the platform. A modular design has been adopted in order to be quite versatile according to the needs. At this stage the platform is able to simulate bidirectional earthquakes. The structure itself consists of steel profiles, whereas the upper platform, where specimens can be fixed, is made of aluminium. Basically, there are two parallel tracks located side by side and connected through transversal rectangular sections (Figure 1).

Figure 1. Shaking table at Politecnico di Torino.

Tracks' profiles are 3 meters long and the section's size is 40x100x4 mm. Upon the steel profiles there are aluminium guides in order to allow the motion, along the longitudinal direction, of two carriages. Each track has its own carriage that consists in a 600x500x10 mm aluminium platform and is moved by an actuator anchored to the underneath structure. Upon this plate, another actuator is fixed along the transversal direction as well as another track with a mobile aluminium platform of the same size on top. Type and section of the steel profiles are the same of the bottom ones, while the length is shorter (600 mm). The two small platform can be located at a certain distance along the longitudinal direction so that a bigger aluminium platform (1500x1500x10 mm) can fit upon them.

(a)


(b)


(c)

Figure 2. Longitudinal electric motor (a). Control panel and workstation (b). Electric and electronic devices inside the control panel (c).

The used actuators are manufactured by LinMot and they are linear and electric as more responsive for high velocities and relatively low loads (Figure 2a). The two longitudinal actuators have a maximum stroke of 510 mm, a peak force of 1020 N and a maximum velocity of 2.0 m/s. The transversal ones, instead, have a maximum stroke of 330 mm, a peak force of 858 N and a maximum velocity of 1.6 m/s. The power supply, the two electric transformers and the four drivers to control the motors are provided by LinMot as well. The drivers of the motors are fundamental for the tuning of the motors that is the initial configuration of all the control parameters in order to have a response coherent with the input data. This operation is done through the software LinMot-Talk that is also used to switch on the actuators and to bring them in the starting position.

The control panel of the shaking table (Figure 2b) has been arranged thanks to the cooperation of students from electronic and electric engineering departments. Figure 2c shows the location and the connections of the various components including safety devices. The software used for the activation and control of the shaking table is LabView. A specific code has been written to handle the input and output data. Control and data acquisition are performed through an embedded device (my-RIO by National Instruments) provided with analog and digital I/O lines, an accelerometer and a FPGA. Simply, it is possible to connect a USB pen drive containing the seismic signal in terms of displacements to my-RIO device and send it to the platform via software. The implemented LabView program features also many functions such as: set the input and output sampling rates, generate a sinusoidal seismic signal, load a real ground motion, scale it, start and stop the test.

After the construction of the platform was complete in both mechanical and electronical aspects, much effort has been spent in the calibration of the system. The calibration procedure consists in a comparison between the input and the output. Thus, two accelerometers were fixed on top of the platform measuring its accelerations in the two main directions. Results are then displayed on the graphic interface of the LabView program, as the accelerometers are directly connected to the embedded device. In this phase, due to the non-correspondence between input and output, many weak points were pointed out, which led to some feedback on the design. Under the mechanical point of view further expedients to reduce friction has been adopted, such as a better alignment of the frame and universal joints between each actuator' slider and mobile platform. Regarding the electrical aspects, more adequate connections have been done, solving problems of interferences. At the end results provide a satisfactory repeatability of the test that document the success in meeting the goals of this educational project. The resulting implementation was satisfactory for both tutors and students, spreading knowledge from different engineering fields to the participating teams. As an example, Figure 3 depicts the comparison between power spectral density (PSD) of the shaking table input and the recorded motion on the platform in terms of acceleration. Furthermore, a satisfactory repeatability and an essential independency of the results to the presence of a specimen (even with different characteristics) has been also observed. It is worth noting that the tuning control parameters of the table remained unchanged during this experiment.

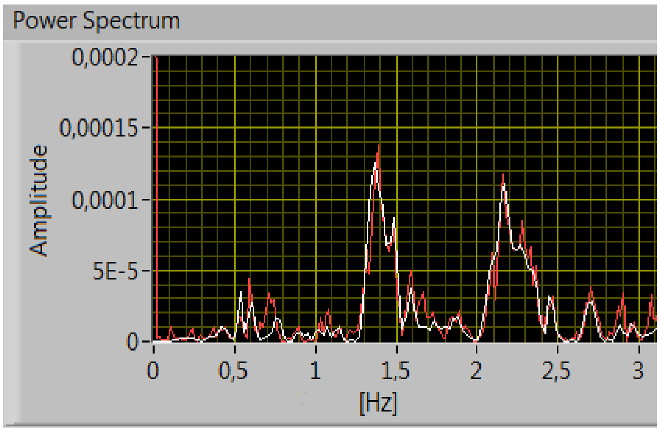
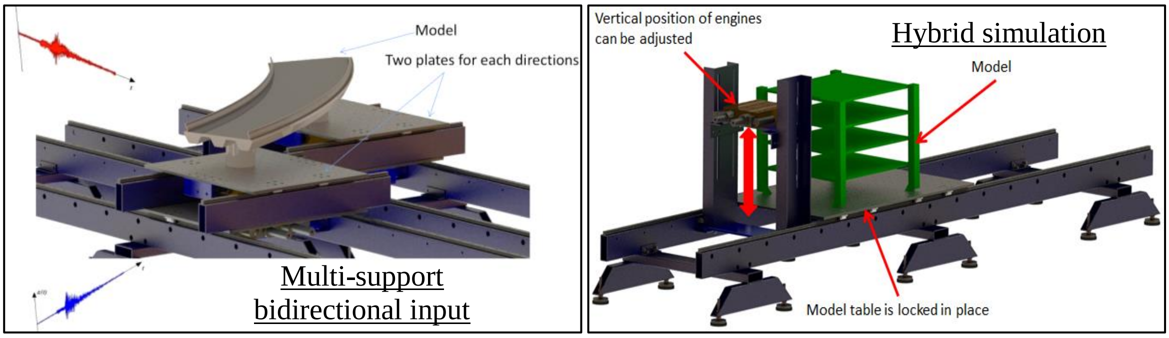


Figure 3. PSD comparison between input and output signals.



(a)

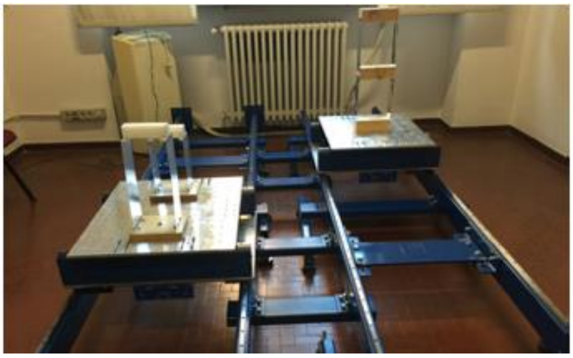

(b)

Figure 4. Different experimental arrangements on the shaking table (a). Examples of simple dynamic tests (b).

Thanks to its particular design, this facility is able to perform different dynamic and hybrid tests (Figure 4a). It is also possible to simulate dynamic space effects with different base excitations that are typical for structures as medium-long span bridges. To perform a hybrid test some elements have to be changed on the shaking table's frame structure. In particular, reaction beams can be installed on the facility for connecting the actuators directly on the specimen, rigidly fixed at the base.
Within the educational program, seminars were organized to allow students attending some experiments. Simple structural models including SDOF systems, passive seismic control systems and a two-story shear frame were tested on the dynamic platform (Figure 4b). During platform preparation and subsequent experiments, the main theoretical concepts and output data were discussed. By this way the cognitive and the psychomotor domains were stimulated, as well as their interaction by handing-on experiments of practical interest and discussing the fundamentals of earthquake engineering for a rapid feedback with the tutors.

3. VIRTUAL REALITY

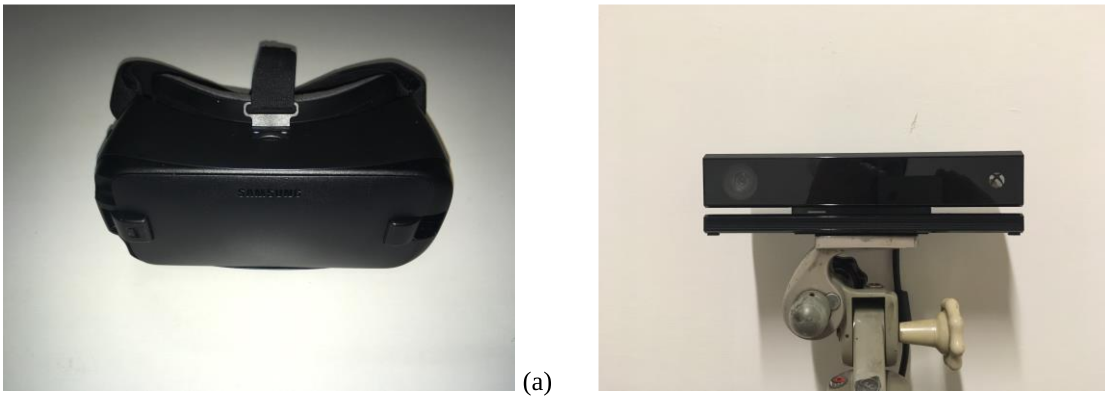
Besides the bidirectional extension, the *Shaking Table Educational Program* is also directed toward an innovative topic represented by the investigation and the analysis of the human behavior during earthquakes. Indeed, while the human losses are positively correlated to the structural damage, injuries have also been found to occur even when no damage was present in the structure. Such injuries are the result of the individuals being struck by objects or falling while trying to escape from the building. Therefore, the shaking itself is deemed a significant cause for injuries and death during earthquakes. In order to understand the ability of people to maintain equilibrium during a ground shaking and to evaluate its effects on human emotions, virtual reality (VR) system is considered. The huge investments by the principal software industries and electronics multinational corporations in Virtual Reality demonstrates that this technology is a reliable solution for many aspects such as training, testing and researches. Virtual Reality has been used for years in medicine as surgery training, for motor rehabilitation and psychological treatments (Sveistrup 2004, Wilson et al. 2007). Professional and free of charge developing environments and electronic devices allows a research opportunity in this field.
The virtual reality system that has been developed in this research is a client-server application that uses the following hardware equipment from the market:

- Samsung Gear VR 2016;
- Samsung Galaxy S8;
- Microsoft Kinect V2 Sensor;
- Windows 10 based computers.

They are possible choices within a number of existing commercial products.
The virtual environment has been developed using Unity3D for the client side, and C# with Kinect V2 SDK for the server side. The simulation system has been designed to achieve three goals:

1) quick development time;
2) cost-efficient software/hardware architecture;
3) connection between movements in real world and those perceived into the virtual environment.

In detail, a smartphone-based head mounted display is used to reduce realization costs: Samsung Gear VR combined with Samsung S8 android smartphone (Figure 5a) represents a good compromise among costs, computational resources and scalability. It allows the user to move his visual field along all the degrees of freedom. Two virtual environments - indoor and outdoor - have been developed in Unity 3D using mesh modelled with Blender and several free available Unity assets (Figure 6). The virtual environment runs on Samsung S8. The spatial variability of the earthquake motion is reproduced by different components. When the virtual environment is shaken every object in the scene is affected and moves in accordance with the input signal: paintings fall off the wall, furniture tilts and overturn. In addition, sound effects are used to increase the realism and the emotional response of the user. Microsoft Kinect sensor (Figure 5b) allows the system to track the 3D user position, so that also the third goal is fulfilled. The user position is transmitted to the virtual environment by control software via Wi-Fi using a text-based message protocol. In order to ensure the delivery of the messages to the client in the same order as sent from the server, a TCP protocol has been chosen. The control software is developed using C# and Kinect SDK, as it allows to choose which virtual environment to load, to define the maximum displacement and the duration of the experiment.



(a) (b)

Figure 5. VR viewer (a) and monitoring camera (b).

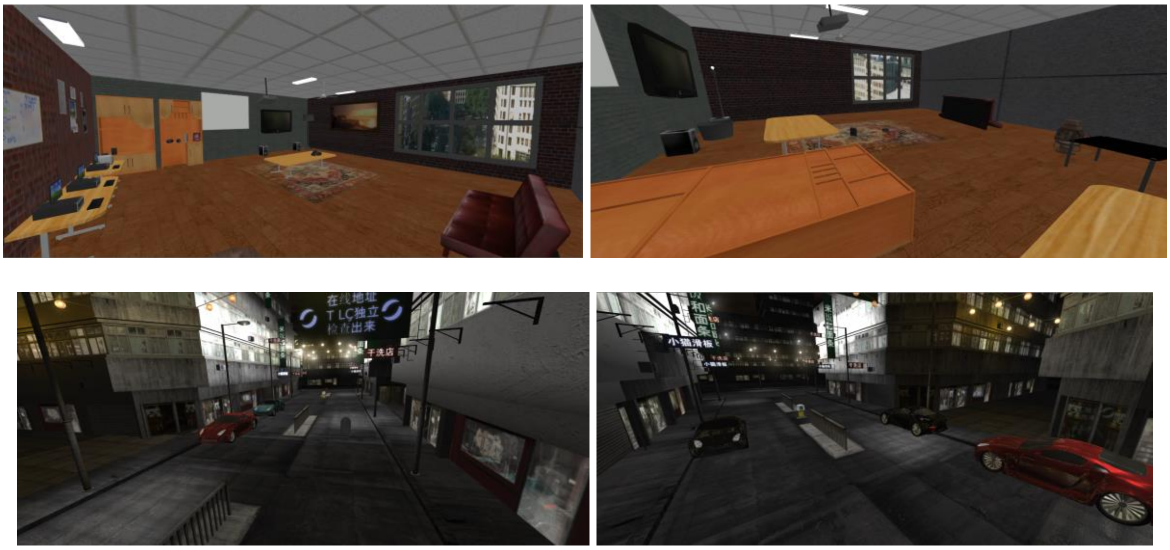


Figure 6. Virtual indoor and outdoor environments, before and after the floor and the ground motions.

4. HUMAN BEHAVIOR TESTS

For investigating the human behavior, several individuals have been tested on the shaking table with the virtual reality set up. For example, one of the performed tests consisted in the evaluation of 14 men and 12 women subjected to two seismic inputs. Each of them consisted in two different displacement time histories along x and y directions. The first was the record of the 2014 South Napa earthquake in San Francisco at the 62nd floor of a residential building (Figure 7a). The second is an artificial signal generated in a frequency range between 1 and 5 Hz (Figure 7b).

Only the movements of the chest and the elbow were considered because the ones of other points like knees, hands, and feet were not representative of the behavior of the tested individuals. The results were collected separately according to the gender only. Other classifications were not taken into account because the size of the tested sample does not allow further classifications. It was noted that almost every individual tried to improve his stability by rising his hands as well as by kneeing down. This general observation was confirmed by the data recorded through Microsoft Kinect (Figure 8). Figure 9 shows the vertical displacements over time of the men's chest and the women's left elbow during the first seismic input. The displacement time history in each graph is the average of all single time histories of the tested samples calculated at each time step. The graphs are anchored to the starting point at rest and the movements of the elbows are relative to the chest. Chest's displacements are negative, meaning a movement towards the ground, while elbow's displacements are positive as everyone was observed to rise and open their hands during the test.

The emotional state of all tested individuals was also assessed during this experiment throughout five criteria: capability to step down from the table, capability to walk, facial appearance, capability to speak, excitement. A score between 1 and 5 was assigned for each of the five criteria, where 1 means a non-natural behavior and 5 means a natural behavior. This evaluation was expressed by observing people's behavior during the test and the way they walked and spoke after the test. Results demonstrated that almost all people behaved quite well as the average value for each criterion ranges between 4 and 5. This means that the individuals were not much affected emotionally by the shaking, probably because they had expected the shaking before it started and the same shaking intensity has been fixed to a lower level for safety reasons.

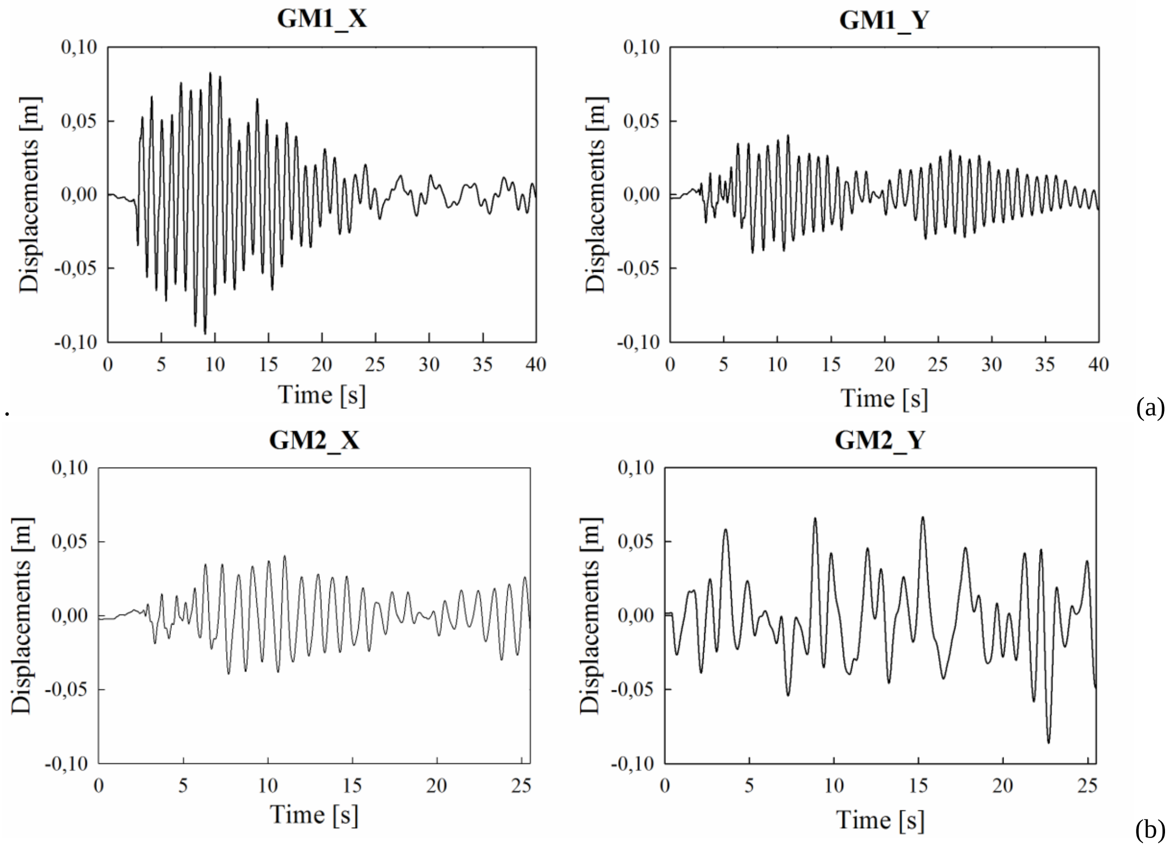


Figure 7. Input signals used in the first simulation (a) and in the second one (b).

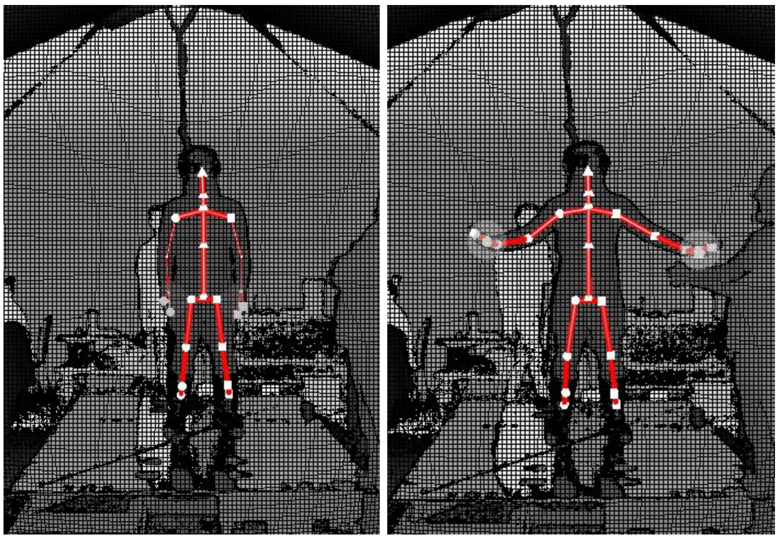


Figure 8. Infrared view of the tested individual through Microsoft Kinect.

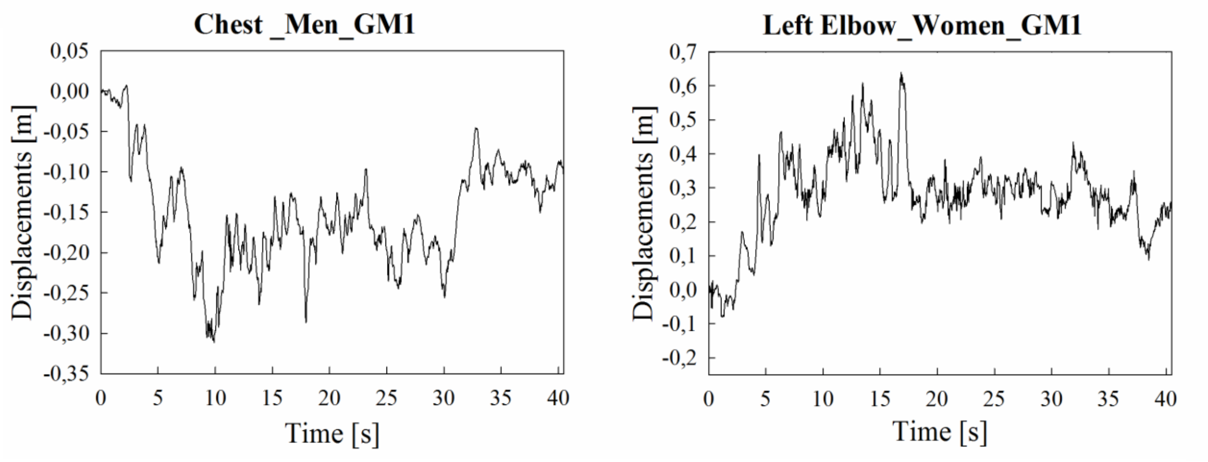


Figure 9. Examples of movements of chest and elbow for men and women during the first shake.

5. THE USE OF THE PLATFORM TO IDENTIFY HUMAN BEHAVIOR PARAMETERS IN AGENT BASED MODELS

The study of human behavior during and after an earthquake can be useful to many purposes. In fact, it is fundamental to simulate evacuation processes and assess whether existing emergency plans are effective or not. Agent based models (ABMs) that consider the actual behavior of the agents (people) are powerful tools to approach this problem. Among the others, Challenger et al. (2009) analyzed the actions of people in a real evacuation process. The relationship *leader-follower* is a recurrent phenomenon during these kind of situations as well as altruism. Considering leaders those who run by themselves towards an emergency exit and followers those who trust the leaders and follow them, to simulate the mentioned aspects it is necessary to define some common actions for leaders and followers during emergencies. This operation has been done by a questionnaire. Obviously methods like this one can be affected by biases. However modern theories have been used to mitigate them. In particular, the developed questionnaire is based on the Theory of Planned Behavior (TPB) of Ajzen (1991). Since people are likely to represent themselves as good people according to the social desirability bias (Fisher 1993), the survey does not use direct questions, but it tries to recreate many dangerous scenarios even through pictures and videos. There are several multiple choice questions where the possible answers are: yes; probably yes; I do not know; probably no; no. The following four different conditions were selected as limit conditions able to affect agents' decisions:

1) the agent sees an emergency exit;
2) the agent is injured;
3) the agent sees another agent which is injured;
4) the agent is with family or friends.

Combining these situations, eight scenarios were defined:

1) the agent is alone, not injured and she can see the emergency exit;
2) the agent is alone, not injured and he cannot see the emergency exit;
3) the agent is alone, injured and she can see the emergency exit;
4) the agent is alone, injured and he cannot see the emergency exit;
5) the agent is with family, not injured and she can see the emergency exit;
6) the agent is with family, not injured and he cannot see the emergency exit;
7) the agent is with family, injured and she can see the emergency exit;
8) the agent is with family, injured and he cannot see the emergency exit.

The possible actions, that are used to formulate questions for each scenario, are:

1) the agent follows a group of people that is running towards another exit;
2) the agent stops to help another inured agent;
3) the agent looks for a member of the family that is lost.

Among 116 questionnaires, 101 people were identified as leaders, while just 15 were followers (Figure 10a). Following these results, further investigations have been done to understand if they were affected by biases. Thus, a new group of people was subjected to the same questionnaire after experienced the shaking table test with virtual reality. Referring to the experimental conditions described in section 4, 14 people were classified as leaders and 12 as followers. From this preliminary test, the experience of the platform before filling the questionnaire results affecting significantly the perception of the scenarios, as the percentage of leaders drops from 87% to 54% (Figure 10b).

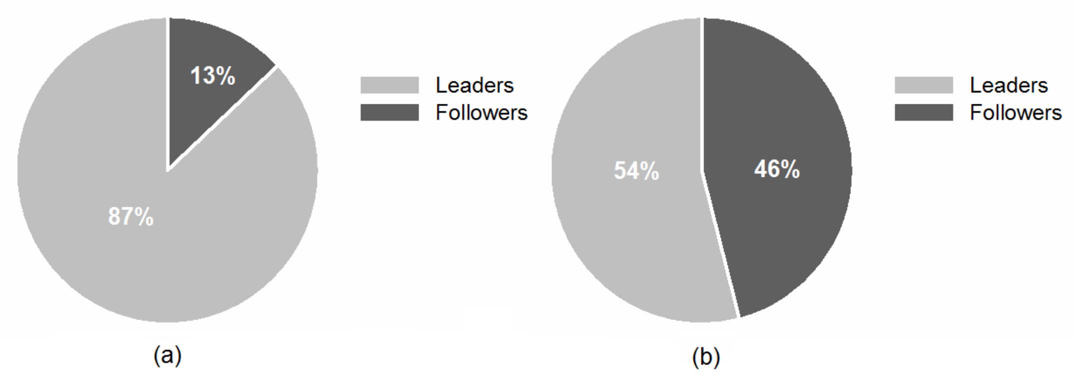


Figure 10. Leader-follower relationship for people with no shaking table experience (a) and after shaking table experience (b).

The social desirability bias is then much stronger when the individual is not familiar with panic and anxiety feelings generated by an earthquake. Data from the questionnaires have been also used to define a behaviour pattern through the Belief-Desire-Intention (BDI) model. This represents the first step for the definition of a more complex and comprehensive Agent Based Model for simulations of building's emergency evacuation in seismic conditions.

6. CONCLUSIONS

This work presented part of the work done within the *Shaking Table Educational Program* for higher education at Politecnico di Torino in Italy. The program represents a novel didactic strategy since it is aimed to achieve a comprehensive education process where the fundamental approaches to earthquake engineering are delivered to students together with laboratory experiments. It provides undergraduate students with the opportunity to understand and deepen some important concepts related to the structural dynamics. In this way, students are actively involved in the learning process, integrating the critical thinking skills of the cognitive domain with the physical tasks of the psychomotor domain.
The program consists in many steps, from the design and construction of the multi modular bidirectional shaking table to its applications in both research purposes and earthquake engineering courses. One of the unique features of this platform with respect to the existing ones, is that the system has been entirely developed by undergraduate students. The facility is designed in order to be used under different configurations and tests. In this paper, the most relevant applications have been described highlighting the outcomes of each experience.
Other two usages of the shaking table were discussed within the present work. The first one is aimed at understanding individuals' behavior and body motions during an earthquake. Virtual environments have been developed and integrated in this test in order to recreate a more realistic experience. Results show how almost every individual tried to improve his stability by rising the hands and lowering the center of gravity. The other reported activity is the development of a questionnaire to investigate human behavior during an emergency situation such as an evacuation process. Also in this case the usage of the shaking table is crucial. It helps to mitigate biases phenomenon.
Future work will include the exploration of new learning and research opportunities, trying to confirm the positive feedback achieved in the earliest years of the program.

7. ACKNOWLEDGEMENTS

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