IABMAS'04

October 18-22, 2004 Kyoto, Japan

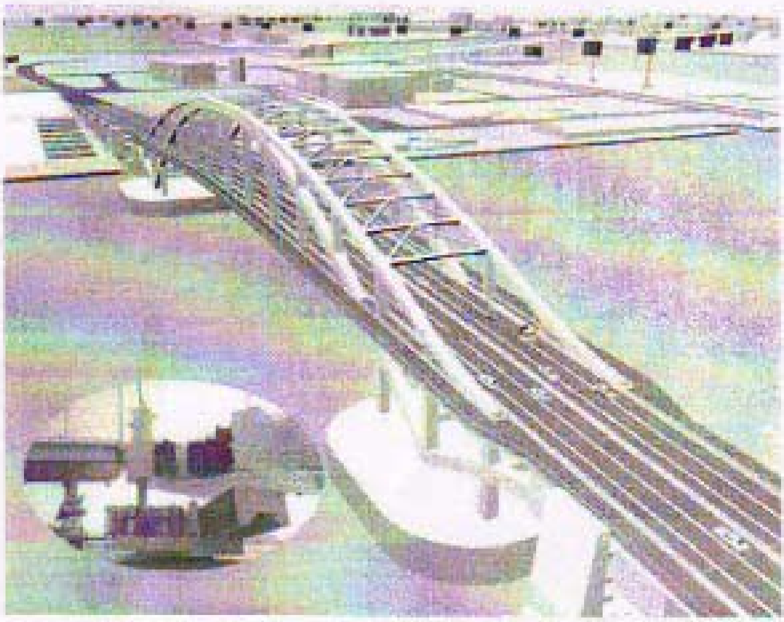
**Second International Conference on
Bridge Maintenance, Safety and Management**

**Organized by IABMAS
International Association for Bridge Maintenance and Safety** http://www.iabmas.org

Mission of Conference:
To bring together all of the very best work that has been done in the field of bridge maintenance, safety and management and
To bridge the gap between theory and practice

[Last updated: November 8th, 2004]

京
都



Evaluation of Fire Damage on a Prestressed Concrete Railway Bridge

E. Proverbio, G. Epasto
Dept. of Industrial Chemistry and Materials Engineering, University of Messina, Italy

V. Venturi
Sidercem S.r.l. Misterbianc, Italy

ABSTRACT: Some spans of a prestressed concrete railway bridge in Sicily (Italy) were exposed to an intense fire. Comparison between concrete residual mechanical properties and concrete microstructure let us to find out that the main cause of concrete damage was the thermal dehydration of CSH gel and of portlandite at almost 600°C. A thermo-mechanical model (FEM) by means of ANSYS® software, developed following the ISO 834 standard, was performed on a beam model to determine thermal loads distribution, temperatures and deformations distribution versus time to be compared to damage maps on the beams.

1 INTRODUCTION

It is well known that microstructure and mechanical properties of concrete are severely influenced when exposed to fire; damage is also observed on reinforcing steel. Mechanical properties decay, at a given temperature, is however more evident for steel than for concrete. Elevated temperatures indeed induce deep structural transformations of the concrete and of the rebars that are the direct cause of the mechanical properties deterioration. For this reason it was developed by the authors an experimental work aimed to characterize concrete at different temperatures and to implement a possible correlation between mechanical properties (compressive strength) and microstructural properties (crystallographic phases by means of X-ray diffraction, porosity, density and ultrasound propagation velocity).

Reinforced concrete deterioration depends on the temperatures reached during the fire in the different sections of the structural element and on the exposition time at the these temperatures, for this reason, their knowlegment is very important to estimate the effective structural damage.

In this paper an experimental procedure for reconstructing thermal history of a real event, a fire damage of a prestressed railway bridge located in Sicily (Italy), is reported.

In order to detect the status of the structure, at a first time, a visual *in loco* examination and, in a second time, a laboratory study, accordingly to an experimental program developed from NIST, were carried out (Phan 2001). The laboratory study was conducted in two phases. In the first phase an evaluation on samples cored from the undamaged area of the structure was carried out, these samples were considered as references (Fig.1a); in a second samples were "artificially" deteriorated in a temperature controlled furnace, in order to stimulate irreversible transformations of concrete consituents at the different temperatures. The second step of the study was performed on samples cored from some areas severely damaged by the fire (Fig.1b). All concrete samples had a cylindrical shape with a 50 mm or 80 mm diameter.

1a 1b

Figure 1. Concrete cored from an undamaged beam (left). Concrete cored from a beam exposed to fire (right)

The laboratory investigation considered in the following evaluations : mechanical compression strength, X-ray diffraction (XRD); mercury introduction porosimetry (MIP); ultrasound propagation velocity (UPV) and density calculation.

Once defined the status of the structure, it was necessary to design a repair intervention, which included verifications of static stability. The study was completed with a thermal FEM modelling of a longitudinal section of a double T beam.

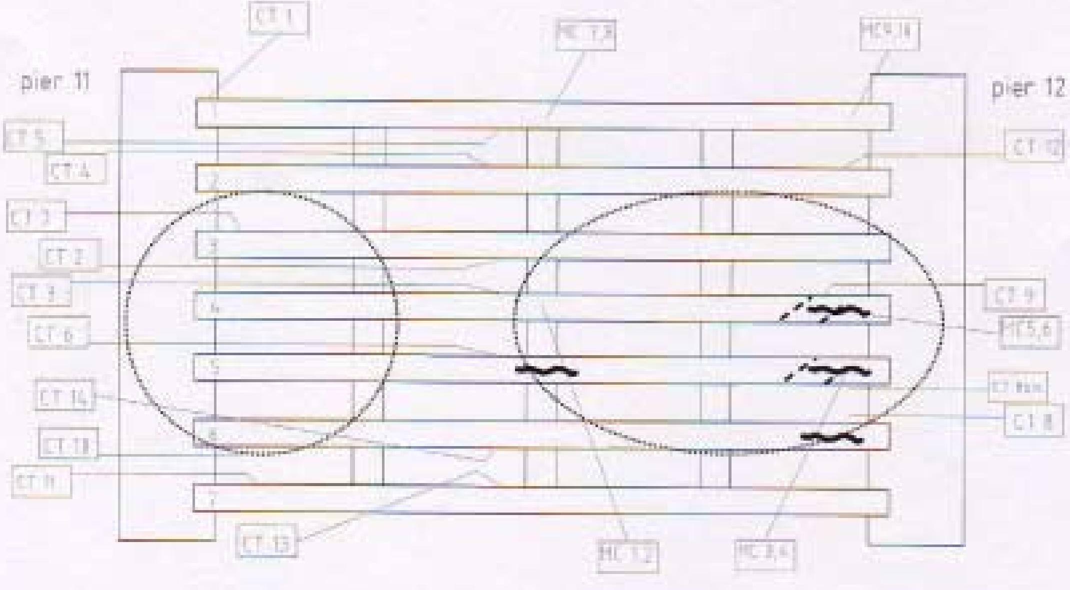


Figure 2. Scheme of the bridge span. Squared numbers refer to cores location. Dotted circles indicate approximately the area subjected to fire. Full lines indicate the position in the beam, as evaluated from cores, of cracks laying on a vertical plane respect to the beam cross section and transversal to core axes. Dashed lines indicate the position in the beam, as evaluated from cores, of cracks laying on a horizontal plane respect to the beam cross section and longitudinal to core axes.

2 VISUAL ON SITE EVALUATION

Some spans of a prestressed concrete railway bridge exposed to an intense fire, developed at the base of the piers, were evaluated. A scheme (bottom side view) of the most damaged span is shown in the Figure 2, where position of the extracted cores are also reported. The damage was mainly localized at the head of the beams, near the two piers.

The fire was artificially extinguished after many hours, during which critical temperatures causing the sudden and violent breaking away of the external hot concrete layer (spalling) were reached. Spalling is a severe problem for reinforced concrete structures since it causes direct rebars exposure to the fire.

Figure 3. Corner spalling and steel deterioration of a prestressed beam (left). Piers spalling; the damage was deep almost 70 mm (right)

For ordinary Portland concretes, spalling is mostly observed during the first 20 minutes of fire; it is caused, not only by the pressure of the free and bulk-water vaporising with the increasing temperature and entrapped in the pores, but mainly by a displacive phase transition of quartz, from *low-quartz* to *high-quartz*, that produces a volume expansion of aggregates and so initiation of cracks. Spalling is more critical for prestressed concrete and it is mainly focused in the edge and in the curve surfaces of the structural element (Hertz 2003).

Visual examination of the bridge evidenced heavily deterioration mainly focused on the lower surface of the beams and at the base of the piers (Figure 3).

3 EXPERIMENTAL PROGRAM AND RESULTS

In the second phase of this work, undamaged samples were characterize mechanically and microstructurally. It resulted a normal strength concrete (in-situ characteristic compressive strength $f_{ck,is\ cube}$ 54,5MPa) made with siliceous aggregates. X-ray diffraction analysis showed that the most important phases of the cement paste present were $Ca(OH)_2$ (Portlandite), $CaCO_3$ (calcite) and CSH (plomberite) gel. Mercury introduction porosimetry carried out on these samples showed a porosity of 18.7%, while the mean value of ultrasound pulse velocity was about 3848 m/s.

Also fire damaged samples (Figure 4) were subjected to a number of investigations to detect how micro-structural and mechanical properties were influenced by elevated temperatures. It was evidenced a global decay of concrete properties in terms of final strength, porosity, shear modulus and density. The graph reported in Figure 5 shows, through normal Gauss distributions, that the dispersion of the values of ultrasound velocity and mechanical strength are lower for undamaged cores than for damaged ones.

Ultrasound velocity is a concrete quality indicator and so it may be considered as a non-destructive diagnostic method to detect voids or cracks caused by concrete phases dehydration or by thermal stresses.

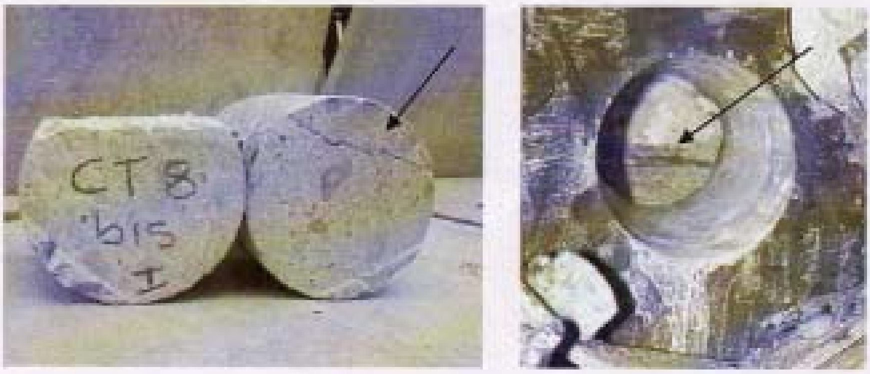


Figure 4. Evidence of a longitudinal crack on concrete cored from a beam

Lower velocities were referred to the more exposed samples. Lower ultrasound velocity suggested microcracking and lower density (higher porosity) of concrete.
X-ray diffraction analysis made on directly exposed samples, revealed the presence of calcite and quartz; but CSH gel (plombierite) and portlandite were absent.

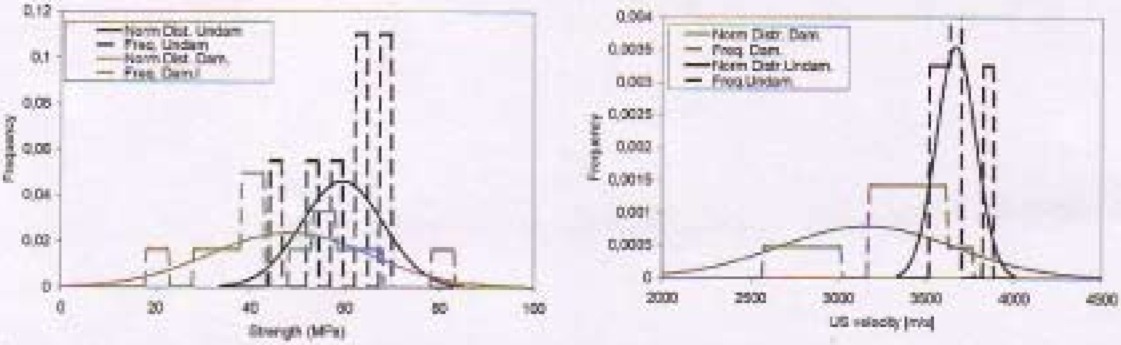


Figure 5. Frequency distribution for concrete strength (left) and US velocity (right) of damaged and undamaged concrete

If plombierite and portlandite were absent, then during the fire, the reached temperatures were over their dehydration starting point (about 750 °C and 400 °C respectively).
To better understand temperature profile in the concrete, a sample, cored parallel to the fire direction, was analysed by XRD to evaluate concrete components transformation and how deep the damage was; the sample was 75 mm long.

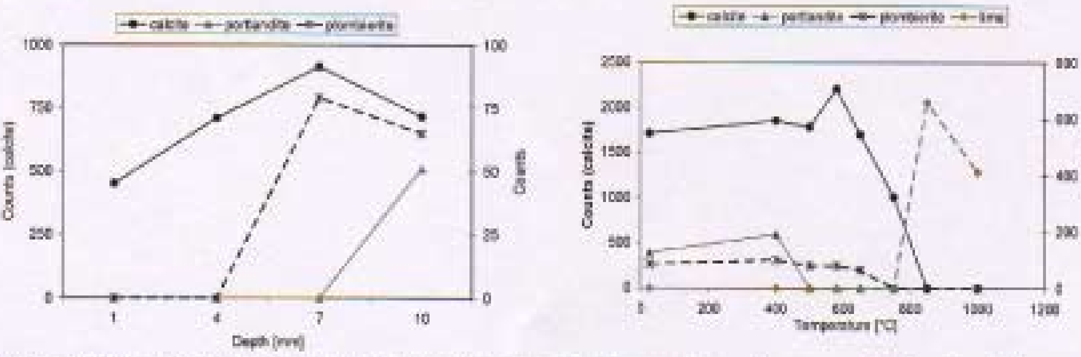


Figure 6. Counts vs depth and count vs temperature in a fire damaged concrete core and in heat treated concrete samples respectively

As reported in Figure 6, going in depth, is evident an increase of calcite content, in particular at the depth of 7 mm; at the same time, portlandite is absent. This evidence was due to carbonation of calcium oxide (lime), produced by portlandite dehydration. The lower calcite content on the exposed surface was due to its decomposition. On the same sample it was also observed (by means of optical microscope observations) microcracks in the aggregates and in the cement paste as a consequence of the above mentioned thermal transformations and displacive phase transition of quartz.

Once focused what transformations had occurred, it was necessary to understand what were the exact temperatures that caused these transformations. For this reason, an experimental study in stationary conditions, was developed: samples were heated, without any external load, to up 400, 500, 580, 650, 750, 850 and 1000°C, in a furnace, with a heating rate of 5°C/min. Once reached the fixed temperature, the samples were maintained for three hours. This test was designed in order to simulate a real fire. After the furnace test, each core was subjected to X-ray analysis and to porosimetry. The principal transformations observed were those ones of calcite and of portlandite, starting respectively at 650°C and 400°C as is shown in the Figure 6.

4 THERMO-MECHANICAL ANALYSIS

Once evaluated the physical thermal transformations activated by the elevated temperatures reached by the concrete components, it needed to develop a thermo-mechanical analysis by means of a finite element method (FEM).

The purpose of this thermo-mechanical analysis was to determine the stress-strain field occurring during the fire. The chosen structural element was a single double T beam belonging to the damaged span of the bridge. The first step of this analysis consisted in the assessment of the reached temperature on the exposed surface, at a depth of 1 mm, to be compared with that one estimated (by XRD) being over 750°C.

A 2D FE model was realized using the code ANSYS ® release 7.0. The beam model was 24 m long and 1,8 m in height reinforced by three post-tensioned steel tendons. The tendons were located in the middle longitudinal plane (tension zone) and their position was symmetric respect to the middle cross-sectional plane, so in the 2D numerical model half of the middle longitudinal plane was considered by applying symmetry boundary conditions to the nodes (Figure 7). Meshing was realized using the elements PLANE 13 for the beam model and LINK 8 for the tendons model with a no bond slippage condition by means of MERGE instruction applied to the common nodes of the beam and of the reinforcement. The mechanical and physical properties of the concrete and the steel materials were considered as a function of the temperature and were taken form literature (Lim, 2000). The following boundary conditions were applied to the model: a pressure of 10105 N/m to consider the weight force, a heat exchange load by convection applied to the lower beam side to simulate the fire, symmetry boundary conditions on the nodes of the middle cross-sectional plane and the vertical displacement was constrained on the node located at the left bottom corner (Figure 7).

The external convection load, applied on the node of the lower surface of the structural element, was chosen accordingly to the International Standard ISO 834 (Eurocode 1 1996) that simulates a real fire, for obtaining temperature distribution versus time.

In the ANSYS code the convection force was defined by means of the convection coefficient and the bulk temperature. The air-concrete convection coefficient was supposed equal to $25 W/m^2K$, for an external temperature of 293 K. The bulk temperature T [K] was defined versus the time t [s] accordingly to the following equation:

$$T = 293 + 345 \cdot \log_{10}(0.13 \cdot t + 1) \qquad (1)$$

The link elements were subjected to an initial strain of $1{,}13 \cdot 10^{-4}$ to simulate the post-tensional loads on the tendons.

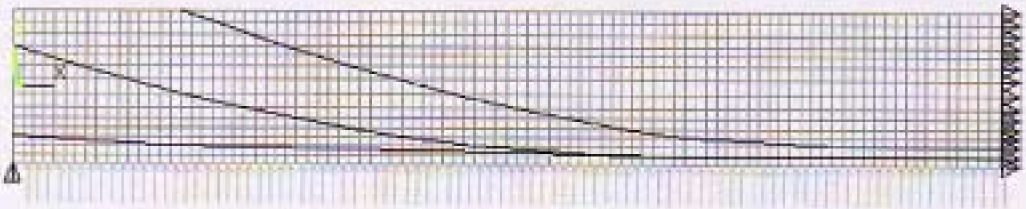


Figure 7. 2D finite element model of the beam

The results of the analysis showed that a temperature of 1110 K were reached on the directly exposed surface of the beam, after about 14400 s (4 hours) accordingly to the values estimated by the diffractometric characterization. The maximum temperature reached by the steel tendons (after a time of 18000 s) was about 537 K. Once determined the heating-curve, the evolution of the stress-strain field was studied through a non linear (transient) thermo-mechanical analysis.

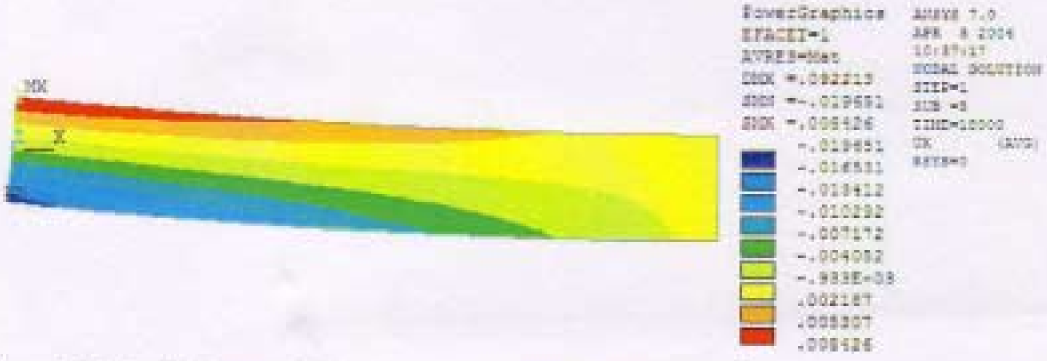


Figure 8. X axis displacement [m] in the concrete beam model after $18 \cdot 10^3$ s.

With the increasing of the temperature, it was obtained from the numerical analysis that, because to the thermal relaxation (expansion) of the tendons, there was a marked displacement of the beam. Figure 8 shows the deformed shape of the beam and reports the numerical values of the horizontal displacement (x-direction), negative displacement (traction) were observed on the lower side of the model accordingly to cracks location observed on extracted cores (Figure 2 and 3).

5 CONCLUSION

Ordinary Portland concrete is subjected to many microstructural and physical transformations under fire exposure. Thermo-chemical reactions of aggregates and of the cement past can be used as temperature indicators, to reconstruct thermal history of the structure. In some extreme events these transformations may cause total loss of the load carrying capacities of the structure. Mechanical and microstructural characterization by X-ray diffraction was performed on concrete cored from a fire damaged structure. As a reference concrete samples were subjected to thermal treatments up to 1000°C. Thermal expansion of steel, thermal stresses and prestressing steel relaxation due to fire exposition caused the formation of internal cracks in prestressed beams. A thermo-mechanical model (finite elements model, FEM) by means of ANSYS® software, developed following the ISO 834 standard, on a beam model allowed to determine thermal loads distribution, temperatures and deformations distribution versus time compatible to cracks and damage maps of the more exposed beams.

6. ACKNOWLEDGMENT

The authors wish to thank the RFI SpA who allowed the publication of technical data and gave us a precious support to the development of the experimental work.

REFERENCES

Eurocode 1, 1996. *Part 2-2 Actions on structures exposed to fire*, ENV 1991-2-2.

Hertz, K.D. 2003. Limits of spalling of fire-exposed concrete, *Fire Safety Journal*, 38 (2):103-116.

Lim L.C.S., 2000. Stability of precast concrete tilt panels in fire, *Fire Engeenering Report*,(3).

Phan, L.T., Lawson, J.R., Davis F.L. 2001. Effects of elevated temperature exposure on heating, characteristic, spalling, and residual properties of high performance concrete, *Materials and Structures*, 34 (3): 83-91.