

Pre- and post-retrofit structural assessment of a fire-affected industrial building strengthened with FRP materials.

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ABSTRACT: The paper focuses on the importance of in-situ assessment of damaged structures finalized to properly design and calibrate innovative structural strengthening solutions such as FRP (Fiber Reinforced Polymers). Accordingly, the paper aims to assess this topic by presenting a remarkable case study of a fire-damaged reinforced concrete industrial structure, located in Dubai (UAE), on which an extensive experimental campaign on materials and structures was carried out to evaluate the damages caused by the fire. The assessment of the building included structural surveys, *in situ* non-destructive testing techniques (NDT), laboratory testing of collected samples and full-scale structural evaluation by means of cyclic load testing. Consequently, a specific strengthening system with FRP materials was designed and realized. In addition, quality control of the retrofit application was carried out with NDT techniques as well as evidence of structural efficiency was given afterwards with the execution of full-scale cyclic load tests on the strengthened structures.

1 INTRODUCTION

The increasing use of FRP strengthening systems in the retrofit and rehabilitation of existing structures together with the more stringent approach adopted by many codes and standards in the analysis and assessment of existing structures, the wide variety of new materials and strengthening solutions, and, last but not least, the reduced financial resources associated with these kind of interventions, lead engineers to optimize the retrofit design. This target can be achieved by reaching the maximum level of knowledge on the actual conditions of the structures, consequently design the strengthening system to reach the required level of safety with reduced costs and, finally, check the quality of the application and prove the efficiency of the system by means of full-scale testing.

Generally, 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, earthquakes, blast, etc. Further, 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.

2 PROJECT DESCRIPTION

This paper presents a significant case study of structural assessment and FRP strengthening of existing structure which SGM *Experimental Engineering* [1] recently completed in the Middle East region, together with the partner companies of the Network “*The First Brick*” [2]. The building hereafter presented is a reinforced concrete (RC) industrial warehouse (Figure 1) located in the Jebel Ali Free Zone of Dubai (UAE).



Figure 1. View of the investigated building

While the construction process of the warehouse was at its last stages, a fire event accidentally occurred at the ground floor, in the area where the construction materials and MEP furnishings were stored. The building is a two stories RC structure of 6,000 m² total and only part of it, about 600 m², was affected by the fire. As expected, the most damaged elements of the structure resulted to be the soffits of the two-way slabs and the upper part of the columns. The damages consisted mainly in concrete cover spalling over large areas of the slab, over-heating of exposed reinforcing steel rebars and overall degradation of materials due to high concentration of dense smoke (Figure 2).



Figure 2. Damages to the two-way slabs caused by the fire

3 PRE-RETROFIT EXPERIMENTAL CAMPAIGN

3.1 Structural Assessment

An extensive experimental campaign was therefore carried out to quantify the damages caused by the fire, to assess the behavior of the structure and consequently provide recommendations for a specific retrofit intervention. Non-destructive and partially destructive tests were carried out on the constitutive materials to investigate potential alterations in the material properties due to the high temperatures. Rebound hammer and ultrasound surveys were carried out to estimate

mechanical properties of materials, concrete specimens were sampled from columns 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 specimens to determine chemical and physical properties of the material with the specific goal of evaluating the depth at which the concrete reached such temperatures capable of modifying its own properties and characteristics. Further, *Videoendoscopy*, *Thermography* and *Ground Penetrating Radar (GPR)* surveys were performed to investigate detachment of concrete cover, structural configuration and consequently verify compliance of measured data with shop drawings and design calculations. In addition, five in-situ cyclic load tests using hydraulic jacks were carried out according to ACI 437.1R-07 [3] in order to assess the overall behavior of the two-way slab and verify compliance with the safety requirements of the code. In the following paragraphs, a brief description of the methodologies applied to complete the structural assessment is presented.

3.1.1 Structural survey

The first step of a structural assessment is the classification of the structural configuration and the geometrical survey of the investigated areas 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 RC structure is the detection of the steel reinforcement by means of type and diameter of the bars and their arrangement. This goal can be achieved either by removing the concrete cover in some areas and directly locate and measure the bars (*structural survey*) or by using special tools, as the *Ferrosan*, capable of locating steel rebars, estimating their diameter and concrete cover depth (Figure 3a). Also advanced NDT tools, as *Videoendoscopy*, *GPR* and *Thermography*, are 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 inspecting areas otherwise not visible, as the internal structures of concrete and masonry walls, slabs, roofs, ceilings, etc. (Figure 3b); *Ground Penetrating Radar (GPR)* uses electromagnetic radiations to image the subsurface of elements 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 3c). 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 3. Captures from: (a) Ferrosan, (b) Videoendoscopy, (c) Thermocamera.

3.1.2 Material Testing

A comprehensive structural assessment cannot be completed without characterizing the mechanical and physical properties of the materials used for the construction. The available *in situ* tests 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 [4]. 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 4a), ultrasonic pulse velocity measurement (Figure 4b), carbonation depth measurement and concrete core sampling for laboratory determination of compressive strength (Figure 4c). Whereas, for steel rebars the most common tests are: measurement of corrosion potential and the *in situ* steel sampling for laboratory determination of tensile strength. NDT 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 [4].



Figure 4. Material testing: (a) Rebound hammer; (b) Ultrasonic survey; (c) Concrete core testing.

3.1.3 In-Situ Cyclic 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 5a), 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 5b) 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 [3]. 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 upgrading technique raises doubts in the mind of owners, engineers, and building officials.

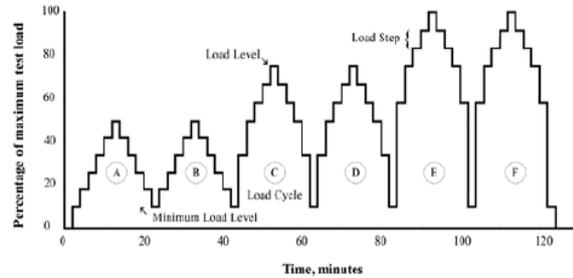
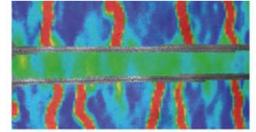


Figure 5. Load testing: (a) Hydraulic jacks and sensors; (b) Load cycles as per ACI 437.1R-07 [3]

3.2 Analysis of test results and damage evaluation

The rise in temperature generated by a fire in a reinforced concrete structure causes a decrease in the strength and modulus of elasticity of the constituent materials, both concrete and steel reinforcement. However, the rate at which the strength and modulus decrease depends on the rate of increase in the temperature of the fire and the insulating properties of concrete [5]. Therefore, if the soffit of a RC slab is subjected to fire, the strength of the concrete and the reinforcing steel will decrease as the temperature increases while steel changes its properties becoming more brittle, so decreasing the overall ductility of the concrete section. As the strength of the steel reinforcement decreases, the moment capacity of the slab decreases as well as compressive-flexural strength of columns (Figure 6), and in addition the ductility of the overall structure decreases as well, so reducing the overall safety factor which it has been designed for [6]. In addition, it is important to point out that the duration of fire that causes the reinforcing steel reaching the critical strength depends on the protection to the steel bars provided by the concrete cover, so the less concrete cover the less time needed for a fire of equal intensity to degrade portions of a reinforced concrete section.

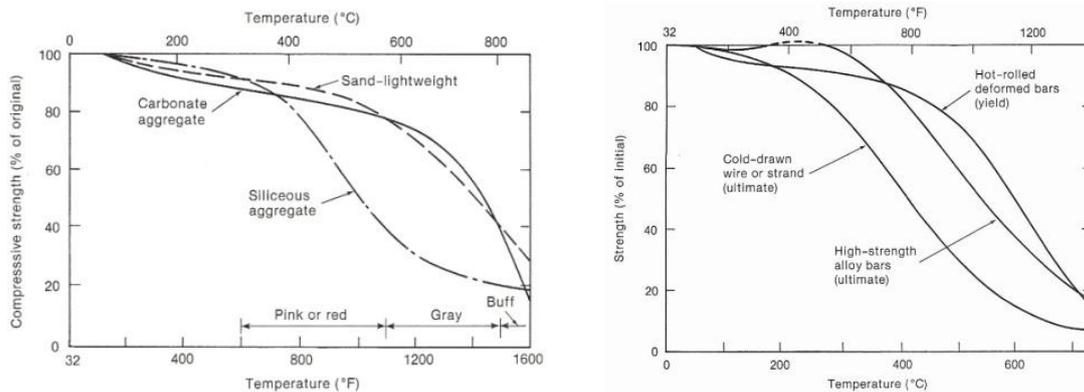
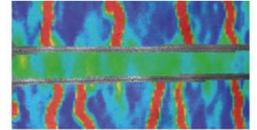


Figure 6: (a) Fire degradation of concrete; (b) Fire degradation of steel [4]

From the structural surveys, ferroskan readings and GPR investigations, the structural elements investigated resulted to be complying with shop drawings in terms of geometry and structural conformity (concrete cover, rebar location, spacing, diameter, etc.). Thermography and visual inspection of the site showed that the fire event extensively damaged relevant portions of the surveyed structure by means of deep concrete spalling and detachment with consequent reinforcing steel exposure and degradation. The test results allowed estimating the fire affected area to be approximately 500 m². From petrography and x-ray diffraction test, it resulted that the maximum temperature experienced by the concrete slab was about 570-580 °C. Non-



destructive and chemical/mechanical tests of the constitutive materials did not show any evident critical value, although experience in analyzing similarly damaged structures induced thinking that a loss in terms of ductility of the overall member behavior occurred, consequently leading to a reduction of the safety design factors. Further, cyclic load tests were carried out on five horizontal structural elements to assess the overall behavior of the structure. It was agreed to apply a maximum concentrated load of about 11,000 daN, equivalent to a uniformly distributed load of about 500 daN/m² (50% of the design live load). From the analysis of the results, the maximum deflections recorded at midspan during the tests always satisfied the serviceability parameters provided by the code [3, 7]. Nevertheless, during the load test on slab n.2, the deviation from linearity, at a certain load level, was recorded to be IDL=24%, very close to the maximum allowed value of 25% provided by the code as one of the acceptance criteria to be monitored during a load test (maximum deflections, recovery of deflection upon removal of test load, repeatability index, crack opening, etc.). For this reason, the test needed to be stopped. As expected, slab n.2 was located in the area mostly damaged by the fire. On the other hand, test results clearly showed how the slabs not exposed to the fire performed indeed better with an overall improvement of the performances moving away from the fire affected area. Therefore, according to the available population of test results and also relying on experience with similarly damaged structures, an average flexural strength reduction of the slabs of 25% was estimated, due to the severe exposition of horizontal elements to the fire event.

4 FRP STRUCTURAL STRENGTHENING

As a result of the above analysis, the engineers agreed on the need of designing a strengthening intervention with Fiber Reinforced Polymers (FRP) technologies for the damaged area of the building in order to restore the necessary level of safety and strength with respect to its initial conditions and requirements of the code. The area of the building affected by fire was about 500 m² including fourteen RC columns and the RC two-way slab. The FRP retrofit intervention was carried out according to CNR-DT 200/2004 [8]. The structural members located in the fire affected area had different levels of damage according to their exposure to the fire and their location respect to the origin of the fire. For this reason, for each member a strength reduction value was assigned and the retrofit system was designed to increase its strength through FRP materials. Also, various materials were selected for the retrofit system according to: structural performance to be achieved, cross section of the members and different level of damage according to their exposure and location.

Specifically, the slab was strengthened for flexure with FRP unidirectional layers of UHTSS high strength steel fiber sheets [9] running along the whole affected area in both directions (Figure 7). The retrofit was increased in those areas mostly damaged by fire, estimated to be about 200 m². Even though the columns were not directly or heavily interested by the fire, they surely had undergone a strong thermal-shock which could have affected not only the concrete but also the steel reinforcement, with decreasing magnitude moving away from the area where the fire originated. Therefore, the columns were strengthened using two different configurations based on their location respect to the origin of the fire. The solution adopted for the columns involved only shear strengthening by complete wrapping. Specifically, six columns were fully confined with UHTSS steel fiber sheets [9] for the total height and eight columns, showing a lower level of damage, were partially confined with FRP basalt unidirectional fiber sheets [9]. Therefore, different strengthening solutions were adopted for the columns based on their geometry, level of damage and target performances.



Figure 7: FRP flexural strengthening of the slab

5 POST-RETROFIT EXPERIMENTAL CAMPAIGN

At the completion of the FRP strengthening intervention, a post-retrofit experimental campaign was carried out to check quality and efficiency of the retrofit system. According to CNR DT-200/2004 [8], various testing procedures were applied to define method, practice and reporting accuracy for qualifying the quality and uniformity of installation of the FRP strengthening system bonded to the concrete surface. Specifically, pull-off tests were carried out on non-critical strengthened areas to evaluate the tensile bond strength of FRP; high frequency ultrasonic readings were carried out adopting the *first peak amplitude variation* technique to localize defects; also, thermographic surveys were performed to detect presence of spots with different heat exchange and temperature variations over the FRP surface; all the quality checks had successful result. In addition, to prove the efficiency of the FRP system, a full-scale cyclic load test was carried out on the most damaged slab n.2 (Figure 8a) which previously experienced structural deficiency due to the high level of damage. The aim of the load test was therefore to assess the performance of the structural member, now strengthened with FRP, by applying an higher load and verify the efficiency of the retrofit against the test results obtained during the pre-retrofit experimental campaign. Hence, in accordance with the responsible engineers, a load test magnitude of about 26,000 daN, equivalent to a uniformly distributed load of about 2,000 daN/m² (200% of the design live load), was applied at the last load cycle. As a result, all the acceptance criteria monitored during the test always ranged within the safe limit values of the code [3]. In addition, the resulting hysteresis diagram (Figure 8b) showed how the slab always behaved in the elastic range as well as it experienced an increase of its elastic modulus compared to pre-retrofit cyclic load test.

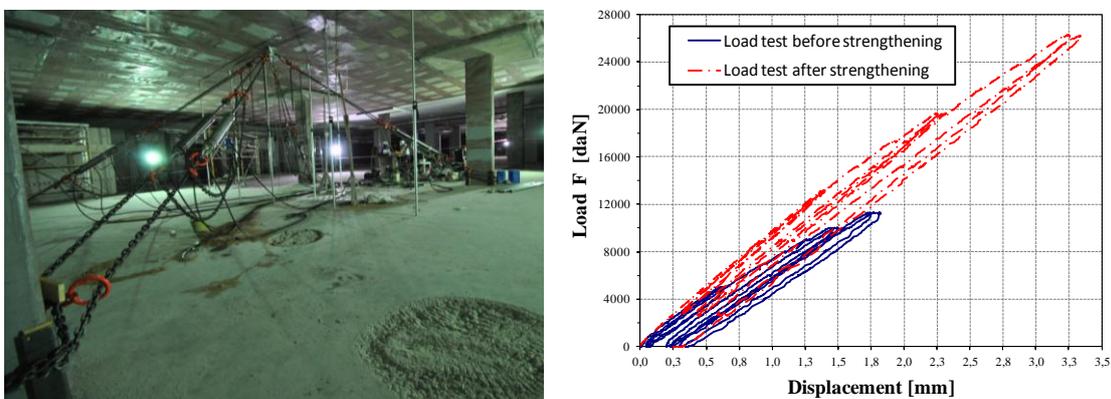


Figure 8: (a) Cyclic load test on slab n.2; (b) Hysteresis diagram

6 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 designing 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. Consequently, the design of a FRP strengthening system can follow a specific approach based on the information derived from an extensive experimental campaign. Also, such testing activities may be applied to check the quality and prove the efficiency of the applied strengthening solution with satisfaction of all the parties involved in the project. Accordingly, this paper aimed to show the importance of in-situ pre- and post-retrofit assessment of structures through the presentation of a remarkable field application completed by SGM *Experimental Engineering* in the recent period.

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