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Evaluating and Strengthening Industrial Buildings Damaged by Fires

Réparation de structures de bâtiments industriels endommagées par un incendie

Brandschäden und nachfolgende Reparaturen von Industriebauten

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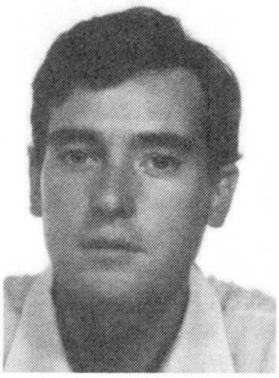

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SUMMARY

The lifespan of an industrial building may be dramatically reduced by fire, even if all safety precautions have been taken. The restoration of a fire-damaged reinforced concrete frame requires, first of all, the evaluation of the damage suffered by the members. In this respect non-destructive testing methods appear suitable for a quantitative definition of the damage; this can lead to the selection of a proper restoration technique. The proposed procedures are illustrated with an example.

RÉSUMÉ

La vie d'un bâtiment industriel peut être réduite de façon dramatique à la suite d'un incendie, même si tous les systèmes de sécurité étaient installés. Le renforcement d'une ossature en béton armé nécessite, au préalable, l'évaluation du dommage aux éléments struc-turaux. Les essais non destructifs sont indiqués pour apprécier la sévérité des dommages pour choisir la technique de réparation, et son intensité. L'utilisation des procédées pré-sentées est illustrée par un exemple.

ZUSAMMENFASSUNG

Die Lebensdauer eines Industriebaues kann durch Brand erheblich reduziert werden. Die Verstärkung eines durch Feuer zerstörten Stahlbetonrahmens bedarf zuerst einer Erhebung der zerstörten Elemente. Zu diesem Zweck scheinen zerstörungsfreie Testmethoden für die quantitative Beurteilung des Schadens günstig. Die vorgestellten Abläufe werden an einem Beispiel illustriert.

1. INTRODUCTION

One of the major events that can dramatically reduce the life span of a structure is fire spread; as a concern, industrial buildings, due to the inherent danger of machinery and plants, show a very high proneness to fire. Moreover, the need of a free plan leads to a generalised use of large span, thin walled, precast prestressed structures which are very sensitive to fire.
Despite the large effort of outstanding Technical Committees in order to produce classification schemes and strengthening guidelines [5,6], a successful run of a fire damaged building restoration requires the crossing out of some critical decisions, and the collection of a large base of quantitative data which are always puzzling their correlation to a general description of the phenomenon.
However, although experience can help to set the correct redesign philosophy, it does not possess any value in establishing the pointwise distribution of strengthening in a large span damaged area.
So, it appears clearly that one of the earlier critical decisions is the selection of appropriate testing and evaluation techniques, as well as the mesh at which to do the measurements. In fact, the difficulty to obtain a reliable base of quantitative data, can sometimes lead to a choice of total demolition.
In the following, we firstly present a summary of critical decisions that can help in the preparation of an operative program to be detailed for a particular site under investigation. After, we reassess the use of combined experimental techniques of both destructive and non destructive type, in order to quantify the damage suffered by R/C structures during the event of a large fire spread. With relation to a far field investigation carried out in the past [2], some practical hints regarding the consistency of data acquisition are presented.
Finally, with reference to a particular case history, we discuss the established repair techniques and their grading on the basis of the damage level assessed; in fact, once the structural strengthening has been detailed, we are able to forecast the life span extension produced by it [10].

2. PLANNING THE OPERATION SCHEDULE AND DATA ACQUISITION

In general, the consulting work begins few days later the fire accident, when some urgent remedies are to be planned immediately. After, we have time for field and laboratory measurements, and finally the building can be restored to its original functionality. These three design steps involve different knowledge levels; so it is important to activate only such operations that agree with the level of understanding gained. As a concern we can cite the following points:

a) *initial operations*
- locking of the chemical pollutant resulting from combustion,
- demolition of unsafe or near collapse structures,
- evaluation with the company management of the conditions needed for the restart of productive lines.

b) *mean time operations*
- collection of experimental data and interpretation,
- restoration of undamaged parts of the building,
- restart of power and fluid distribution plants all along the safe or undamaged zones.

c) *final operations*
- generalised rehabilitation of structures and technological systems in the damaged parts of the building,
- support to the company management in setting the reports relevant for the submission of the insurance refund request.

The definition of the activities involved in a given time schedule detailing the previous list, is a complex task that cannot be discussed in a general way; so, we shall reconsider only the strategies available for the damage evaluation.

2.1. In Situ Strength Determination of Concrete

Several combined non destructive (NDT) and destructive (DT) testing techniques have been prepared and studied in the past [4,7]; however the complex nature of interacting phenomena underlying the fire withstands their rational use.
More precisely the temperature gradient due to fire induces non homogeneous property distributions which are not likely to be detected by NDT sensing surface properties. So we recognise that Schmidt Rebound Hammer, Windsor probe and pull out methods give information only on an external layer, and cannot be combined with volume averaging probes such as ultrasonic or x-ray scanners.
In the industrial site of Merloni Company at Nocera Umbra, Italy, which is a deeply studied interesting example [1,2], we used both DT and NDT procedures:
- ultrasonic pulse velocity (UPV) measurements of both direct and indirect type;
- Schmidt rebound index measurements (SRH);
- drilled core sampling and analysis (DC, as described later),
- load testing of simply supported elements up to the serviceability level (LT).

With relation to the statistical robustness of the measures [8], we adopted the following procedure (see fig.s 2.1÷2.3):

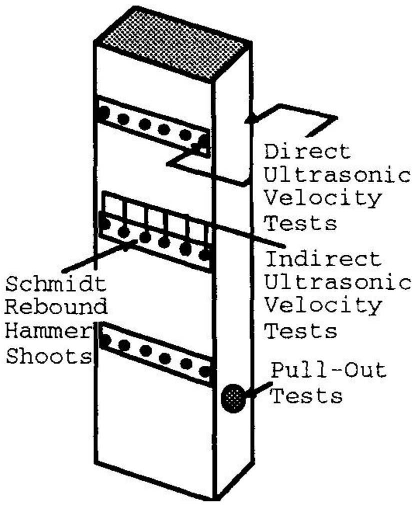

Fig. 2.1: *Test positioning arrangement for a column*

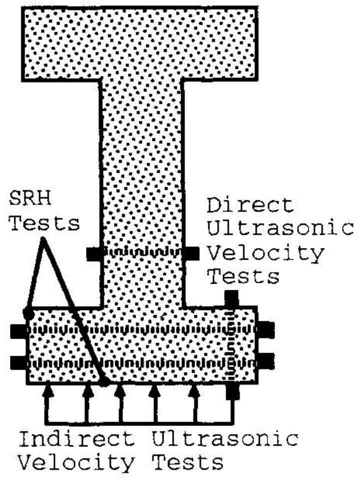

Fig.2.2: *Test positioning arrangement for a beam*

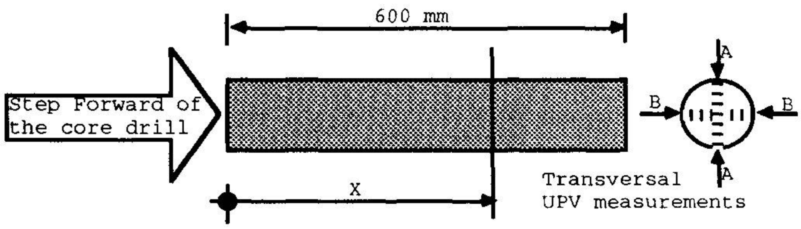

Fig. 2.3: *Test procedure for the assessment of transversal UPV in cores*

a) *data collection*
   - definition of three representative sites in each investigated element,
   - execution of ten SRH index evaluation for each site,
   - execution of three UPV direct transmission evaluation for each site,
   - execution of indirect transmission UPV test on the more damaged site,

b) *calibration tests*
   - extraction of CD samples for the whole length of a member side,
   - UPV transversal measurements along the cylindrical core at a fine mesh,
   - preparation of standard height cylinders cutting the core,
   - execution of axial UPV measurements and strength tests on the cylinders.

The correctness of the calibration tests can be improved doubling the sampling in some typical elements and charging for tests two different Laboratories; this care can be used also for the in situ measurements charging a second team for the repetition of some investigations. With this technique systematic errors or incorrect workmanship execution can be detected and compensated.

2.2. Damage evaluation

Several different damage pattern are present in a fired building and the strongly non homogeneous distribution of the residual strength can withstand the selection of a representative damage measure. On the other hand we must remember that scientific knowledge does not shadow engineering interpretation which is the main tool for redesign.

As a matter of fact we can try to construct residual strength distribution inside damaged elements, but the only necessary information is the mean residual strength of the core and the depth of the superficial deteriorated layer.

In the Literature there are several proposal for the damage evaluation of concrete structures [6], but the lack of specific analytical methods let us resort to phenomenological models. In detail we have:

- strength vs. ultrasonic velocity calibration curves,
- damage vs. ultrasonic velocity decay experimental relationships,
- indirect analytical and numeric methods.

In this last set up we make use of one or more transition variables, such as expressing the max. temperature with relation to the ultrasonic velocity, and the damage as a function of the temperature [1,3].

In the evaluation made in the past we found that SRH has low sensitivity in predicting the average strength, so we decided to use this method only for the detection of debonded layers. In fig. 2.4 the experimental correlation of SRH is illustrated for the cited example.

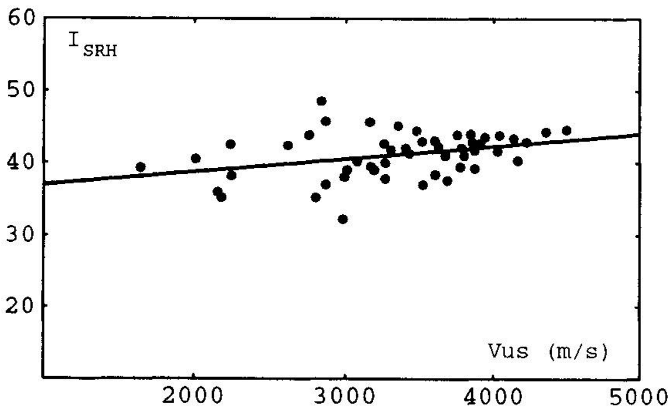

Fig. 2.4: *SRH Index as a function of the direct UPV measure*

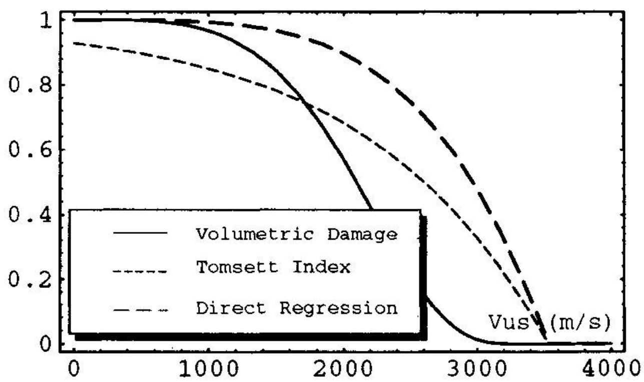

Fig. 2.5: *Damage evolution resulting from the three models*

As a matter of exposition we present the following relationships (the index "T" denotes a quantity reduced by temperature rise):

a) *direct regression of calibration core data:*

$$f_{cT} = k\, V_{usT}^{4} \; ; \qquad (1)$$

the coefficient k, can be obtained from a statistical analysis of core tests.

b) *Direct damage index evaluation (Tomsett [12]):*

$$\mathrm{Ln}\left(\frac{f_{cT}}{f_c}\right) = \mathrm{Ln}\,(\rho_{cT}) = -\frac{f_c}{f_{ref}}\,\frac{V_{us}}{V_{ref}}\left(1 - \frac{V_{usT}}{V_{us}}\right), \qquad (2)$$

where the reference strength and ultrasonic velocity correspond approximately to the lower allowable concrete class ($f_{ck} \approx 15$ MPa);

c) *Indirect set up [2]:*

we postulate the functional relations:

$$\frac{V_{usT}}{V_{us}} = \Lambda(x_\alpha) \ , \qquad \frac{f_{cT}}{f_c} = \Phi(x_\alpha) \ , \qquad \alpha=1,n \ , \tag{3}$$

where the internal variables x_α must be connected by n-1 relationships; we can then construct the following damage ratio formula:

$$D_{cT} = 1 - \frac{f_{cT}}{f_c} = 1 - \rho_{cT} = 1 - \Phi\left[\Lambda^{-1}\left(\frac{V_{usT}}{V_{us}}\right)\right] . \tag{4}$$

A more involved problem is the evaluation of the depth of the external deteriorated layer (for a deeper discussion see[2]); however, the demolition works of the concrete cover corresponds to a generalised consistency test, which allows to leave out more involved evaluation tests.

3. A SUMMARY OF REHABILITATION TECHNIQUES

With relation to the cited example (which will be discussed later), we set up different restoration strategies for the element classes composing the building:

a) prestressed precast this sections: total substitution,

b) massive R/C beams and columns: graded levels of restoration.

It should be pointed out that massivity (high volume over surface ratio), is a determinant feature toward fire resistence of structures.

3.1 Column Restoration

Under the proposed restoration techniques [1,6] lies the notion that transversal confinement can improve by far the allowable axial load. The work schedule is:

a) Demolition of the external cover up to steel reinforcement net and locally, of the still remaining low compactness concrete,

b) execution of the holes for the connecting steel ties,

c) clamping of steel ties in the R/C core by means of epoxy resin mortars,

d) construction of a new steel reinforcing net linked to ties,

e) erection of the wooden case and cast of the new external layer using super fluid additivated high strength micro concrete (gravel size < 8 mm).

3.2. Beam Restoration

In this case we had a very small damaged layer on the lower flange but care was to take of the anchorage zones; we provided a sequence similar to that of the columns, with the only difference that the concrete was cast in place by means of grouting of a tixotropic no shrinkage mix and hand levelling.

4. AN EXAMPLE: THE MERLONI INDUSTRIAL BUILDING

We conclude presenting some interesting features of a restoration work completed few years ago; in fig. 4.1 the appearance of the building after the fire event is outlined. One of the preliminary requests of the company management was to allow for a production restart as soon as possible.

So we decided to test the survived thin roof shell prestressed elements in order to define the extent of roof owed to substitution. In fig. 4.3 is presented the final dismount line as defined making use of direct load tests on all the tiles placed up to the line itself. The complexity of a decision problem of this type can be suggested by the number of parts included in the damaged zone: we dealt with three modules comprising each 77 columns, 66 beams and 260 roof shells.

The wide experimental investigation carried out onto the beams and columns of the two highly damaged modules, allowed for the construction of a chart describing average residual concrete strength ratio ρ_{cT} shown by columns (fig. 4.4), and to apply rehabilitation techniques graded to the damage distribution.

We concluded also that the beams, due to their high massivity, were only deteriorated in the thin superficial layer acted on by fire. A reason for this can be inferred from the relatively low (500°-700°C) temperatures suffered by the R/C frames [3], as a consequence of the premature collapse of the roof.

Fig. 4.1.: *A.Merloni industrial Site after the great 1993 fire*

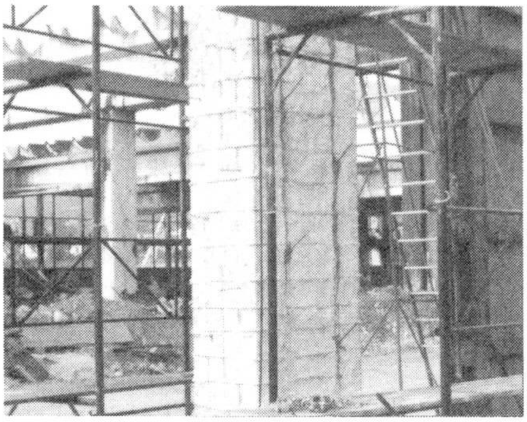

Fig. 4.2: *A column core during the rehabilitation works*

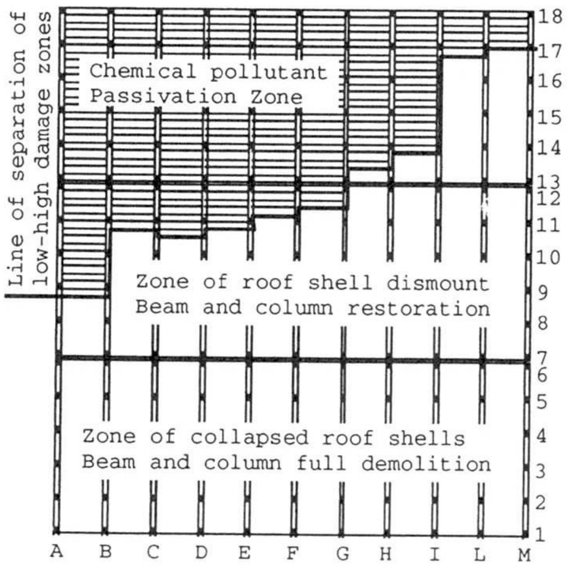

Fig. 4.3.: *After tests definition of restoration zone*

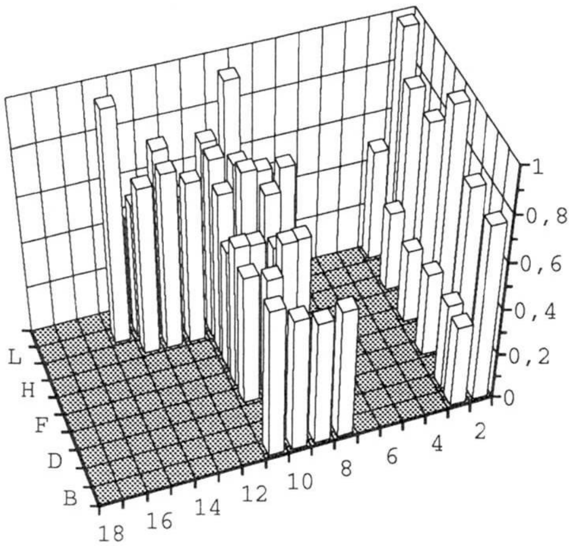

Fig. 4.4: *Residual strength plot of investigated columns*

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