Three dimensional integrated survey for building investigations

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CASE REPORT

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Three-Dimensional Integrated Survey for Building Investigations

ABSTRACT: The study shows the results of a survey aimed to represent a building collapse and the feasibility of the modellation as a support of structure analysis. An integrated survey using topographic, photogrammetric, and terrestrial laser techniques was carried out to obtain a three-dimensional (3D) model of the building, plans and prospects, and the particulars of the collapsed area. Authors acquired, by a photogrammetric survey, information about regular parties of the structure; while using laser scanner data they reconstructed a set of more interesting architectural details and areas with higher surface curvature. Specifically, the process of texture provided a detailed 3D structure of the areas under investigation. The analysis of the data acquired resulted to be very useful both in identifying the causes of the disaster and also in helping the reconstruction of the collapsed corner showing the contribution that the integrated surveys can give in preserving architectural and historic heritage.

KEYWORDS: forensic science, data integration, laser scanning, photogrammetry, topography, modeling, feature extraction

Historical Notes

Salerno is a town of Campania, a region of Italy, which is located on the Gulf of Salerno (Tyrrhenian Sea).

In the whole of Europe, between the late XIX and the early XX century, a movement, that was a characteristic of the visual arts and architecture spread out. This movement, that in Italy was called "Floral" or "Liberty" (so called from the name of a historical company in London that was specialized in articles of furniture on art nouveau), developed at the same time in France (with the name "Art Nouveau"), in Germany and Svizzera (called "Jugendstil"), in Spain (with the name of "Modernism"), had as main characteristics the asymmetry, the linearity, the use of polychrome materials, and the naturalism of the ornaments (mostly inspired by the shapes of the vegetable world). Common themes, in Liberty architecture, were the extensive use of materials such as wrought iron and glass, the recurrent presence of towers and pillars, the widespread use of stucco and decorative floral motifs as well as the ornamental shapes of the curves. Salerno is mainly affected by this kind of architecture, that spread mostly between 1900 and 1920 in the districts of the new urban development and that can be easily seen on the facades of the buildings along the Trieste promenade and in the harbor area, as well as in several areas affected by demolition and architectural restoration. There are many villas, palaces, and also some smaller buildings in this style, which nowadays are considered as an important architectural heritage; unfortunately, some buildings were suppressed by the large and unsightly ones of a later period.

Palazzo Edilizia, that is the object of this article, was built in the twenties of the twentieth century in the late Art Nouveau style; it takes its name from the "Società Anonima per l'Edilizia", which undertook its construction. The Società Anonima Esercizi Riuniti (SAER), also known for some time as a Società Anonima Elettrotranvie Romagnole and, next, as Società Anonima per l'Edilizia Residenziale, was active both in the construction industry and in the public transport sector. The Palazzo Edilizia, overlooking the Trieste promenade and the Amendola square, has the main entrance on the side of Queen Constance street. It consists of six storeys in elevation plus one basement, and two staircases.

The Collapse of the Structure

The structure of Palazzo Edilizia is a mixture of tuff masonry walls, reinforced concrete (RC), structural elements (columns and beams), and floor slabs composed by RC joints and hollow bricks. The rooms at the ground floor are used principally for various business activities and there is also a bank, a restaurant and a bar.

On June 15, 2007, at about 3.30 a.m. a whole corner part of the building suddenly fell down. The collapse did not cause any victims only because there were no people that early in the morning in the rooms on the ground and first floors, and the corner part of the building contained only living rooms. Figure 1 shows, on the left side, the corner of the building before the collapse, while in the right one, you can see the same corner after the collapse.

Generally, the main causes of a building collapse are to be found among a lack of preliminary inspections and assessment

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FIG. 1—*The building corner before and after the collapse.*

of the construction; some possible wrong or invasive restoration work or repairs; a lack of temporary shoring structures; no, or inadequate, recognitions of alarming cracks; and no timely safety measures for the parties involved (1). In the case of Palazzo Edilizia, some restoration work were put into effect several years after its construction, mainly aimed at widening the rooms on the ground floor, which was the entrance of trade activities (2). In March 2007, some restoration work was started on the ground floor of the building and specifically at the corner that faced the seafront of Salerno. Moreover, such restoration work consisted of repairing some masonry walls by a partial substitution of the old mortar joints with some new cementations-based ones. After the clearing and substitution of the plaster had started, some cracks on the masonry piers were observed, as shown in Fig. 2 (3), but no adequate and timely safety measures were carried out.

In order to identify the causes of the collapse and the related responsibilities, the Judicial Authority started a criminal procedure after the accident. The authors of this article took part in the investigations as technical consultants of the structural engineer and their selection was made thanks to the expertise they had acquired in the field of Terrestrial laser scanner technologies and in photogrammetry. In fact the request for high-definition surveys represents one of the main factors which have promoted the use of these technologies in several fields with applications such as judicial investigations or cultural heritage preservation projects. By measuring millions of points within relatively short time periods, terrestrial laser scanners allow to derive complete and detailed three-dimensional (3D) models of real objects from acquired point clouds. A great number of articles about the comparison and the integration between laser scanning and digital photogrammetry as surveying and 3D modeling techniques have been published so far and most of the works report about their application to Cultural Heritage. In this way a wide variety of objects, like small and large statues, historical buildings as well as some whole archeological sites were scanned and modeled for various purposes such as preservation, in-built documentation, reconstruction, and museum exhibitions. The results achieved have shown that these two technologies can integrate each other in creating high-quality 3D recordings and explanations, but so far despite the wide spread of Terrestrial Laser Scanning (TLS) technology, the use of such a system for the stability control of buildings is still a research field not so much investigated.

FIG. 2—*Cracks on the masonry piers.*

Photogrammetric and Laser Scanning Survey

Terrestrial laser scanners (TLSs) are modern instruments for geomatic data acquisition that offer several benefits to surveys including fast 3D data capture, remote and noncontact (i.e., targetless) operations, a permanent recording of the visual and a dense data acquisition. However, the accuracy of the measurements carried out by TLSs is not perceived adequate for deformations monitoring (4–6). The advantage of TLSs is that, although individual sample points are low in accuracy (e.g., ± 2 to ± 50 mm), the modeling of the whole point cloud may be effective to represent the change in the shape of a structure. A modeled surface will be a more precise representation of the objects rather than the one performed by unmodeled observations. To meet the requests of the judicial, Palazzo Edilizia was surveyed by means of close-range digital photogrammetry and TLS technology, as specified in the following subsections. During the related work a Leica Geosystems HDS 3000 (7) was used; this TLS instrument is able to get 3D points at a scan rate of up to 4000 points/sec.

The scanner's range accuracy is ± 4 mm (1σ) and it is able to achieve a coordinate with an accuracy of ± 6 mm (1σ). With reference to the images' resolution it has a minimum sampling interval of less than 1 mm (at 10 m) but this resolution is somewhat reduced by a laser beam width of *c*. 6 mm at the same range (8). In relation to the details of the structure concerned by the collapse, the close-range photogrammetry was applied in order to integrate the data acquired by TLS; specifically it used a Nikon camera (Tokyo, Japan) with Digital single-lens reflex camera and Sensor CCD, 23.7×15.6 mm DX format, $1.5\times$ FOV crop fitted with a 14 mm fixed lens. Obviously the camera was calibrated before the survey (9). More specifications on these instruments can be acquired from the respective manufacturer's website.

High-resolution digital images of the building were captured for the photogrammetric processing and about 150 images were collected in 1 day. The image resolution was set at the highest level to acquire a good image quality, in order to obtain suitable orthophotos and an adequate DEM of the surface surveyed. Standoff distance ranged between 5 and 20 m according to the geometry of the building and the need to get at least an image overlap of 50%; this requirement was achieved by using a telescopic handler. Specifically a MRT 1840 Easy of the MANI-

FIG. 3—*Photogrammetric and laser survey with telescopic handler and station on the ground.*

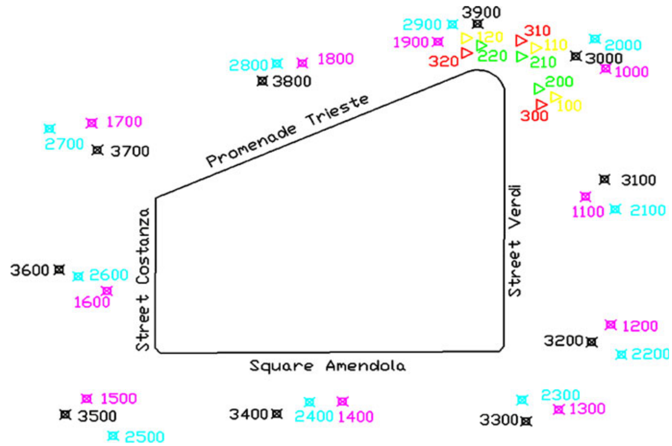

FIG. 4—*Laser stations locations.*

TOU (Fig. 3- left side) was used. This machine is able to safely operate in work configuration of off-road tires or stabilizers and reaches heights of up to 27 m in a complete safety; for the specific survey it was equipped with an aerial work platform. The MRT Easy has a stabilizer designed in order to ensure a perfect stability on any kind of terrain thanks to the support surface (4 × 4 m) which allows an excellent adaptation to any ground surface, and moreover the stability control is carried out by the measurement of the pressure exerted by the pads on the ground.

For the survey it was necessary to locate and materialize 50 ground control points (GCP) points on the ground whose coordinates were surveyed by a total station (specifically a Leica TCRP 1201, Leica Geosystems AG, Heerbrugg, Switzerland). These points have been employed both for the photogrammetric processing and for the merging of the laser scanning 3D model.

As stated earlier, the survey of the exterior of Palazzo Edilizia was performed by a TLS Leica HDS 3000 instrument. This scanning system, based on Time-Of-Flight measuring principle, enables a large Field of View (Table 1) thanks to the adoption of a dual-window structure. It ensures a low beam divergence (<6 mm at 50 m) and a good measuring accuracy at the same time. In addition to the intensity of the reflected beam, this laser instrument is able to acquire RGB data at different resolutions (low, mid, high) by means of a 1 Megapixel built-in CCD camera.

Scans were taken from 36 standpoints, placed at a distance ranging from 20 to 100 m from the building. The map in Fig. 4 shows the locations of the laser stations carried out during the survey. Specifically these locations are marked with a label specified by the numbers 1000, 2000, and 3000, respectively, for the first level (on the road corresponding to approximately zero quota), the second one (about 8 m from the ground), and the third level (about 15 m from the ground). With the same criteria labels specified by the numbers 100, 200, and 300 show the locations from which the laser survey of the collapsed corner was carried out.

It has to be noted that the laser surveys at the second and third levels were performed by means of the same telescopic handler used for the photogrammetric survey.

In this work the point clouds were acquired at various spatial resolutions ranging from 1.5 cm (the four fronts of the building) to 0.5 cm (collapsed area). These values were chosen as an acceptable compromise between the level of detail of the 3D model and the computing resources needed for data processing (10). During the 3 day survey, 24 scans to the fronts and four scans to the collapsed area were thoroughly collected, filling in that way a dataset of 70-million-points.

Topographic measurements were carried out by a total station Leica TCRP 1201 Pin Point R300 and the compensation was worked out by 3D adjustment Starnet software (srl Roma, Italy). After the realization of a polygonal consisting 8 vertices around the building, the survey of the four fronts was performed and it required another 2 days of work. The natural points and the targets, as the GCPs that had been used for laser scanning and photogrammetric measurements, were collimated. The outcome of the GCPs measurements are shown in (Table 2).

TABLE 1—*Leica HDS 3000 technical specifications.*

Instrument	Leica HDS3000
Acquisition speed (points/s)	Up to 2k
Measurement range (m)	1/100
St.dev. of single range meas. (mm)	4 at 50 m
Angular resolution (deg)	0.0034
Horiz. & Vert. FOV (deg)	360 × 270
Laser beam width (mm)	532
Integrated CCD camera	Internal

TABLE 2—*Outcome of topographical survey.*

	Adjusted Coordinates (m)					
Point	N (Y)	rms Y	E (X)	rms X	Elev (Z)	rms Z
101	−13,316	0.002	24,271	0.001	22,724	0.001
102	−12,999	−0.001	23,409	0.002	21,588	0.002
103	−12,353	0.002	22,953	−0.001	19,354	−0.001
104	−3769	0.002	24,356	−0.004	21,538	0.001
105	−5666	−0.001	23,857	0.002	22,723	−0.001
106	−14,226	−0.001	18,945	−0.001	21,491	0.001
107	−13,338	0.003	20,277	−0.002	22,881	0.001
108	−11,768	−0.002	19,037	−0.003	23,015	0.001
109	−14,333	−0.001	15,437	−0.001	22,370	−0.001
201	−4459	−0.003	16,239	−0.002	19,979	−0.001
202	−11,255	−0.001	12,971	−0.003	18,943	0.001
203	−6300	−0.004	10,848	0.002	22,223	0.002
301	−12,456	−0.001	9476	0.001	20,817	−0.001
302	−13,926	0.002	10,911	−0.004	17,808	−0.001
303	−7511	0.004	7325	−0.002	22,451	−0.001
801	−14,191	−0.001	7835	−0.003	22,105	−0.001
802	−13,984	0.003	7087	−0.002	21,383	0.002
803	−14,633	−0.004	4807	0.002	18,285	0.002
804	−13,679	0.004	4264	−0.002	19,987	−0.001
805	−15,130	−0.001	11,454	0.004	20,334	0.001

Data Processing

Data processing was performed by several softwares, and specifically by Cyclone, Geomagic, and others. After the phase of data filtering followed by noise removal, a process of alignment for each front of the building was realized; this alignment was based on the recognition of the control points corresponding to the reflecting targets and natural GCPs (11). The georeferencing was cornered because it was unable to locate these targets; an automatic georeferencing was hence carried out by using the retro-reflecting targets of the TLS instrument which were automatically detected and identified by the supplied software. For each front an average of 20 targets appropriately distributed was recognized. On the collapsed area, a data registration procedure, based on the spin-images algorithm, was improved by means of the use of a multi-resolution method that was be able to generate a pyramid of spin-images in order to speed up the matching phase between the adjacent scans (12). An rms included in a range from 0.001 to 0.008 m for almost all the tie points was obtained. Figure 5 shows the point cloud image carried out to Verdi Street situated in front of Palazzo Edilizia.

Simultaneously, a photogrammetric survey of the collapsed corner was performed both for production of ortho-photos (Fig. 6) and for the integration of more complex elements of the collapsed area that, in connection to the considerable morphological variability had shown significant gaps in the laser scanning data processing (13,14).

The fact of having put together the two survey methodologies allowed the authors to perform a complete photogrammetric coverage of the collapsed area. The most suitable integrations were chosen in the processing step. Specifically the metric photos were acquired and processed by PhotoModeler Scanner software (Eos Systems Inc., Vancouver BC, Canada) (15,16) that was able to produce a dense point cloud for the more detailed areas.

Results

The conclusive point cloud of the collapsed corner was subsampled at various settings according to the level of detail required: such a strategy was implemented in order to agree on a good compromise between the level of detail and the related computational complexity. Indeed, the 3D model was used as primary dataset to carry out a finite element analysis on the structure. In order to achieve this purpose, the software currently available on the market was unqualified to manage a large amount of points, such as that typically obtained by TLS surveys; so a decrease in the number of data was a necessary step. For the 3D modeling, some common issues related to the development of models and their management by various software were addressed. Consequently more information was obtained by modeling by Rhinoceros software, by checking the model (relatively to the properties of the mesh) and by defining the criteria for the creation and the optimization of the 3D model (Fig. 7) (17).

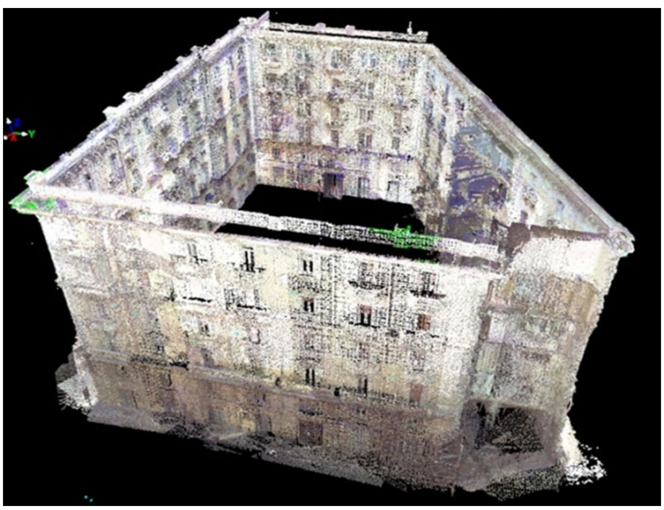

FIG. 5—*Point cloud image to Verdi street front.*

It is important to note that the integrated use of both the orthophotos and the 3D model worked out during the surveys allowed the authors to carry out a detailed analysis of the area involved in the collapse. Specifically, they were able to focus on each component of the original load-bearing structure by performing several specific and accurate measurements on the structural parts involved in the collapse and that were still evident during the survey. The measurement results carried out at sub-centimetric accuracy were provided to the judge consultant structural engineers and were used, with some other elements arising from the investigation, in order to identify, as below specified, the main cause and the contributing factors of a so sudden and devastating collapse.

In order to obtain a two-dimensional (2D) representation of both the whole building and of the area of the collapse, an experimental algorithm developed by the authors (18) was used. Specifically, the overall numerical model was converted in the ASCII format for further processing by Geomagic software. Therefore, a surface model was generated and, next, standard processing proceedings were carried out on it: the Cleaning, the Reducing of Noise, the Filling of holes, and the Repairing of normal and intersection lines Some sections planes parallel to the XY plane at various levels were obtained and thereafter they were converted, at a constant step, into points and then all the results were exported in the dxf format. At the end, the resulting vector file was converted into an ASCII one. The result was a continuous curve with a discontinuous derivative, thus of differentiability class C^0.

The interpolation error was proportional to the distance between data points, raised to the n^{th} power. In order to manage all the digital information defined by the algorithm in a CAD environment, a further proceeding to save the results in the dxf format was carried out. For each file related to a 3D polyline in which each element of the line is identified by X, Y, and Z coordinates, the proceeding, by means of the corresponding polyline and N vertices, was able to create a dxf file. The continuous 2D information worked out from the data that had been acquired by means of the laser scanner surveying of the building were used to identify a suitable methodology for a correct 3D modeling. Starting from the vector data corresponding to the planes placed at various levels and some sections planes and integrating them with appropriate information the authors were able to produce a set of drawings suitable as reference in the technical consultation, as aforementioned. Specifically these are the planes of various tiers (Fig. 8), meant as horizontal sections planes of the building, made at some significant levels, and then projected at right angles to a horizontal reference plane which corresponded to the floor.

Furthermore, for each front of the building, the related prospect was carried out, and a reconstruction vector was simulated (Fig. 9).

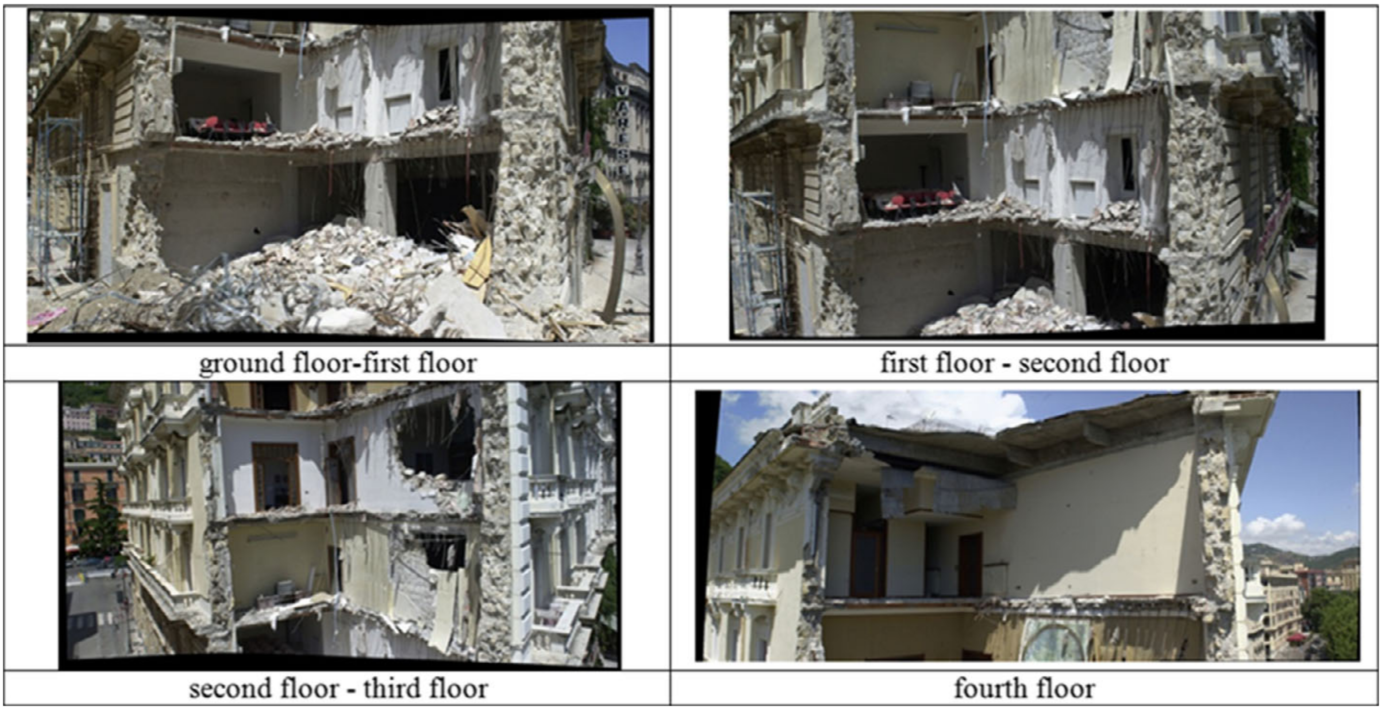

FIG. 6—*Ortho-photos of collapsed corner.*

FIG. 7—*3D model of collapsed corner.*

In most of the published work, the concept of “integration” or “combination” of 3D models derived from photogrammetry and laser scanning is basically considered in two different, alternative, ways: as a texture mapping of the meshed TLS model or, on the other hand, as a production of orthophotos using aligned and triangulated point clouds as a DEM. In the present case the melting of data is aimed to create a single 3D representation in which photogrammetric and laser scanning data are merged together so that the final product can be seamlessly explored. This kind of utilization of a 3D modeling can benefit from the use of both of the surveying techniques. For example, in the case of historical buildings, such as Palazzo Edilizia, 3D information about pretty regular parts of the structure can be deduced by photogrammetry, while more interesting architectural details and areas with higher surface curvature can be reconstructed by means of laser scanning data. In this case the texture processing was used to provide a detailed 3D structure of the most significant areas for the investigations. Specifically, a survey was carried out for all the areas of the masonry where the detachment had occurred. Some rectification work were also necessary in order to put together several images in only one photo, playing also with brightness and contrast of the images, to define an homogeneous texture (19). The results of the texture process are showed in Fig. 10.

Conclusions and Discussion

In the case of the collapse of Palazzo Edilizia, the object of the analysis performed by the experts of the court was, primarily, the identification of the main and the contributing causes of a collapse so devastating. The experts carried out, starting right from the day of assignment (June 29, 2007) by the GIP, many systematic and thorough investigations, surveys, tests, and inspections, aimed to acquire knowledge of all the useful information to accomplish the given assignment. In order to conduct these activities, experts were constantly supported by specialist auxiliary consultants. It is important, however, to note that the authors were only interested in carrying out surveying and data processing phases and that the activity of structural analysis was

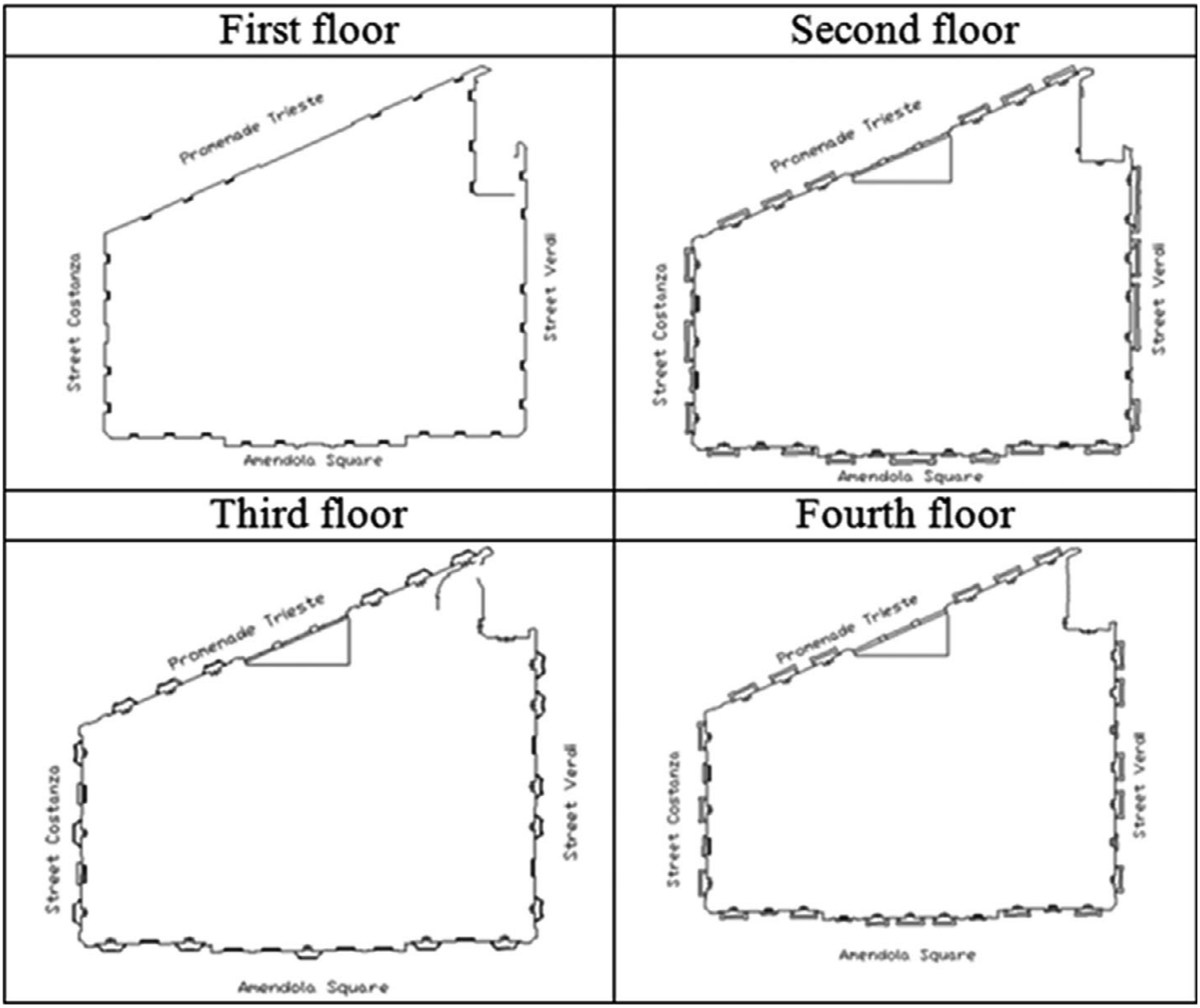

FIG. 8—*Planes for various tiers.*

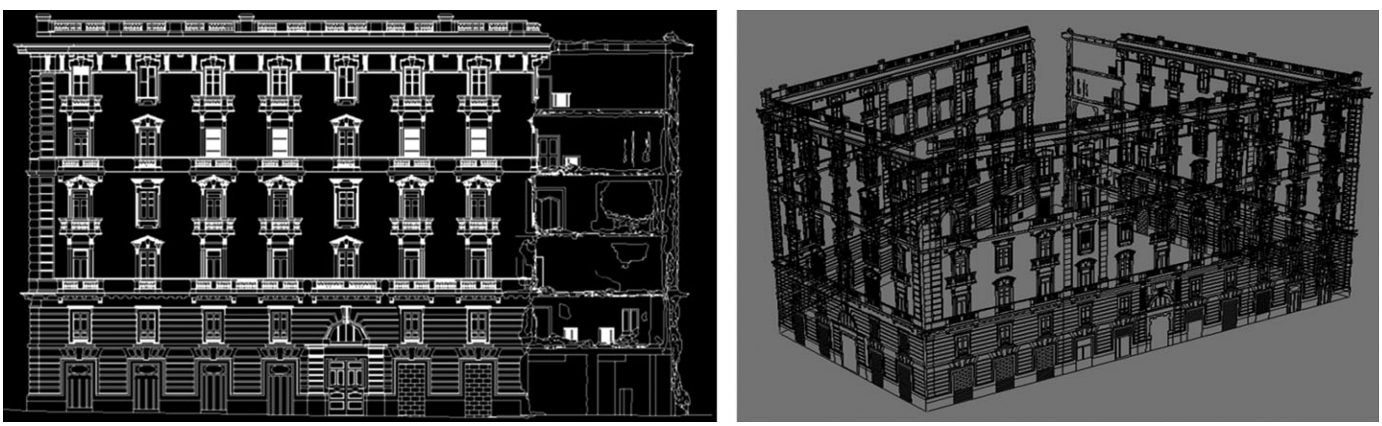

FIG. 9—*Prospect to Verdi Street (left) and Reconstruction vector (right).*

strictly a responsibility of the consultants. The acquired elements of knowledge were taken as reference to carry out several researches, to perform analyses on the acquired data and to evaluate the final results. These elements (information, papers, remarks, technical data, etc.) mainly derived from the examination of documents that were found in private and public entities

FIG. 10—*Rectified texture.*

as well as from examination of every piece of information acquired during the work in progress on the field investigation. In this regard the survey of the building and of the collapsed area as well as the evidence resulting from laboratory tests assumed a significant importance. In the end, we must not forget the contribution given by examining videos and photos taken during to the phases of the survey and clearance of the rubble as well as the live observation of the works related to the clearance.

Both topographical survey of the collapsed area, as previously described, and the laboratory tests, were of considerable support for the analysis, some of them inferred by 3D metric knowledge and by available graphical representation. In cases such as the present one, of ruinous collapse, involving a whole building, or its relevant parts, it is not uncommon that the phenomenon originates from a "first cause" (and therefore damage)which is highly localized. Therefore, under such circumstances, it occurs that the conclusive damage is reported as "disproportionate" to the cause which has triggered off it; that happens in consequence of a ruinous propagation of the collapse in a part of the building (if not of the whole construction) of larger extension compared to the original damaged area. In the performed analysis, therefore, it was a distinction between the so-called "root causes of the collapse" and the "causes of the extent and the mode of effects in the first local cracks". After the on-site inspection on the bubbles and the survey of the building's characteristic were concluded, all the loads that had been adding to the structure at the moment of the collapse were estimated. All the technical consultants agreed that the disaster was caused by the crushing of the masonry piers between the openings of the rooms placed on the ground floor in which the restoration works were in progress. Instead, findings about the liabilities for the collapse were different. The technical consultants of the examining judge said that the disaster had been induced by the vulnerability of the building and by the low compression strength of the tuff masonry. So, they said that the building's owners should have been considered responsible for the collapse (3). Augenti N. agreed in believing that the collapse was due to the weakening of the masonry piers after the removal of the mortar joints from one of the wall (1,20).

It is obvious that the experts of the examining judge would not have been able to accomplish the given assignment in such a short time and with the certainty of the goodness of the data without the results of topographic survey carried out by the technical consultant. The integrated use of Laser scanning and Photogrammetric technologies supported by classical topographical measurements, as in the case of Palazzo Edilizia, even if it requires further studies, is able to give a very important contribution for building monitoring and investigations, given, in such a way as an indispensable support to the preservation of the cultural and architectural heritage, and more.

At the end of the article authors want to give some remarks about the trial related to the collapse of a corner of Palazzo Edilizia:

On the collapse of the east wing of Palazzo Edilizia, the GUP (Judge for the Preliminary Hearing) of Naples had not doubt: the implosion of June 15, 2007 was, from the standpoint of the judiciary, a culpable disaster. So all people that prosecutors of Salerno had entered in the docket a few months after the collapse were committed for trial and specifically: the designer engineer and construction manager, administrator of the contracting firm, the manager for the subcontractor works and the person responsible for the safety.

In relation to the situation of the condominium administrator, he also entered in the docket, but only next to the filing of the expert evidence of engineers appointed by the GIP (Judge for Preliminary Investigations); for him there was only one count of indictment because "in 2007, he took note of the instability phenomenon, and he didn't take all the necessary urgent measures to avert the danger and to protect public safety". Therefore, if at the beginning of the appearance of the cracking phenomenon some topographical monitoring activities, aimed to identify its causes, had been started on, it could have been avoided the damage to the cultural and architectural heritage as well as the disruption to the condominium. In fact it took a full 18 months of work to renovate the collapsed wing and to allow the owners to return to their apartments.

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