Fire-induced damage in prestressing steels

By José Miguel Atienza and Manuel Elices
Madrid Polytechnic University, Spain

Abstract:
After a fire, even if no collapse happens, there is a possibility of fire-induced damage in the structure. Correct knowledge of residual properties of wires after fire is of major importance for the assessment of the residual load-bearing capacity of a prestressed structure. This paper studies the non-visible fire-induced damages in prestressed wires, including the reduction of the prestress loads and the strength of steel wires produced by the exposure to high temperatures.


Atienza


Elices

José Miguel Atienza teaches in the materials science department at Madrid Polytechnic University, Spain, where he started as a researcher in 1998. His areas of scientific interest include steel wire for prestressed concrete and biomaterials. He holds a Ph.D. degree in civil engineering from Madrid Polytechnic. Manuel Elices is full professor of materials science and technology at Madrid Polytechnic and dean of the faculty for materials science and engineering. His professional and research work has been centered mainly on cracking and fracture of materials.

ABSTRACT
After a fire, even if no collapse happens, there is a possibility of fire-induced damage in the structure. Correct knowledge of residual properties of wires after fire is of major importance for the assessment of the residual load-bearing capacity of a prestressing structure. In this work, the non-visible fire-induced damages in prestressing wires have been studied: the reduction of the prestressing loads and the strength of steel wires produced by the exposure to high temperatures.

1 INTRODUCTION

When fire occurs either in buildings or bridges, depending on the relative severity of the fire, there is a possibility of fire-induced damage, which affects the performance of the structures, even if no collapse happens. The extent of damage depends on the very intensity and duration of the fire, as well as the geometry, materials used in construction and load intensity.

After fire, the question which then arises unavoidably, is whether the structure should be replaced or whether it is still possible to use it, either as it is or after some partial repairs. In many cases, the structural members can be restored through repairs. However, before undertaking such repairs an assessment of the load bearing capacity of the structure has to be carried out, even if it seems that no repairs are needed, since a misjudgement at this point can lead to unsafe situations.

The financial aspect of the question is of course an important issue and may, in some cases, lead to the decision of destruction rather than repairing of the remaining structure. However, the essential question that the engineers have to face is whether the structure is still safe. What is the load bearing capacity of the structure now? How has it been affected by the fire? Appropriate knowledge of the behavior of construction materials after a fire is of major importance for answering these questions.

Much experimental work on the characterization of the mechanical properties of steels at high temperatures, aiming at structural fire design, has been done in the past decades

[1-7]. However, less work has been performed in the characterization of the mechanical residual properties after fire. Correct knowledge of such properties is of major importance for the assessment of the residual load-bearing capacity of the structure. In this work, the behavior of prestressing steel after fire is studied, examining the two main factors which can affect the security of the structures:

- The permanent deterioration of the material properties, specially the strength and elastic limit.

- The modification in the distribution of actions and loads due to the increase in the stress relaxation losses of prestressing steels produced by the exposure to high temperatures. This can reduce the prestressing load after fire, with a subsequent reduction in the safety of the structure.

2 AN EXAMPLE OF FIRE DAMAGES IN PRESTRESSING WIRES

2.1- Fire Simulation

A prestressing wire has been subjected to a fire scenario to simulate the effects of a fire on the mechanical behavior of prestressing steel wires when the structure does not collapse. The key feature of the fire relevant to the prestressing steel behavior is the temperature-time curve endured by the material. Given that structural steel has a high thermal conductivity coefficient, when directly exposed to a fire it acquires immediately the fire temperature. However, as concrete surrounds steel wires and has low thermal conductivity, its thickness protects steel wires, delaying the values of temperature reached inside the structural elements. Standards provide curves to predict the temperature inside concrete elements during the nominal fires.

The time-temperature curve (Fig. 1.a) used in this work represents a realistic and conservative fire scenario, even considering the bearing capacity of the wire is not surpassed. The heating velocity is around 3°C/min representing a typical temperature curve inside concrete elements during the nominal fires. Maximum temperature is reached at the end of the fire, three hours after the beginning.

An additional aspect should be considered to model the effects of fire: temperature produces a dilatation of the structural members which, in general, could not expand free due to the external constraints. Standards distinguish between "restrained" and "unrestrained" assemblies. The term restrained means that thermal expansion of the specimen is restricted during the fire test. If a fire occurs beneath a portion of a large structure, the heated portion will expand and push against the surrounded unheated portion. In turn, the unheated portion exerts compressive forces in the heated portion, altering the service load during the fire. In the case of unrestrained assemblies, the dilatation of the element is free.

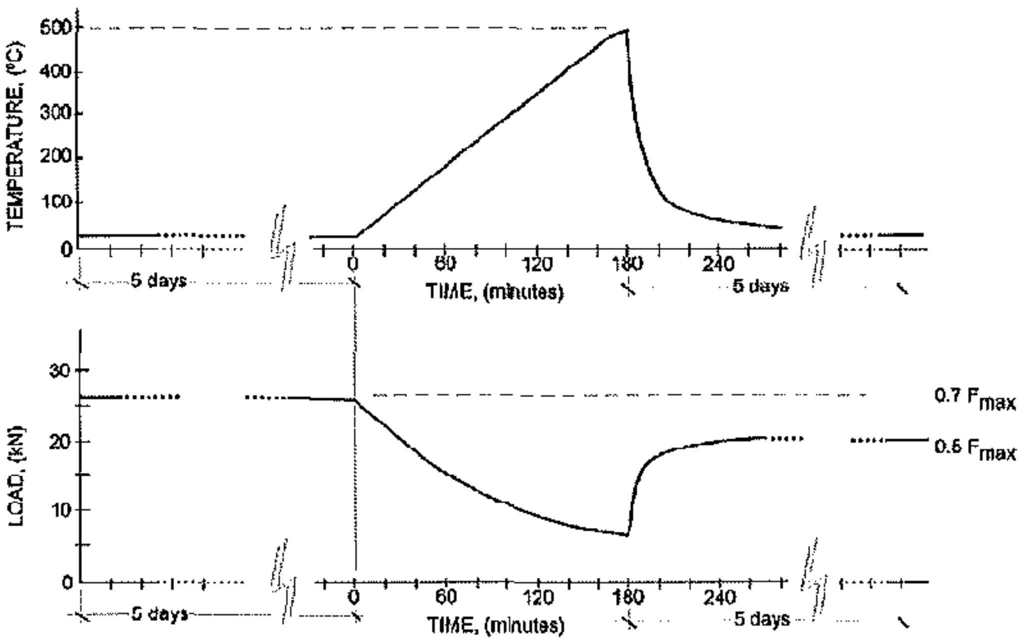

Figure 1. a) Time-temperature curve endured by the steel wire during the fire simulation. b) Evolution of prestressing load during the fire simulation.

In our case, the length of the specimen remains constant during the fire. This is a typical case of a restrained assembly, in which the service load would diminish during the heating because of the constrained dilatation. The fire scenario was simulated following the next steps:

- The prestressing steel wire (specimen length: 1.2 m) is loaded at 20°C. The initial load has been 70% of the maximum load, the value proposed by Standards for the stress-relaxation tests. The curve load-time is recorded continuously.

- Once the majority of the stress relaxation losses have occurred, after five days, the effects of fire are simulated using a furnace (size: 0.7 of the specimen length). The fire duration was about three hours. Then the furnace was turned off and left open, so that the wire would cool in air. The curve load-time is recorded continuously during the whole process.

- The test continues five more days at room temperature. Again, the curve load-time is continuously recorded.

- After that, conventional tensile test and stress relaxation test at room temperature were performed on the final wire to study the residual properties.

2.2- Fire-Induced Damages

Figure 1.b shows the evolution of the prestress load before, during and after fire. It can be observed that during the fire there is a significant reduction of the bearing load, as a consequence of the restrained dilatation and the increase of stress relaxation at high temperatures. When cooling, the part of this lost load due to the constrained dilatation is recovered, but not the stress relaxation losses. Although the wire has successfully supported the fire without any visible damage, the prestressed load after fire has been considerable reduced.

Additionally, the results of the conventional tensile and stress relaxation tests at room temperature showed that the residual strength has been affected (20% less than the original value) as well as relaxation (five times larger than the typical for a "low relaxation" wire).

In summary, even the fire has not produced visible damages, the strength of the wire and the prestressed load were reduced, with the subsequent reduction of the residual load-bearing capacity of the structure.

3 CHARACTERIZATION OF PRESTRESSING STEEL RESIDUAL BEHAVIOR AFTER FIRE

- Stress relaxation losses at high temperatures

By definition, stress relaxation refers to the decrease in stress at a constant deformation. In prestressed concrete structures, steel tendons in tension provide compressive stresses to the concrete. Throughout the life of the structure there should not be an appreciable loss of tension, because a reduction in prestressing loads would affect the structural safety. Design codes place limits for keeping the relaxation losses within safe margins. Stress losses are measured according to a standardized test (ASTM E328, ISO15630/3) and the figures should be provided by the manufacturer for the acceptance of the steel tendons; those with a figure of stress losses of less than 2.5% of the initial stress — after 1000 hours, at room temperature, when stressed at 0.70 of the tensile strength — are called "low relaxation" tendons and are those used in prestressing at present [8].

Temperature has a great influence on the stress relaxation; an increment of temperature produces a large increase in stress relaxation losses. During a fire, the wire temperature increases and, depending on the boundary conditions, initial wire load can decrease due to the restrained dilatation. Since no results under such conditions were found in the literature, a detailed experimental study on the effects of temperature on the stress relaxation losses of the wires was performed. Stress relaxation tests at different temperatures and at different initial loads were carried out. The duration of the tests was four hours, longer than the duration of the conservative fire scenarios proposed by standards (EC1 2002, EC2 2005). Temperatures studied were: 20, 100, 200, 300, 400, 500 and 600°C. Initial loads considered were: 10-30-50-70-90% of the tensile strength.

In Figure 2, the time-stress relaxation losses curves are depicted as a function of temperature and initial loads. It can be seen that as temperature increases the stress relaxation losses increase significantly, and, consequently, the prestressed compressive loads provided to concrete decreases. Clearly, this is a fact to be considered when assessing the fire-induced damage after cooling.

- Residual mechanical behavior at room temperature

After a fire, even if no collapse happens and no effects can be visually seen in the structure, damage can be-induced in the materials due to previous exposure to high temperatures. The term "residual" will be used here to indicate the properties that the prestressed steel exhibits after a complete cycle of heating and cooling.

In our work, to simulate the effects of fire, wires were subjected to a complete cycle of heating and cooling (four hours), while loaded at 70% of their tensile strength. The effects of fire will depend upon the fire duration and the loading of the wire, in this case testing conditions are a conservative simulation since the duration of the fire is longer than the nominal fires (BS811, EC1, EC2), and the load is the maximum load experimented for the wires in service.

Temperature was raised at a rate of around 20°C/min and the different maximum temperatures studied were the same as the rest of this work: 20, 100, 200, 300, 400, 500 and 600°C.

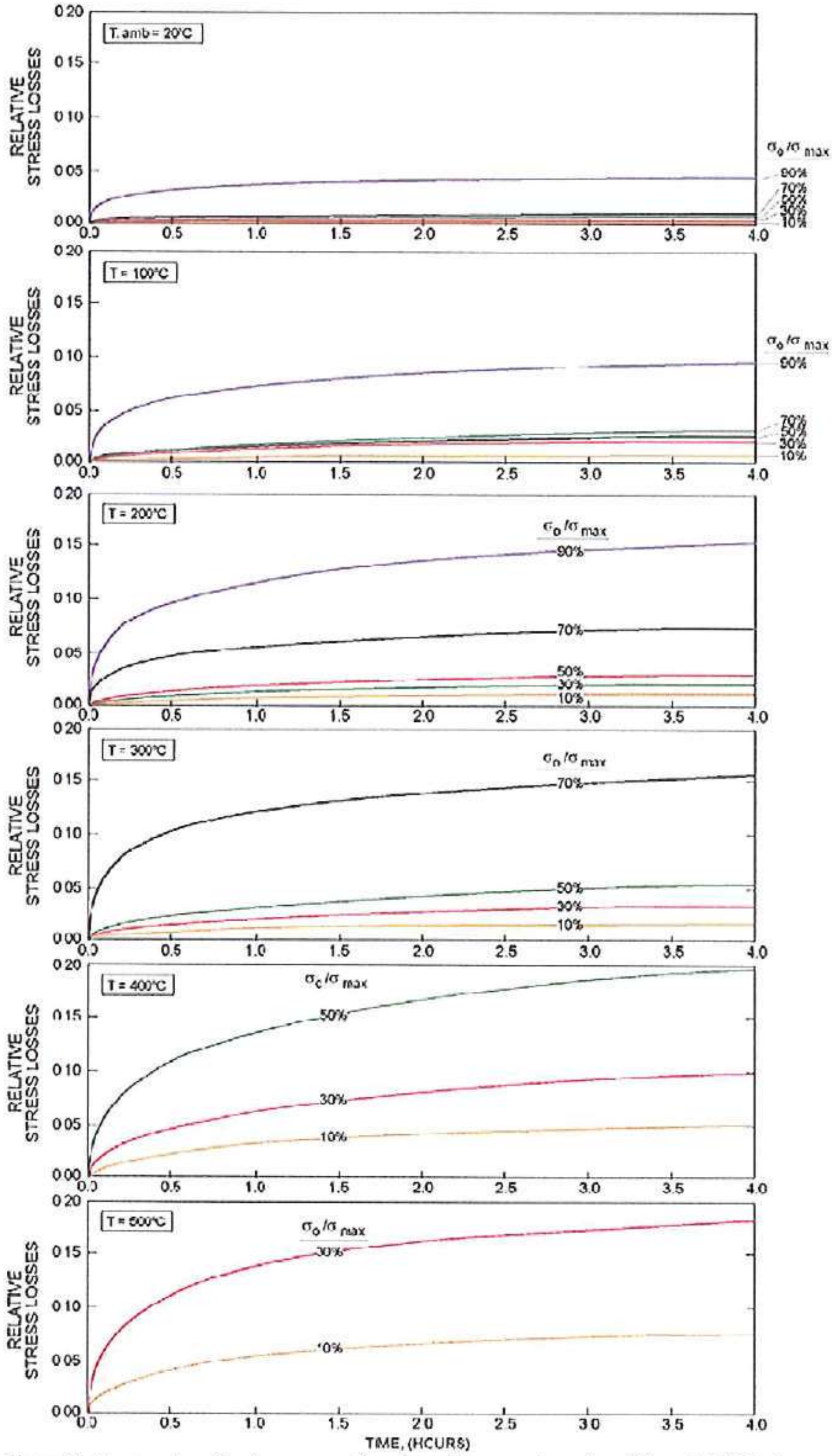

Figure 2. Stress-relaxation losses as a function of temperature, for different initial stresses. The relative values are given as stress loss/strength

After cooling, tensile tests and stress relaxation tests at room temperature were performed to obtain the residual mechanical properties of the wires. Table 1 shows the variation of the tensile strength, the yield stress and the stress relaxation losses after 250 hours for the different maximum temperatures reached during the fire simulations. The reference values of the original wires (control samples without thermal treatment) at room temperature have also been included. The values of the residual tensile strength for the tested prestressing steel remain approximately constant up to temperatures around 300ºC. If the wire suffers higher temperatures during fire, the residual strength, the elastic limit and the stress relaxation behavior are affected.

Table 1. Residual mechanical properties after a fire (duration: 4 hours, loaded at 70% maximum strength).

Max. Temp (ºC)	Yield Stress (MPa)	Strength (MPa)	Str. Relax (%init. load)
20 (Room)	1770	1950	2,2%
100	1765	1947	2.2 %
200	1770	1940	2.4 %
300	1752	1926	2.5 %
400	1590	1755	6.2 %
500	1380	1521	13.2 %
600	887	1014	Breaks

4 SUMMARY

Fire safety should consider not only the performance of the structure during the fire but also the behavior of the structure after cooling. Even if a fire does not give rise to apparent damage in the prestressed structure, mechanical properties of materials as well as load distribution can be affected. After fire, a verification of residual load-bearing capacity is necessary to determine if the structure can be maintained in use. The extent of damage in prestressing steels depends on the intensity and duration of the fire, the temperatures reached in the wires, as well as the load intensity they bear during a fire.

In this work, we have tried to attract attention to the possible non-visible fire-induced damages produced in prestressing steels after fire:

- Reduction of the prestressing loads due to the increment in the stress relaxation losses during the exposure to high temperatures.
- Damage of the mechanical properties of steel wires produced by the exposure to high temperatures: residual strength and stress relaxation behavior at room temperature depend on the maximum temperature reached in the wire during fire.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Ministerio de Fomento in Spain, by means of the "Durability of prestressed concrete tendons" grant. They are also indebted to Mr. Luis del Pozo, from Emesa Trefilerias, and Mr. Mariano Ortez for their highly beneficial comments and help with the material and the tests.

REFERENCES

[1] Harmathy, T.Z. & Stanzak, W.W. 1970. Elevated temperature tensile and creep properties of some structural and prestressing steel. Fire Test Performance, ASTM STP 464. American Society for Testing and Materials 186-208.

[2] British Standards Institution BS8110: Part 2, 1985. Structural use of concrete, Code of practise for special circumstances. BSI, London.

[3] CEB (Comité Euro-International du Beton) 1991. Fire design of concrete structures. Bulletin 208, Comité Euro-International du Beton (CEB), Laussane, Switzerland.

[4] Cristofano, A.H. & Martin, L.D. 1989. Design for fire resistance of precast prestressed concrete. Second Edition, Prestressed Concrete Institute PCI.

[5] EC1 2002. Eurocode 1: Basis of design and actions on structures, Part 2.2: Actions on structures exposed to fire, EN 1991-1-2: 2002. November 2002.

[6] EC2 2005. Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural Fire Design EN 1992-1-2: 2002. February 2005.

[7] fib 2007 (Federation Internationale du Beton) Working Party 4.3-1. Fire design of concrete structures – materials, structures and modelling. State of art report. fib Bulletin 38.

[8] Atienza, J.M. & Elices, M. 2007. Role of residual stresses in the stress relaxation of prestressed concrete wires. Journal of Materials in Civil Engineering, 19(8), 703-7.