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In-situ assessment and structural health monitoring of reinforced concrete structures: case studies and recent developments

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ABSTRACT: Due to seismic events occurred recently in Italy, the design standards and codes are evolving and becoming more stringent either in the design of new constructions as well as in the analysis and assessment of existing structures, specifically leading engineers to increase the level of knowledge of the structures in need of strengthening. For this reason, it becomes fundamental to develop new tools and procedures to optimize the design of strengthening systems by means of reaching the required level of safety with reduced costs. This goal can be reached thanks to the design flexibility of FRP (Fiber Reinforced Polymers) technologies together with the achievement of the maximum level of knowledge of the actual conditions of the structure under investigation. Accordingly, this paper focuses on the importance of in-situ assessing of structures, also finalized to properly design innovative strengthening systems, and on the use of new technologies to monitor and real-time control the behavior of structures as well as the effectiveness of strengthening systems. Particularly, the paper presents an overview of the current methods of performing structural surveys and in-situ material testing, techniques for structural evaluation as in-situ cyclic load testing and a review of structural health monitoring (SHM) techniques. In addition, significant case studies of in-situ experimental campaigns and structural health monitoring activities are presented and discussed.

1 BACKGROUND

All the modern developed countries base their economy on a complex and extensive system of structures and infrastructures as roads, highways, bridges, buildings, etc. to maintain economic prosperity and high quality of life. Although, nowadays, a significant portion of structures and infrastructures worldwide is in urgent need of strengthening and rehabilitation. Structural deterioration may be due to various reasons as long-term exposure to harsh environments, poor initial design or construction, increased loads, changing design standards, increased safety requirements or catastrophic events such as fire or earthquakes, etc. At the same time, public funds are not generally sufficient for the required replacement of existing structures or construction of new ones, therefore, improvements depend on innovative solutions which aim to reduce the costs associated with traditional methods of assessing, monitoring, inspecting and eventually strengthening structures. Short-term and long-term structural evaluation represent, therefore, the most fundamental aspect when the target is the safety assessment or the rehabilitation of existing structures and revaluation of historical buildings. Specifically, the procedure of a qualitative structural assessment comprises the following:

- Identifying geometrical and structural characteristics of the building;
- Characterizing mechanical and physical properties of constituent materials;
- Assessing real performances and overall behavior of structural members through full-scale load testing;
- Real-time monitoring and control of the structure for a long term safety assessment.

1.1 Structural Survey

The first step of a structural assessment is the classification of the building type and the geometrical survey of the investigated area and structures. Visual inspections and observations are important to identify the specific parameters influencing the overall performances of the structural elements, and in particular: load paths, geometry, type of connection between the elements, presence of cracks, weak or soft storey, etc. A fundamental step in the characterization of a reinforced concrete structure, is the detection of the steel reinforcement by means of type and diameter of the bars and their arrangement, this can be achieved either by removing the concrete cover in some areas and directly locate and measure the bars or by using special tools, as the *Ferroscan*, capable of locating steel rebars, estimating their diameter and concrete cover depth (Figure 1a). Also advanced non-destructive tools, as videoendoscopy, geo radar and thermography, can be used to improve the level of knowledge of the investigated structure by characterizing each construction element. Particularly, *Videoendoscopy* is performed using a remote visual inspection tool, instrumented with a video camera and a led light source, capable of illuminating and inspecting areas otherwise not visible, as the internal structures of concrete and masonry walls, slabs, roofs, ceilings, etc. (Figure 1b); *Geo-radar (GPR)* uses electromagnetic radiations to image the subsurface of elements made of many different materials and to detect objects, changes in material, voids and cracks. *Thermography* also is a non-destructive test which uses an infrared camera to investigate the surface of a construction element previously subjected to a thermal distress to define different isothermal areas within the concrete surface (Figure 1c). This test allows emphasizing any non homogeneity within the element, presence of cavities, analysis of cracks, mapping of humidity, analysis beyond frescos and plastered walls or detachment of plaster and concrete substrate.

Figure 1. Captures from: (a) Ferroscan, (b) Videoendoscopy, (c) Thermocamera.

1.2 Material Testing

A comprehensive structural assessment cannot be completed without characterizing the mechanical and physical properties of the materials used for the construction, therefore it represents a fundamental aspect when dealing with existing structures. The in situ tests available for concrete range from the completely non-destructive tests (NDT), through those where the concrete surface is slightly damaged, to partially destructive tests, such as core sampling and pull-out tests, where the surface has to be repaired after testing, IAEA (2002).
The range of properties that can be assessed using non-destructive and partially destructive tests is quite large and includes such fundamental parameters as density, elastic modulus, compressive and tensile strength, surface hardness, etc. The most common in situ material surveys for concrete are: Schmidt rebound hammer test (Figure 2a), ultrasonic pulse velocity measurement (Figure 2b), carbonation depth measurement and concrete core sampling for laboratory determination of compressive strength (Figure 2c). Whereas for steel rebars the most common tests are: measurement of corrosion potential to estimate the level of corrosion damage of the reinforcement and the in-situ steel sampling for laboratory determination of tensile strength.

Figure 2. Material testing: (a) Rebound hammer; (b) Ultrasonic survey; (c) Concrete core testing.

Non-destructive testing can be applied to both old and new structures. For new structures, the principal applications are likely to be for quality control or the resolution of doubts about the quality of materials or construction, IAEA (2002).

1.3 *In-Situ Load Testing*

One of the most useful techniques to perform a structural evaluation of an existing building is represented by the in-situ load testing. This non-destructive load test allows determining the actual behavior of structural elements, such as slabs, beams, cantilevers, stairs, etc. by subjecting them to successive loading and unloading cycles and consequently to evaluate whether a structure or a portion of a structure satisfies the safety requirements of the code. The procedure of a cyclic load test consists in the application of a certain number of concentrated loads through the use of hydraulic jacks (Figure 3a), in a quasi-static manner, having magnitude capable of equalizing the uniformly distributed design load, and in the measurement and monitoring of deformations at specific critical sections of the member being tested. Utilizing loading cycles up to a predetermined maximum load (Figure 3b) allows the engineer to perform a safer real-time assessment of member characteristics, such as linearity and repeatability of response, as well as permanency of deformations, ACI 437 (2007).
This technique is very popular thanks to its ease of execution and thanks also to the variety of important information provided to the engineers who will be able to assess the structure and eventually design a “tailor made” strengthening intervention in order to meet the requirements of the code with minimum costs. An additional field of application of the in-situ load testing is the validation of the performances of structural members strengthened with innovative materials, and therefore to verify the efficiency of the strengthening system where the novelty of the upgrade technique raises doubts in the mind of owners, engineers, and building officials.

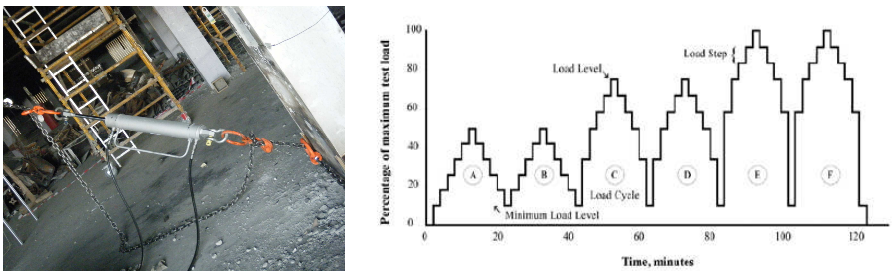

Figure 3. Load testing: (a) Hydraulic jack; (b) Load cycles as per ACI 437.1R-07.

1.4 *Structural Health Monitoring*

Structural Health Monitoring (SHM) represents a non destructive in-situ structural evaluation method through the use of sensors either embedded or mounted on the structure to be investigated. This technique has gained a growing interest in order to asses maintenance state of existing structures and to directly control real-time system performance over time. The variety of sensors available on the market allows monitoring many parameters such as, forces, loads, stresses, displacements (Figure 4a), rotations, vibrations, strains, crack openings (Figure 4b) but also key environmental parameters can be monitored such as temperature, humidity, precipitation, wind (Figure 4c), traffic, etc. Therefore among its advantages, SHM can lead to an increased understanding of in-situ structural behavior, early damage detection, decreases down-time for inspection and repair, development of rational maintenance, management strategies and also it encourages the use of new materials and techniques for repair and strengthening interventions. Despite these promising advantages, conventional SHM presents also two disadvantages which dramatically restrain its use: the initial investment required for the installation and the time consuming task of drawing cables, placing sensors, access areas, etc. and these problems assume particular importance when monitoring high-rise buildings, bridges or other gigantic structures. A valid alternative to conventional SHM techniques is represented by the Smart Brick® device (Figure 4d), an innovative and unique solution for structural health monitoring structures minimizing costs and improving speed, storage and managing of acquired data without compromising results accuracy. The device incorporates a variety of self-referenced structural sensors, such as load cells, strain and displacement gauges, it is battery-powered and communicates using the GSM/GPRS mobile phone network, which eliminates the need for cables of any type and facilitates remote monitoring. Concurrent measurement of several environmental and structural parameters facilitates capture of an accurate snapshot of the state of the structure, Bastianini et al. (2007).

An additional modern technique for the structural health monitoring of civil structure is represented by the fiber optic sensing technology and specifically by the Brillouin optical time domain reflectometry (BOTDR) which add the unique capability of measuring strain and temperature profiles along optical fibers. Measurement is performed by establishing the correlation between fiber strain and temperature, and the frequency shift of the Brillouin backscattered light induced by a monochromatic light pulse. The technology holds potential for use on large structures and integrated transportation infrastructure, Matta et al. (2008).

Figure 4. Monitoring devices: (a) Displacement transducer; (b) Crack transducer ; (c) Wind anemometer; (d) Smart Brick® device.

2 CASE STUDIES

This section presents some of the latest significant case studies and field applications of the aforementioned structural assessment and monitoring techniques which SGM completed in Italy and overseas.

2.1 Fire-exposed structure: Industrial Warehouse, Dubai (UAE).

The building under investigation is an industrial warehouse located in Dubai (UAE) which was affected by a fire developed during its construction. The building is a two stories reinforced concrete structure of 6000 m^2 total (Figure 5) and only part of it, about 600 m^2, was interested by the fire (Figure 6a).

Figure 5. View of the industrial warehouse under investigation.

An extensive experimental campaign was carried out on August 2010 to quantify the damages caused by the fire, to assess the behavior of the structure and consequently to provide recommendations for a specific retrofit intervention. Non-destructive and partially destructive tests were carried out on the constitutive materials to investigate any change in the material properties due to the high temperatures. Rebound hammer and ultrasound readings were carried out to derive indirectly mechanical properties of concrete, core samples were withdrawn from columns (Figure 6b) and slabs for laboratory determination of compressive strength and for carbonation depth measurement. Also, petrography and x-ray diffraction tests were carried out on concrete cores to determine chemical and physical properties of the material and specifically these type of tests allowed evaluating the depth at which the concrete reached such temperatures capable of modifying its properties and characteristics. Further, videoendoscopy, thermography and GPR surveys were performed to investigate detachment of concrete cover, construction typology and consequently verify compliance with shop drawings. In addition, five in-situ pull cyclic load tests (Figure 6c) were carried out according to ACI 437.1R-07 (2007) to assess the overall behavior of the two-way slab and verify compliance with the safety requirements of the code. Non-destructive and chemical/mechanical tests of the constitutive materials did not show any evident critical value, although experience in analyzing similarly damaged structures, as well as from the scientific literature, would induce thinking that a loss in terms of ductility of the overall member behavior shall have occurred, consequently leading to a reduction of the safety design factors. This assumption was partially confirmed by the results of the static load tests on the damaged slabs, where some of the critical parameters did not meet the requirement of the code. As a consequence, the engineers agreed on the design of a retrofit intervention, through the use of fiber reinforced polymer (FRP) technology, for the damaged parts of the structure in order to restore the necessary level of safety and strength with respect to its initial conditions and requirements of the code.

Figure 6. (a) Fire damages on the slab; (b) Concrete sampling at columns; (c) Static load test.

2.2 *Building damaged by earthquake: San Demetrio's School at L'Aquila.*

On April 6th 2009, a strong earthquake occurred in the Abruzzo region, central Italy, causing more than 300 deaths and heavy damages to civil structures and infrastructures. The S. Demetrio's school of L'Aquila, a two stories reinforced concrete building, experienced cracks openings on the structural elements as well as on the partition walls. SGM was appointed to carry out an experimental campaign to assess the actual conditions of the structures in order to verify the need of a strengthening intervention and to install a real-time monitoring system connected to the civil defense department in order to constantly monitor the structural behavior and immediately alert and evacuate the building in case of further seismic shocks. Non-destructive investigations on materials and concrete core sampling (Figure 7a) for laboratory testing were carried out to assess quality of materials. Also, in-situ structural load pull tests with hydraulic jacks on slabs (Figure 7b) at various locations were performed to investigate overall behavior of the structural elements (typical hysteresis diagram of a slab is shown in Figure 7c).

Figure 7. (a) Concrete core sampling; (b) Static load test; (c) Hysteresis diagram example.

After the analysis of the test results provided by SGM, the engineers recognized the need of a strengthening intervention to improve the overall performances and ductility of the structure, resulting in a flexural and shear strengthening of the beams and confinement of the columns with FRP materials. Once the retrofit intervention was completed, additional NDT tests, as thermography and ultrasound surveys, were carried out to check the correct installation of the FRP materials. In addition, two Smart Brick® devices were installed (Figure 8a) for the long-term monitoring of crack openings, strain level in the FRP strengthening system and accelerations due to seismic actions. Figure 8b shows the acceleration at roof level recorded in occasion of a seismic shock occurred later on September 2009.

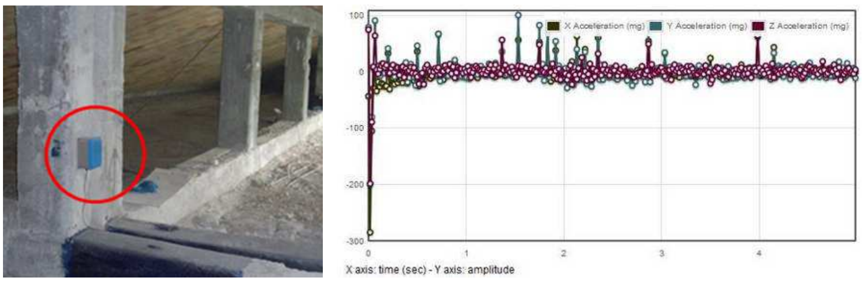

Figure 8. (a) Smart Brick® installed at roof level; (b) Acceleration recorded during seismic event.

2.3 *Structural assessment of the Mingardo Viaduct, Salerno.*

In 2005, the new motorway S.P. 430, connecting the city of Salerno, Italy, with the southern area of the Campania region, was completed by the National Society for Roads and Highways. Due to the impervious landscape of the region, the 70 km long motorway comprises many viaducts, bridges and tunnels. Assessments of the suspended structures needed to be carried out in order to get the final authorization from the traffic department as complied by the code. SGM was appointed to test many of these viaducts and the Mingardo's represents one of the longest along the whole route (Figure 9a). The viaduct, crossing the Mingardo river, is 16 m wide, 720 m long and composed by 16 spans. The longitudinal structural system, designed as a simply supported continuous beam, consists of two 2.6 m deep steel girders, 10 m spaced, connected through transversal steel beams; a reinforced concrete platform is then mounted on the steel substructure. The purpose of the tests was to measure maximum deflections and strains at critical sections due to the maximum traffic load. As described by the code, different load conditions were considered and the spans were tested at various locations, as midspans and supports (Figure 9b).

Figure 9. (a) View of the Mingardo’s viaduct; (b) Static load test execution.

Due to the scale of the structure, static load tests were performed by placing several fully-loaded trucks (360 kN each) along the testing area at specific locations (Figure 10a). During the test, deflections were monitored through special optical and laser systems placed at ground level, strains were recorded through strain gauges mounted on the steel structures (Figure 10b) and inclinometers were placed at road level to monitor rotations and consequently derive the deformed shape of the concrete platform. At completion of the experimental campaign, all the test measurements resulted to be in accordance with the safety requirements of the code and consequently the viaduct was opened to the traffic (Figure 10c).

Figure 10. (a) Loading scheme; (b) Displacement transducer at the support; (c) View of the road.

2.4 *Structural Evaluation of a R.C. building: Italian Embassy in Beirut, Lebanon*

On May 2010, SGM was appointed by the Italian Minister of Foreign Affairs to perform a pre-purchase extensive experimental campaign on a 3B+G+4 reinforced concrete building, built in 2006, and intended to become the new headquarter of the Italian Embassy of Lebanon (Figure 11). Initially, a geometric and structural survey of the whole building was performed. Afterwards, NDT tests, as rebound hammer and ultrasound readings, were carried out to derive indirectly mechanical properties of concrete. Also, concrete and steel samples were withdrawn at foundations, columns and beams for laboratory determination of compressive and tensile strength of the materials. In addition, videoendoscopy surveys were carried out to determine slabs and foundations typology as well as depth of the foundation level.

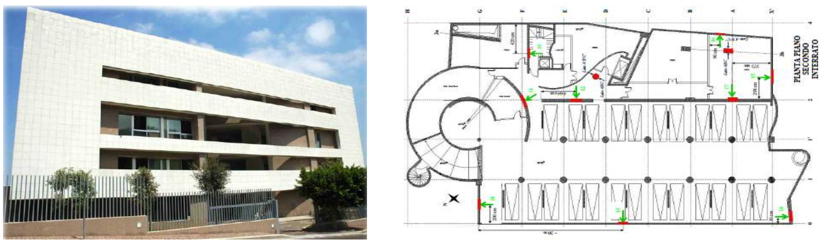

Figure 11. General view and floor plan of the building.

The structural behavior of the building and its compliance with the requirements of the code were investigated through the execution of eight static load tests at different levels and locations, and by measuring deflections and strains at critical sections. At the end of the experimental campaign, the building was declared able to accomplish its functions for the intended destination use.

2.5 Various case studies completed overseas

Since its foundation, SGM - *Experimental Engineering* has completed more than 35,000 site investigations and some of the most remarkable experimental campaign carried out overseas are (Figure 12): the Italian Embassies of Athens and Vienna, the European Community in Luxemburg, the Ashford building in Atlanta (USA) and the S. Peter's Church in Vatican City.

Figure 12. (a) Italian Embassy of Athens; (b) Italian Embassy of Vienna; (c) The Economic European Community of Luxemburg; (d) The Ashford Building in Atlanta; (e) S. Peter's Church in Rome.

3 CONCLUSIONS

As design standards are evolving and becoming more stringent about the analysis and assessment of existing structures, engineers are requested to thoughtfully understand the structure being studied and therefore achieve the maximum level of knowledge on materials and structural behavior, in order to be capable of recommending a specific strengthening solution. This goal can be reached by characterizing constitutive materials with in-situ testing activities and performing full-scale load tests to assess the overall behavior of the structural elements. Ultimately, an additional way to improve safety by generating early warnings, especially in seismic areas, and to reduce costs associated with maintenance issues, is the real-time monitoring of structures (SHM). Accordingly, this paper aimed to show the importance of in-situ assessing of concrete structures through the presentation of remarkable field applications completed by SGM – *Experimental Engineering* in the recent period.

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