Seismic vulnerability of existing buildings: non-invasive approach for dynamic behaviour assessment

by Gianluca Acunzo, Michele Vicentino, Antonio Bottaro

In recent years, the partnership between the Department of Mathematics and Physics of Roma Tre University and GEOWEB S.p.A. has led to the creation of an applied research program named *Metior*. The main aim of this program is the research and development of a set of innovative tools for the creation of easy-to-manipulate virtual models, where the concept of measurement and geometric survey can be enhanced.

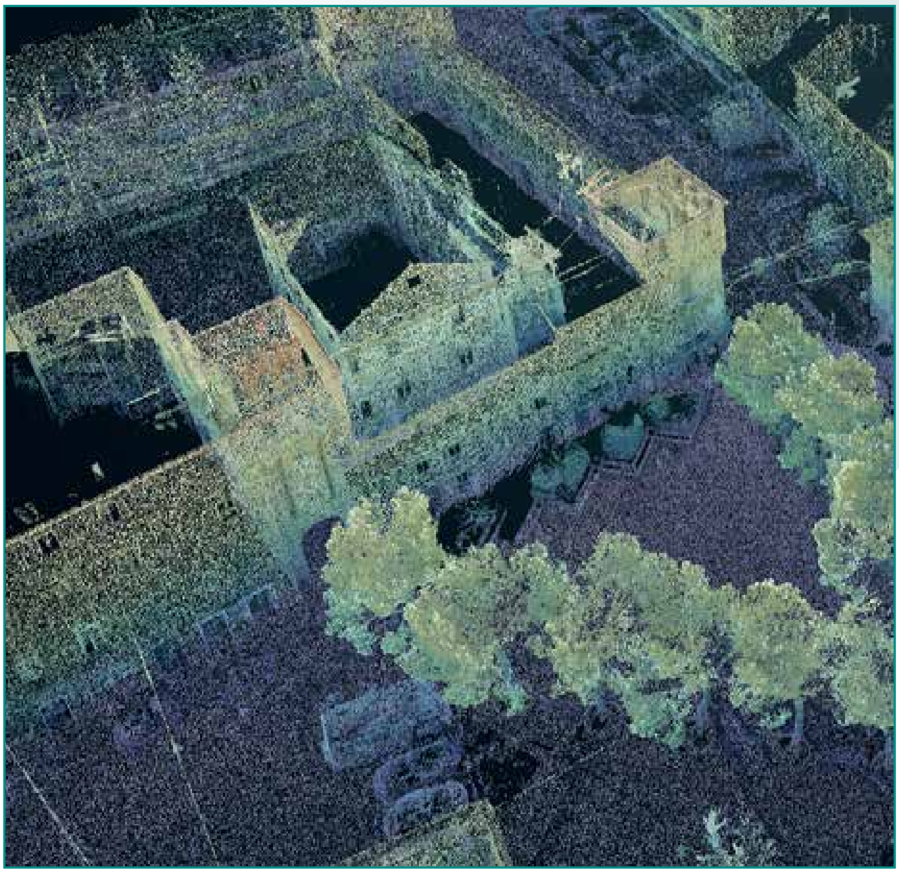

Fig. 1 - Example of 3D point cloud created in the Metior platform.

Such virtual reality environments are built through photogrammetric techniques like stereoscopy, orthophotography, Digital Terrain Modeling (DTM), Digital Surface Modeling (DSM) and 3D Point Clouds joined with advanced 3D modeling and computational geometry techniques developed by the research groups of Roma Tre University (Fig. 1).

Nowadays, it is well known how 3D virtual reality, and augmented virtual reality as well, can support any kind of geometric, topologic and numerical ex-post analysis just by relying on a certified instrumental data acquisition campaign.

In the framework of this agreement, also a research fellowship has been set up with the purpose of researching and developing new techniques and tools which may give a contribution to the workflow aimed to the reduction of the seismic risk for civil buildings.

In the field of seismic vulnerability assessment there is a very useful, non-invasive and not so well-known typology of survey that can provide significant added value to such a kind of assessment. This measurement is commonly known as environmental vibration measurement. In order to understand the potential of the environmental vibrations and how they can be used, we will give a brief overview of some of the key concepts to keep in mind when talking about "seismic risk".

Therefore, what do we mean when we talk about seismic risk for a civil building?

To answer this question, it is appropriate to briefly introduce the three main factors that are involved and whose combination defines the seismic risk:

seismic hazard (H), seismic vulnerability (V) and exposure (E). The seismic hazard is related to the site where the building is located: the hazard of a certain area is determined by the characteristics (in terms of frequency and intensity) of the earthquakes that may occur. On the other hand, seismic vulnerability is something related to the building itself and to the potential damage that could occur during a seismic event of a given intensity. Finally, exposure is related to the number of assets that are exposed to risk and takes into account the possible consequences of an earthquake, such as loss of human lives, damage to cultural heritage and damage in economic terms.

The so-called seismic risk is given by the combination of these three factors and can be conceptually expressed as the product of the previously introduced terms:

$$R = H \times V \times E$$

In the first part of this article we will synthetically discuss some aspects related to hazard and vulnerability, in order to understand how the expected seismic input at the base of the building is determined for a considered site and what is important to consider when a seismic vulnerability verification is performed for a civil building.

The current Italian legislation envisages that only architects and engineers are the professional figures who can deal with the seismic vulnerability assessment, in particular with regard to the aspects related to numerical modeling, structural analysis and retrofitting design. Moreover, GEOWEB strongly believes that the role of the surveyor, who is typically involved in the due diligence processes related to the certification of the actual state of buildings, can undoubtedly be actively involved in the seismic vulnerability analysis by designing, executing and validating the results of environmental vibration measurements, supporting the following structural analysis delegated by the legislation to architects and civil engineers.

So, after the overview about the environmental vibrations analysis approach, some of the tools that are being developed in the context of the cooperation between GEOWEB S.p.A. and Roma Tre University, will be discussed.

Seismic hazard and expected seismic input

As previously introduced, the seismic hazard of an area is basically given by its seismicity: it is expressed in probabilistic terms and it is defined, in a given area and in a certain interval of time, as the probability of an earthquake occurring beyond a certain intensity threshold.

Thinking about the seismic hazard in the Italian peninsula, the first image that comes to mind is the Seismic Hazard Map produced by the Italian National Institute of Geophysics and Volcanology (INGV) (Fig. 2).

The colors show the value of the Peak Ground Acceleration (PGA) for each area of the Italian soil, with colors ranging from light gray (lowest value) to purple (highest value).

How should this map be read? We have just said that the hazard is defined in probabilistic terms as the probability that in a certain time lapse an earthquake with a certain intensity occurs: in this map, as described in its upper banner, what we can read is the maximum ground acceleration that has a probability of 10% to be exceeded in a time lapse of 50 years on stiff soils. Without going into the details of formulas, this means that the value of acceleration we are reading is the one that has a return period of 475 years, that is the one of the seismic action used to design and verify ordinary buildings according to the Italian Building Code (NTC).

Table in Fig. 3 shows the relation between the value of PGA and the corresponding seismic

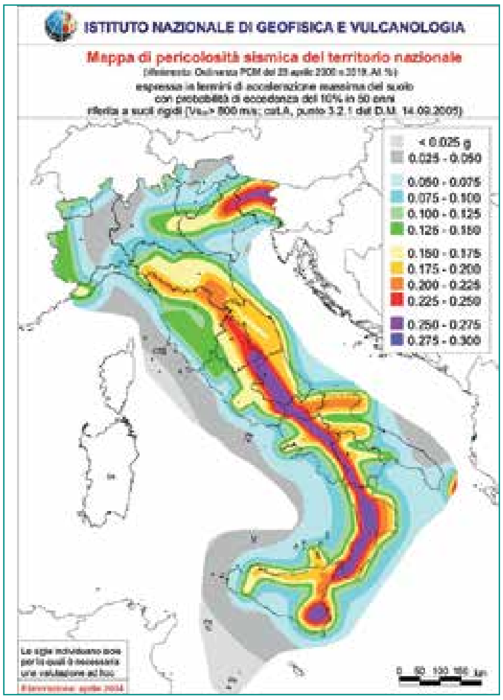

Fig. 2 - Seismic hazard map for Italian peninsula (INGV).

Seismic Zone	Acceleration with 10% of exceeding probability in 50 years (ag) [g]
Zone 1	ag > 0.25
Zone 2	0.15 > ag ≥ 0.25
Zone 3	0.05 > ag ≥ 0.15
Zone 4	ag ≤ 0.05

Fig. 3 - Seismic zone classification and PGA values.

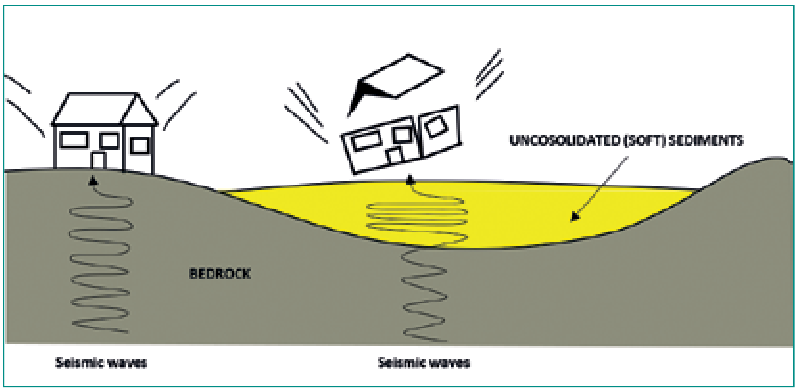

Fig. 4 - Amplification of seismic waves (site effect).

zone, from Zone 1 (highest hazard) to Zone 4 (lowest hazard).

Furthermore, as specified in the description of the map, the value of PGA we can read is the one expected on a hard soil, corresponding to the bedrock. This allows us to introduce another fundamental aspect that must be considered to determine the value of acceleration expected at the base of the building: the soil effect.

The layers of soft soil act like a filter and modify the seismic waves that arrive from the bedrock, emphasizing some of the frequencies in the signal and modifying the actual accelerations that will reach the base of the building (Fig. 4). Basically, it is like an equalizer in a hi-fi audio system: the original input signal passes through the filter that modifies its frequency content, giving the equalized signal as its output. In terms of amplitude, when a seismic wave passes from a stiffer layer to a softer one, it decreases its speed. As a consequence, in order to conserve the energy, its amplitude increases. In general, we can say that the softer the ground is, the more the accelerations on the ground level will be amplified. In light of the above, the soil plays an important role in the seismic hazard of a given site: depending on the situation, a building lying on a soft soil in a seismic zone 3 could be actually subject to a higher acceleration than the one lying on a hard soil in a seismic zone 2.

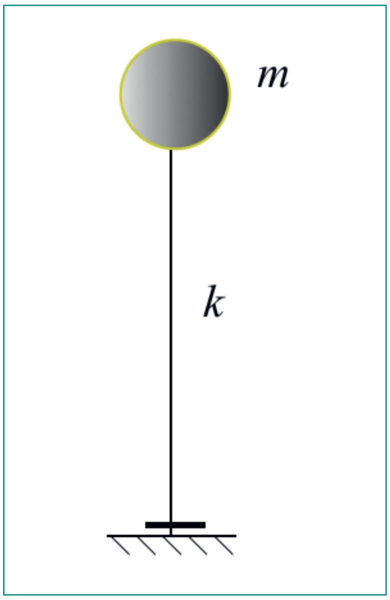

Fig. 5 - Simple oscillator.

In conclusion, the seismic hazard gives us the value of acceleration we expect at the base of a given building, depending on the site location and the characteristics of the soil.

Can we say that this acceleration is the same that acts on the building?

To answer this question, let's make a little mental experiment: let's consider a sphere with a given mass m that lies on top of a stick, with a given stiffness k (Fig. 5). If we take the base of this object and start to move the base back and forth, the sphere on the top will start to move as well. It is easy to imagine that the sphere will not exactly follow the movement of the base, but will move in a different way, depending on the stiffness k of the stick and the mass m of the sphere. This is exactly what happens when a building is subject to an earthquake: the way in which the building tends to behave depends on the input excitation, obviously, but also on its characteristics in terms of stiffness and mass. In particular, the way a structure behaves when subject to vibration is described by its mode of vibration, that will be described further into this article.

Seismic vulnerability of buildings: the local mechanism of collapse

When an earthquake occurs, the ground starts moving horizontally and vertically and the building starts to sway and deform. The way in which buildings respond to a given seismic action can be very different, depending on factors like structural typology, materials, age, level of maintenance.

The seismic action at the base results in an additional load that induces a further stress distribution in the structural parts. When the building has a box-like behaviour and acts as a single body, the stresses are distributed among the elements according to their stiffness and the whole structure gives a contribution in terms of resistance. This is the typical behaviour of a Reinforced Concrete (RC) building, where the frame composed by beams and columns is a continuous structure that internally distributes the stresses

among the elements.
Unfortunately, although this kind of behaviour is highly desirable, this too often doesn't happen in masonry structures: during the seismic event the masonry building can experience partial collapses due to the loss of equilibrium of some masonry portions. These kinds of collapses are called local collapse mechanisms and they are one of the main issues in the seismic analysis of masonry buildings. The causes of this behaviour generally lie in the lack of construction (e.g. poor masonry quality, poor connection between orthogonal walls, no connection between slabs and walls) or lack of maintenance during the building's lifecycle.
One of the most common and dangerous mechanisms of local collapse is the overturning of the perimeter walls (Fig. 6): due to poor connection with the transversal walls, a portion of the building subject to the earthquake comes loose from the rest and overturns on its base, involving one or more floors depending on the connections between the elements.
When the condition of the building makes this local mechanism possible, this is generally the one that activates first, for relatively low levels of acceleration. Another local mechanism that is pretty common in masonry building is the vertical bending (Fig. 7): during the seismic event, the slab pushes against the facade and the wall bends out of its plane.
This kind of mechanism is generally caused by a poor masonry quality and no connection between slabs and vertical walls and the level of acceleration required for its activation is pretty higher than the previously described overturning. For this reason, it can take place when the first mechanism is prevented by an effective connection at the top of the perimeter wall.

Seismic vulnerability of buildings: the global response

From a seismic point of view, a well-designed building must not be damaged by a low intensity earthquake, not structurally damaged by a medium intensity earthquake and must not collapse when a strong earthquake occurs, despite severe damages. The concept of low, medium and strong intensity is closely related to the previously described seismic hazard of the site. This is the basic philosophy of today's seismic codes.
A building in its operating conditions is mainly subject to the static loads induced by the permanent and variable loads, where the former are the weights of its structural and non-structural parts and the latter are those that are not constant over the time (e.g., the presence of people, furniture in the rooms and the action of the wind).
The analysis of the previously described local mechanisms is a fundamental part in the seismic vulnerability assessment of masonry buildings, as their prevention shall ensure the desired box-like behaviour in which the structure responds to the seismic action as a single body involving all of its structural parts.
In order to check how this single body will behave under a given seismic event, we have to introduce the concept of mode of vibration.
Each building, and more in general each physical object, is characterized by a series of vibration modes that describe the way in which the system tends to oscillate naturally, i.e. with no excitation force. The frequency value at which it oscillates is called natural frequency and the shape it assumes during the oscillation is called mode shape.
When the frequency of the exciting vibration is equal, or very close, to the natural frequency of a given mode of vibration, we have the phenomenon of the resonance and the system starts to oscillate according to the mode shape. A simple example of this phenomenon is given by the diapason: when you hit the diapason, it starts to vibrate ac-


Fig. 6 – Example of overturning of perimeter wall.


Fig. 7 - Example of vertical bending.

Fig. 8 - Apartment complex collapsed after the 1985 Mexico City earthquake.

cording to its natural frequency at 440 Hz (corresponding to the musical note A4) and if we put a vibrating diapason near a still one, after a few seconds the latter will start to oscillate in the same way.

The same happens for buildings: the seismic waves of an earthquake contain a number of frequencies and if the frequency content is very close to the natural frequencies of the building the resonance phenomenon induces an amplification of the strong motion. An even worse case is the double resonance phenomenon: this happens when the soil and the building have similar frequencies and they are both strongly excited by the earthquake, so that they both acts as amplifiers of the seismic motion. One of the most famous cases of double resonance is the earthquake which struck Mexico City in 1985 (Fig. 8).

In general, the damages produced by an earthquake tend to decrease as the distance from the epicenter increases, because the seismic waves are subject to an attenuation but in the case of Mexico City the most of the damage occurred at about 400 Km from the epicenter: the softness of the soil where the city lies caused an amplification of the seismic waves and the very similar frequencies of buildings and soil has led to a double resonance phenomenon (Fig. 9).

In the light of above, the correct estimation of the structural modes of vibration plays a fundamental role in the seismic vulnerability assessment. In general, they are determined through a modal analysis using a numerical model like a Finite Element (FE) model, built on the basis of data like the structural geometry, the mechanical features of the materials, the masses and their disposition (Fig. 10).

Once a suitable seismic input is defined, the stress acting on the structural elements due to the seismic action are determined on the basis of the vibrational characteristics obtained with the modal analysis. Finally, the structural elements of the buildings are verified according to their material strength, considering the state of stress induced by both the static and dynamic loads, in order to assess the vulnerability of the considered building.

The accuracy of the results clearly relies on the accuracy of the numerical model and one of the key aspects is a proper assessment of the mode of vibration of the structure. Upstream of a numerical model, a number of inspections and surveys are carried out in order to get the information about geometrical and mechanical features of the structural elements which will be included in the FE model.

Of course, the more comprehensive these local surveys are the more accurate the global model will be in terms of modes of vibration estimation and, consequently, assessment of dynamic response of the structure. Which begs the question: is it possible to identify the real modes of vibration of an existing building, in order to compare them with the ones calculated numerically?

Yes, it is. Through the dynamic identification.

Dynamic identification of existing buildings

Basically, a building subject to a vibration tends to act as a filter which modifies the original signal on the basis of its physical characteristics. Once again, the

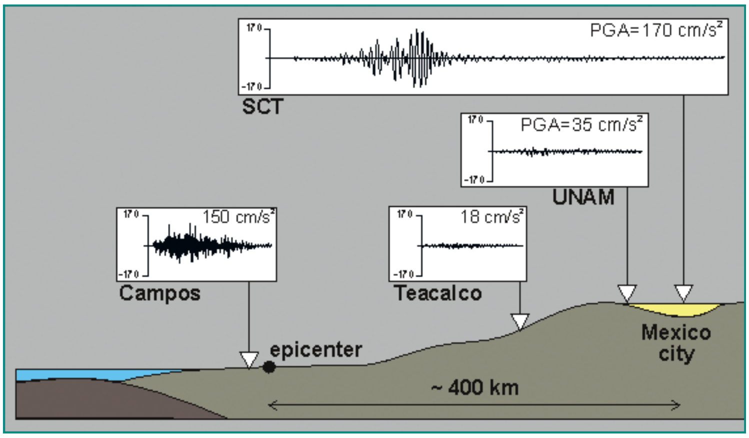

Fig. 9 - Soil effect during the 1985 Mexico City earthquake.

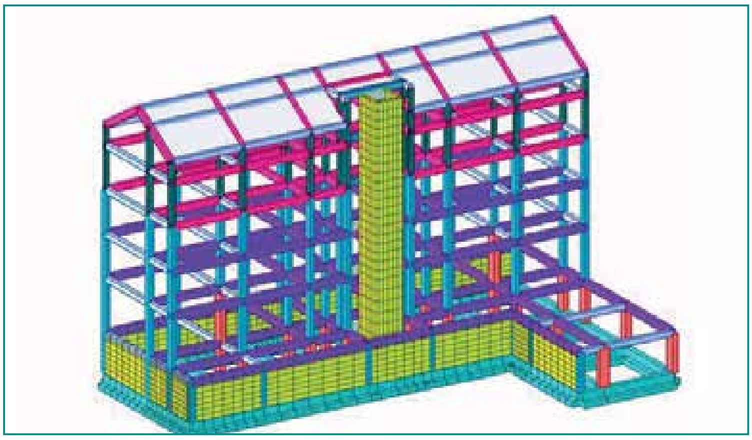

Fig. 10 - Example of FE model.

Fig. 11 – A vibrodyne used to apply an input to a building.

example of the equalizer in a hi-fi audio system that we used when talking about the soil has a good match with our specific case. The way in which the original signal is modified when passing through the building is highly dependent on its dynamic characteristics and a suitable analysis of these signals allow us to extract the vibrational characteristics of the building, i.e. its modes of vibration.

The dynamic identification of an existing building can be carried out using two main techniques, which differ in terms of required equipment and implementation rules: the Experimental Modal Analysis (EMA) and the Operational Modal Analysis (OMA).

Both of the techniques require the positioning of sensors in different points of the building under examination (typically accelerometers or velocimeters) in order to acquire the structural response, but the main difference between the former and the latter is due to the exciting force.

In EMA, the structure is artificially excited by using equipment which applies an external known excitation (Fig. 11). As these machines must be able to induce forces that involve the entire building, it is easy to imagine that they are massive equipment that have to be fixed to the structural parts, generally at the top level of the building, making their transportation and assembly very onerous. As a consequence, this kind of measurements are quite invasive and lead to the interruption of the serviceability in the examined building until all the equipment has been removed.

On the contrary, in the case of OMA no external excitation force is required: the sensors placed in the structure acquire the very small vibrations induced by external factors like the people moving inside, the wind, the traffic in neighboring streets and so on. This feature implies an important advantage over the previously described EMA: such measures do not require the building to become off-limits location, as the target of the measurements are the vibrations of the building in its operational condition when subject to the so-called environmental noise. Furthermore, due to the low level of vibrations, the sensors can be often just placed on the floor with no need to drill holes in the walls. Of course, there is also some drawback: as the amplitude of the environmental vibrations can be orders of magnitude lower than the ones induced by the heavy machines used in EMA, the accelerometers to be used must have a very high sensitivity, which leads to a higher equipment cost.

Despite this, it's quite clear that in the application to the civil engineering field a non-invasive approach like the Operational Modal Analysis is much more suitable than the Experimental Modal Analysis, which remains a profitable technique widely used in fields like mechanics and aerospace engineering.

Regardless of whether EMA or OMA is performed for the identification, the knowledge of the experimentally identified modes of vibration provides a significant added value to the seismic vulnerability assessment of buildings. When performing a typical seismic vulnerability analysis, the theoretical frequencies and mode shapes computed through the numerical model can be compared with the experimental ones in order to improve the accuracy of the calculation model, making it closer to the real behaviour of the considered structure.

For example, the model can be calibrated by fine-tuning some of the parameters characterized by a greater uncertainty, e.g. the stiffness of the infill walls in a Reinforced Concrete building. When modeling complex buildings, the comparison between the numerical and experimental mode shapes can also highlight the need to include other structural blocks whose influence on the dynamic global response cannot be neglected.

Furthermore, experimental modes of vibration can also be used to check and valida-

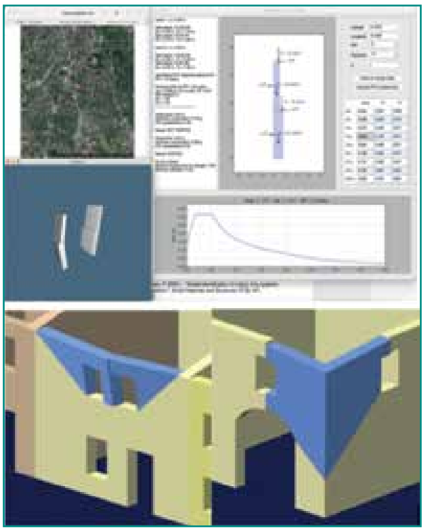

Fig. 12 - Tool for the analysis of the local mechanisms of collapse (top) and example of two custom mechanisms (bottom).

te the efficiency of a seismic retrofitting, by verifying the actual match between the real dynamic behaviour and the designed one.

Another application is in the structural health monitoring: the natural frequencies of a building depends on its mechanical features. The occurrence of a damage produces a reduction of the structural stiffness and a decrease in the natural frequencies. As a consequence, the comparison between the modes of vibration identified before and after a seismic event may point out a non-visible damage, which can be also located and quantified by using appropriate techniques.

Tools and instruments: work in progress

As part of the collaboration between Roma Tre University and GEOWEB S.p.A., some tools are being developed relating to the topic of seismic risk. In particular, two of them are related to the topics briefly described in this article.

The first one is designed for masonry buildings and allows the practitioner to verify the potential occurrence of local mechanisms of collapse (Fig. 12 - top), in accordance with the provisions of the Italian building code. This tool will be integrated in the Planner, the 2D/3D graphical editor developed by GEOWEB in its Metior Platform, which easily allows the user to create 3D models of buildings from the 2D floor plans (Fig. 13), to be used for several purposes: in the context of the Selective Deconstruction, for instance, they allow to schedule, quantify and support either the demolition or the refurbishment activities aiming to maximize the amount of materials recycled or even reused, and minimizing the amount of materials dumped to landfill; an ad-hoc version of the Planner, named BaM (Building and Modeling), has been adopted in an education program which is currently being carried out at the first level of Italian secondary school to promote the adoption of recycling best practices and to raise awareness about energy saving issues.

Thanks to the implementation of the previously described tool, its integration in the Planner will enable the user to choose the portion of the building – i.e. its modeled geometry - to analyze and to calculate the acceleration required for the activation of a local mechanism of collapse, comparing it with the provisions of the building code.

In addition to the more common mechanisms like the previously described ones, the user is also able to define and analyze custom mechanisms, which may be required for the structural situation under examination (Fig. 12 - bottom).

The second tool is focused on the dynamic identification of existing buildings and allows the practitioner to analyze the environmental vibration signals acquired by the accelerometers, supporting all the steps that lead from the model definition to the identification of the experimental modes of vibration. The software implements some robust and reliable algorithms from scientific literature for the modal parameters extraction and offers several advanced tools for signal preprocessing and the validation of the final results (Fig. 14).

The software is specifically designed for application in the field of civil engineering, and thanks to its building-oriented nature, specific control indices have

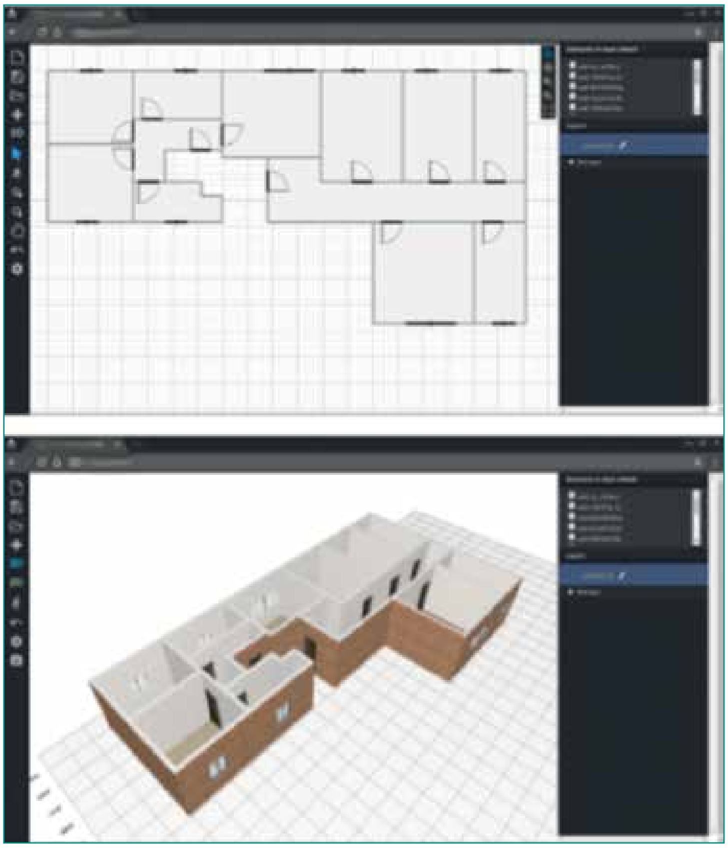
Fig. 13 - 3D model created from 2D floor plan in Planner.

been implemented given their relevance in the identification of buildings dynamics.

The geometric information input is very flexible: geometry data import can be carried out from several widespread formats, like spreadsheets and CAD files; it is also possible to directly import geometry data from a model created in the Planner (Fig. 15).

The equipment used for the acquisition is generally quite expensive, due to the high level of sensitivity required to detect small amplitude vibrations like environmental ones, and when a significant number of measuring points is required this set of instruments can cost several thousand Euros. Given the importance that this kind of measurements has in the seismic behaviour assessment of buildings, efforts are being made to develop a measurement system with a suitable trade-off between the required performance and the cost.

A significant cost reduction, both in terms of hardware and software, together with the development of tools able to assist the user during the design and the execution of the measurement phase, would certainly help to increase the usage of the dynamic identification in the seismic vulnerability assessment.

The implementation of a low-cost hardware will also lead to the development of an affordable monitoring system, designed to be permanently installed on the building, in order to periodically acquire environmental vibrations and perform a check of its vibrational characteristics over time.

Nowadays, the Building Information Modeling (BIM) process is becoming increasingly important and widespread in the building sector, playing a key role in all stages of the building's lifecycle - from its design to its maintenance.

The tools developed in the framework of the Metior research project allow the user to create a virtual reality in which the 3D representation of the real-world objects is combined with their semantics, i.e. their features and the role they play in the building system, in full accordance to the BIM philosophy whose aim is to create a digital representation of physical and functional features of the building.

As a consequence, with a view to enhancing this 3D virtual reality model, relevant information which would be helpful in safeguarding and maintaining of existing buildings can be added. One of the next targets in the Metior platform is the integration of the semantic model with the data related to the experimental modes of vibration of the building.

And this is something that, as we have seen throughout this article, can offer a huge added value in understanding the real dynamic behaviour of the existing building stock.

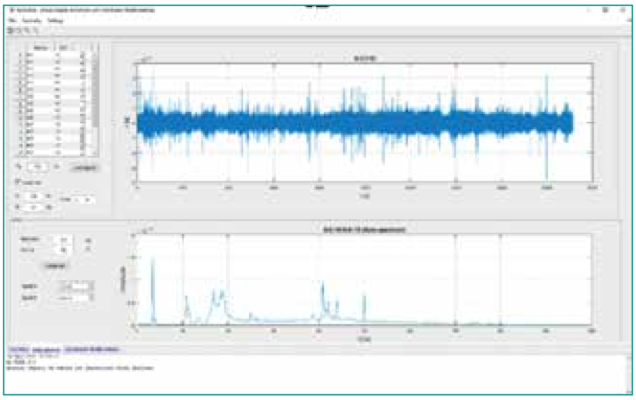

Fig. 14 - Software for dynamic identification: signal acquisition and pre-processing panel.

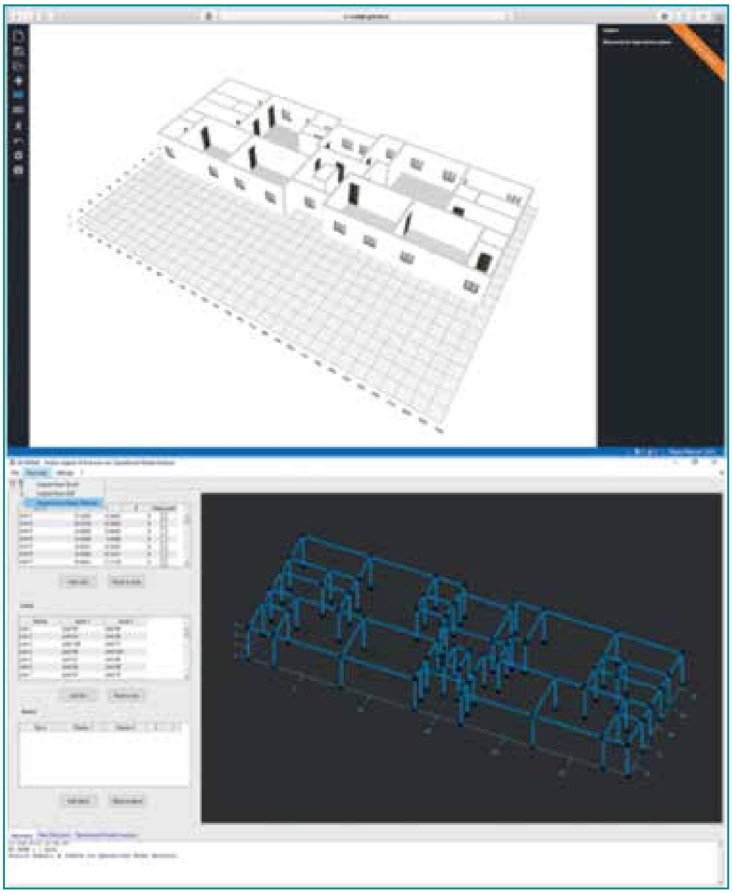

Fig. 15 - Import of geometry from Planner 3D model.