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A finite element insight on reinforced concrete tunnels under fire conditions

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ABSTRACT: Fire performance evaluation is becoming an important part of the overall structural performance assessment and is assuming an increasing role within international standards. Simple approaches, based on single section performance, fail often to give a realistic description of the phenomenon especially for statically indeterminate structures, where thermo-mechanical coupling and non linear dependency of stress, moduli and expansion need to be accounted for. In the present work, the concrete tunnel section is discretized using longitudinal and shear truss fibers, together with stiff coupling elements where a transient heat fire analysis takes place. A single model can be thus employed to perform a full quasi static one-way-coupled thermo-mechanical analysis, where first temperatures and then internal forces are computed. Due to the number of temperature dependent constitutive relationships adopted within a single model, many simplified tuning exercises where investigated to match known results for situations where some of the simulation variables were kept constant. The computation of the internal forces by integration over groups of fibers is obtained by an automatic API procedure. Finally, a case study is presented where the structural performance is evaluated after 120 minutes of fire exposure for the railway tunnel located in Florence and denominated "Imbocco Nord Riffredi – Opera di Scavalco – Tratto E-M" part of the Italian Milano-Napoli Railway.

SCOPE OF WORK

Accidental scenarios such as structural performance under fire conditions are becoming of increasing importance for structural designers. Especially for tunnels of significant length, the latter conditions may result in reduced post-fire operating performance with consequent severe reduction of the overall service efficiency.

International standards are becoming increasingly aware of the importance of fire events in structural design. A transition from the traditional prescriptive methodology to a new performance-based approach is taking place within many codes worldwide. The availability of complex simulation software both for CFD and non linear structural analysis has given a significant contribution to the practical implementation of new approaches.

Simple models are often a good choice to achieve accurate results and to produce reasonable designs at the same time. However, phenomena such as fire response of structures are intrinsically non linear and simple assumptions may result in member/section oversize.

The present article investigates a possible modeling technique which can be applied to fire analysis of reinforced concrete tunnels. The size of the model in terms of total degrees of freedom is kept reasonable but a complete description of temperature dependent material constants is to be specified to obtain a realistic model response.

FIRE ANALYSIS OF TUNNELS: THE EUROCODE APPROACH

Although fire design procedures can be found within many international standards, the present article focuses on the Eurocode guidelines.

Procedures for structural analysis and verification of concrete structures under fire conditions can be found in UNI-EN 1992-1-2.

Three approaches are possible within the latter standard:

1. Detailing according to recognized design solutions.
2. Simplified calculation methods for specific types of members.
3. Advanced calculation methods for simulating the behaviour of structural members.

The most effective approach to follow can be typically chosen with reference to the peculiar geometry under investigation, external restraint distribution and internal degree of continuity.

Concrete tunnels are typically statically indeterminate structures interacting significantly with a surrounding non linear material such as soil. An advanced calculation method is therefore the only possible way to obtain a realistic time dependent response that accounts for temperature variations.

THERMO-MECHANICAL MATERIAL MODELS

EXTERNAL ACTIONS: FIRE RAMP

The increase of ambient temperature during a fire event can be described by a temperature vs. time curve as specified within the UNI11076 standard (see Figure 1).

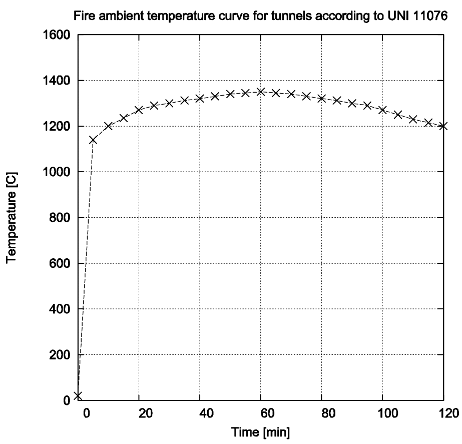

FIGURE 1 - UNI FIRE RAMP.

THERMAL PROPERTIES

Thermal properties as functions of temperature are specified for concrete. Steel bars are assumed to give a negligible contribution to the heat transfer due to fire exposure.

CONCRETE

The following temperature dependent material properties are needed to perform a transient thermal analysis which results in a through-thickness temperature distribution for the tunnel walls at different instants in time:

§ Thermal conductivity vs. temperature.
§ Specific heat vs. temperature.
§ Density vs. temperature.

The adopted curves are highlighted in Figure 2, Figure 3 and Figure 4

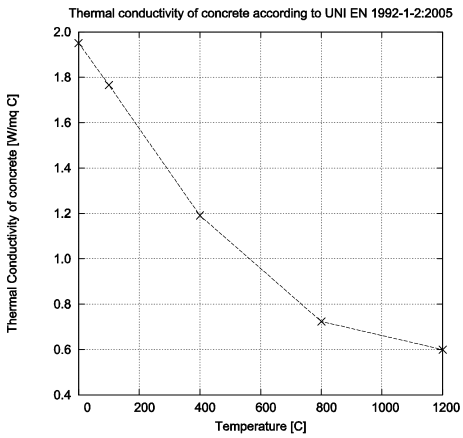

FIGURE 2 - THERMAL CONDUCTIVITY OF CONCRETE.

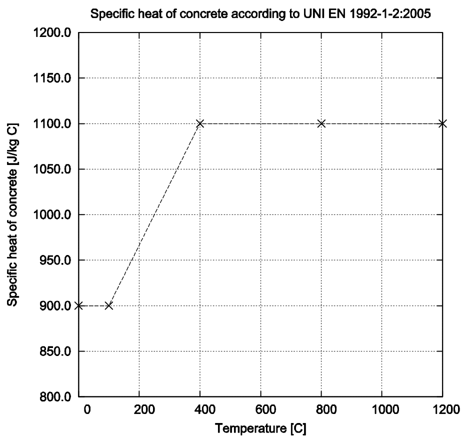

FIGURE 3 - SPECIFIC HEAT OF CONCRETE.

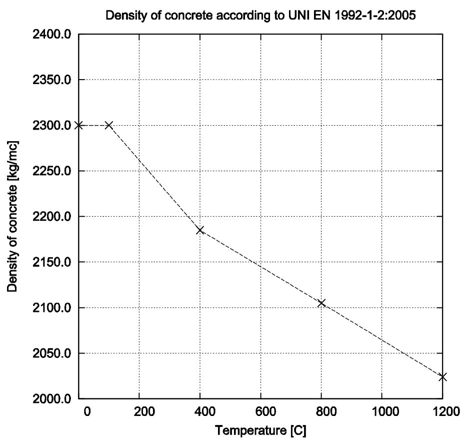

FIGURE 4 - DENSITY OF CONCRETE.

MECHANICAL PROPERTIES

Mechanical properties of steel and concrete are specified through stress vs. strain curves.

The following temperature dependences are considered:

- Yield stress vs. temperature.
- Elastic modulus vs. temperature.
- Linear thermal expansion coefficient vs. temperature.

The thermal expansion coefficients used within the numerical simulations are illustrated in Figure 5.

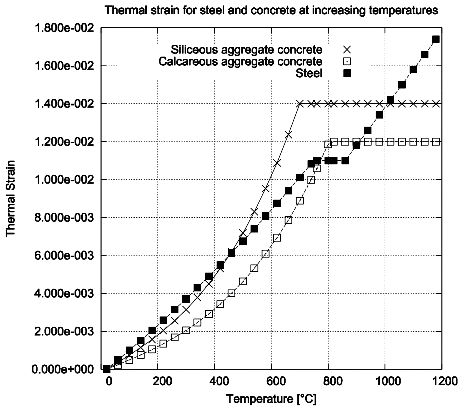

FIGURE 5 - TEMPERATURE DEPENDENT THERMAL STRAIN FOR STEEL AND CONCRETE.

CONCRETE

Temperature dependent stress vs. strain curves for concrete are illustrated in Figure 6.

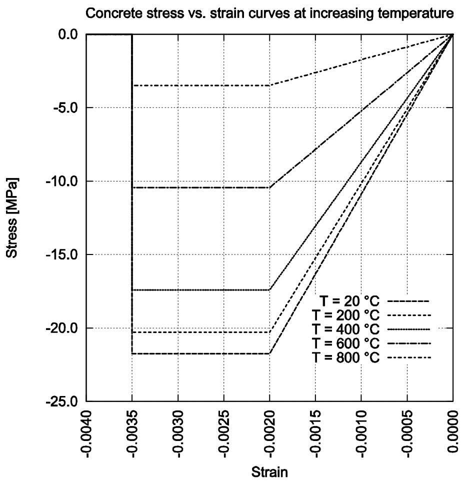

FIGURE 6 – STRESS VS. STRAIN RELATIONSHIPS FOR CONCRETE.

Only compression stiffness is considered for concrete throughout the present article.

Concrete softening in compression gives little contribution for the tunnel sections adopted. Non linear analyses were performed to confirm the latter influence for the geometry under investigation. In particular, concrete yielding occurs mainly where high thermal gradients arise that is, where the boundary fire condition is applied. As a consequence, a different post-yielding behavior have a small impact on global internal forces. As it can be seen from Figure 7 and Figure 8, very similar axial force distributions are obtained and conservative bending moments can be expected in case perfect plasticity is assumed.

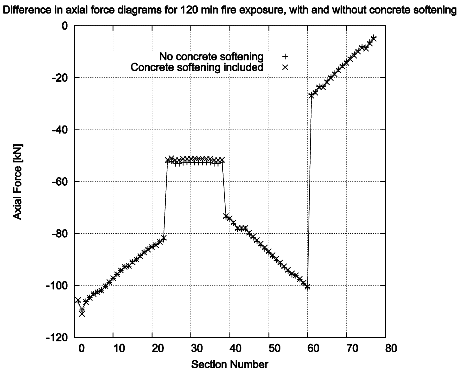

FIGURE 7 - AXIAL FORCE DISTRIBUTION AT 120 MINUTES WITH AND WITHOUT SOFTENING.

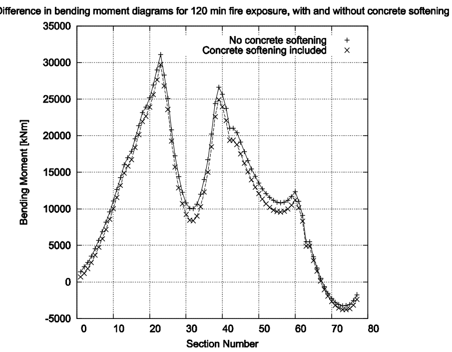

FIGURE 8 - BENDING MOMENT DISTRIBUTION AT 120 MINUTES WITH AND WITHOUT SOFTENING.

STEEL

Temperature dependent stress vs. strain curves for steel are illustrated in Figure 9.

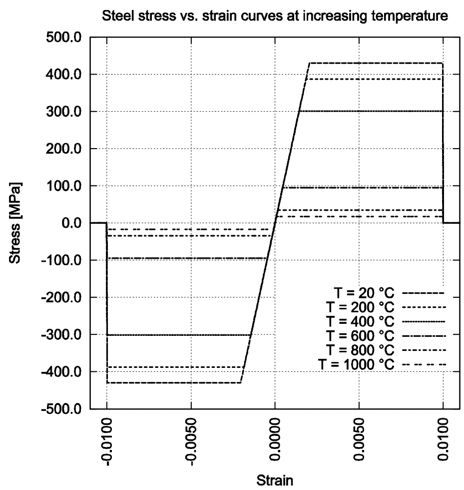

FIGURE 9 - STRESS VS. STRAIN RELATIONSHIPS FOR STEEL.

BOUNDARY CONDITIONS: THERMAL CONVECTION AND RADIATION

Section heat transfer analysis is performed in 1D using both convection and radiation boundary conditions.

A convection coefficient equal to 25 [W/mq °C] is assumed for surfaces with direct exposure to fire. A value equal to 9 [W/mq °C] is adopted for all other surfaces.

An emissivity equal to 0.56 is adopted for boundary radiation.

The ambient temperature for both convection and radiation heat exchange is applied using the UNI11076 fire ramp.

The latter temperature rise is uniformly applied to the tunnel ceiling and the portion of the side walls directly exposed to air. The remaining part of the side walls is protected by the lateral walkways and rail installation layout; a constant room temperature equal to 20 °C is specified for the latter locations.

FINITE ELEMENT MODEL

The main purpose of the finite element model is to simulate the evolution in time of the structural response to a fire event in the most realistic way.

Due to the complex material models outlined above, an advance calculation methodology was considered appropriate to perform the fire verification task. A finite element model is thus put in place, keeping the following important features in mind:

- Computational light-weight: due to the number of variables affecting the material properties, full solutions need to be obtained within minutes.
- The model needs to account both for thermal and mechanical analysis. A one-way coupling between these fields has been assumed.
- Reinforced concrete needs to be simulated with particular reference to the interaction and congruence of concrete matrix and steel bars.
- Section resistance should be easy to check using hand calculation or simple spreadsheets. Longitudinal truss fibers are thus introduced where non linear temperature dependent material properties are specified. Shear truss fibers are also considered; axial/bending and shear stiffness are separated within the current approach.

MODEL DESCRIPTION

A typical model set up is highlighted in Figure 10.

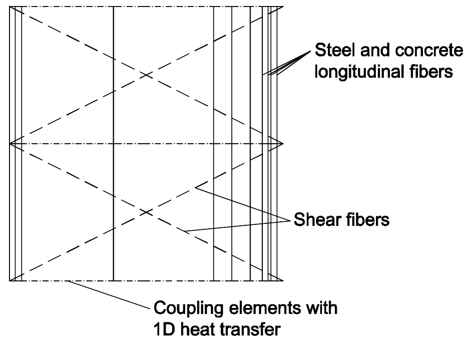

FIGURE 10 - TYPICAL PORTION OF FIBER MODEL FOR TUNNEL FIRE ANALYSIS.

Each concrete beam is an assembling of the following components:

- Longitudinal concrete or steel fibers.
- Shear fibers.
- Stiff coupling thermal elements.
- Skin elements for distributed load application.

Longitudinal fibers are simple truss elements with non linear temperature dependent stress vs. strain curves. A non linear modulus vs. temperature curve is also specified for concrete. A higher number of fibers is located close to the wall exposed to fire, due to the fact that significant thermal gradients normally arise. Bending is not taken into account for the latter elements as it may cause singular behavior due to progressive development of plastic hinges. A zero thermal conductivity is assigned to these elements; it is therefore easy to apply the fire conditions to a limited portion of the structure and to implement alternative fire scenarios.

Shear fibers allow a simple, statically determinate, uncoupling between shear and axial/bending deformations. Post-processing operations and shear force recovery is greatly simplified by the latter elements. No thermal expansion property is assigned to them. A symmetric, cross shaped, geometry for the latter elements is used with the aim of avoiding spurious (coupled) internal forces to be generated.

Stiff coupling elements act as rigid links between longitudinal fibers. They allow the model section to remain straight consistently with standard beam assumptions. All temperature dependent heat transfer properties are applied to the latter elements together with convection and radiation applied at the end where fire exposure takes place.

Skin elements are useful when distributed loads need to be applied to the fiber model. Usually, constant or linear distributed loads are applied all around the model to account for permanent loads, train forces or earth pressures.

FINITE ELEMENT SOFTWARE

All finite element analysis were performed with the Strand7/Straus7 finite element analysis system.

MODEL BENCHMARKS

Various benchmarks are performed with scenarios of increasing complexity from the simple heat transfer to the fire analysis under external loads.

ONE DIMENSIONAL HEAT TRANSFER

Nodal temperatures are essential to assemble the correct model stiffness at given simulation times. As a consequence, thermal heat transfer was considered as a proper starting point for the benchmark procedure.

The following figure shows a comparison between a bi-dimensional section analysis and the proposed one.

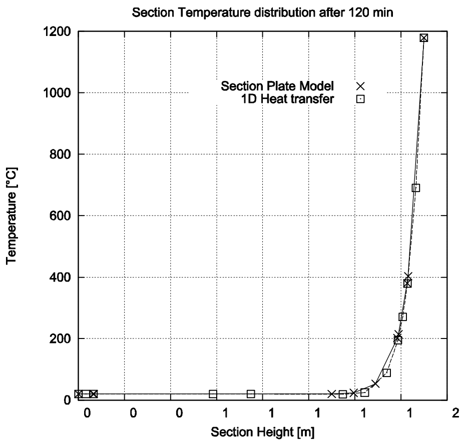

FIGURE 11 - TEMPERATURE DISTRIBUTION BENCHMARK AFTER 120 MIN OF FIRE EXPOSURE.

MOMENT-CURVATURE RELATIONSHIP AT ROOM TEMPERATURE

A simple supported beam with constant bending moment was used to test the fiber model in terms of resultant elastic-plastic moment curvature relationship. An increasing rotation is applied to one end of the beam and the corresponding moment reaction is plotted in a graph (see Figure 12).

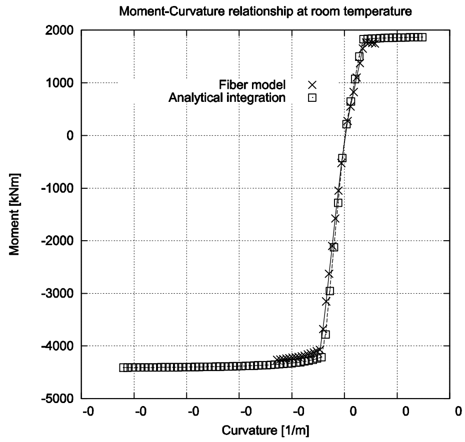

FIGURE 12 - MOMENT CURVATURE BENCHMARK AT ROOM TEMPERATURE.

MOMENT-CURVATURE RELATIONSHIP AT 120 MINUTES

A simple supported beam is first exposed to a 120 min heat transfer fire analysis; an end rotation is then enforced at one beam end to produce a moment-curvature relationship for the calculated temperature distribution.

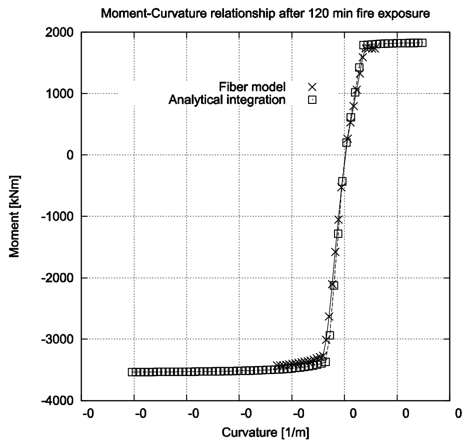

FIGURE 13 - MOMENT CURVATURE BENCHMARK AFTER 120 MINUTES OF FIRE EXPOSURE.

As it can be seen by comparing the two moment-curvature relationships reported above, a significant reduction only for negative plastic moments is obtained; strength reduction of tensioned steel bars is hence of primary importance for the section under investigation.

INTERNAL FORCE DISTRIBUTION FOR VARIOUS EXTERNAL ACTIONS

A Strand7/Straus7 API procedure was implemented to extract axial forces and bending moments acting over the whole section. Due to the fact that concrete members are made up of a significant number of fibers, this task was useful to significantly decrease post-processing effort.

The internal force distribution obtained by the application of various external actions to the whole tunnel model, was thus automatically recovered and compared to that evaluated by a simple beam model.

The most severe ULS combination is chosen as the one acting on the structure at the beginning of the fire event. Unitary values for the partial coefficients were adopted according to the reference standard.

As illustrated in Figure 14 and Figure 15, very similar distributions are obtained for resulting axial forces and bending moments. However, differences can still be observed in the bottom slab element. This difference is due to the fact that for the single beam model the same location is used for the application of external loads and soil springs; within the truss fiber model, distributed loads are applied to the upper fibers and spring restraints to the bottom ones.

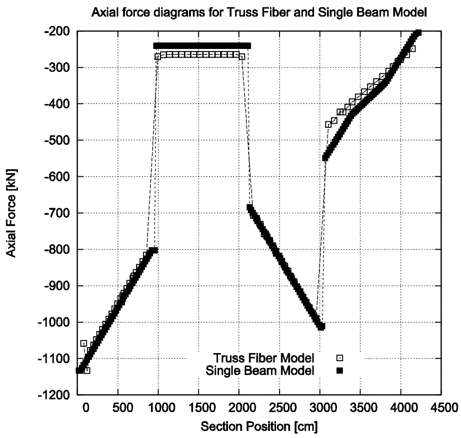

FIGURE 14 - AXIAL FORCE DISTRIBUTONS FOR TRUSS FIBER AND SINGLE BEAM MODEL.

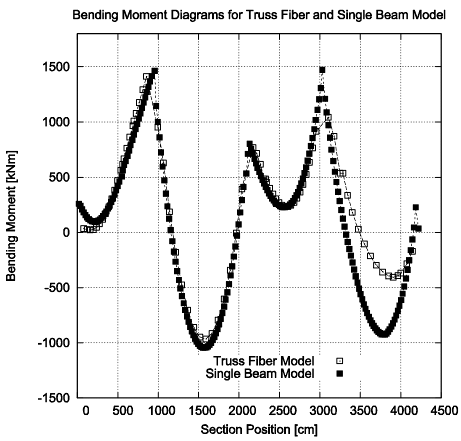

FIGURE 15 – BENDING MOMENT DISTRIBUTONS FOR TRUSS FIBER AND SINGLE BEAM MODEL.

CASE STUDY

The principles outlined above, are applied to perform the fire verification of tunnel sections part of the high speed railway “Milano - Napoli” in Italy.

LOCATION OF TUNNEL SECTION

A steel reinforcement layout drawing for section M-M is illustrated in Figure 16.

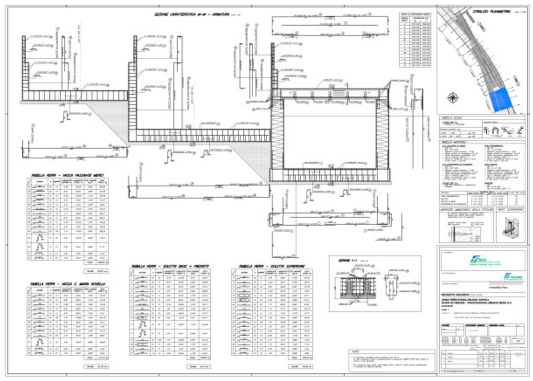

FIGURE 16 – STEEL REINFORCEMENT LAYOUT DRAWING FOR SECTION M-M

A typical tunnel section is made up using the following components: a 150 cm thick base concrete slab poured directly on site. Precast concrete panels with a 150 cm thickness are employed as vertical side walls. The upper slab has a total thickness of 120 cm and is built according to the following construction stages:

- Concrete precast beams are used at the first stage. A simple supported static behavior is thus obtained.
- The upper slab is then completed on site so that moment continuity between the upper slab the vertical side walls is restored.

The resulting bending moment distribution on the top slab is hence different for the short and long term situations due to concrete creep.

LOADS, FREEDOMS AND TYPE OF ANALYSIS

A complete set of external load conditions are considered acting on the tunnel at the beginning of the fire event.

- Self weight of concrete.
- Hydraulic pressure.
- Live loads.
- Concrete shrinkage.
- Load from the lateral walkways.
- LM71- 2: vertical train load with dynamic amplification factor.
- Train skewing.
- Centrifugal force.

Partial amplification factors comply with Eurocode specifications for accidental load combinations.

Vertical and horizontal Winkler-type linear springs are introduced below the bottom slab to simulate soil-structure interaction.

A quasi-static analysis is performed were no inertia terms are accounted for. Static loads are applied at the first time increment and nodal temperatures are read from the transient heat analysis file at increasing simulation times.

RESULTS

One of the possible fire exposure scenarios is depicted in Figure 17.

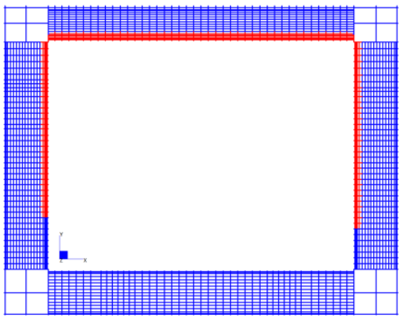

FIGURE 17 - TEMPERATURE PENETRATION AFTER 120 MINUMTES OF FIRE EXPOSURE.

Axial forces and bending moments as extracted from the tunnel model are illustrated in Figure 18 and Figure 19 for 30 minutes increments. Section number 0 is located at the bottom left corner and increasing sections are numbered clockwise.

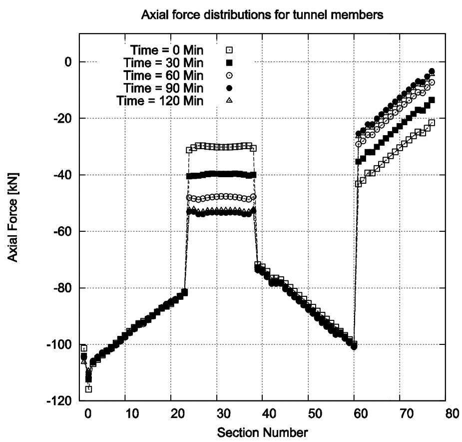

FIGURE 18 - CONCRETE TUNNEL AXIAL FORCE DISTRIBUTION AT GIVEN TIME INCREMENTS.

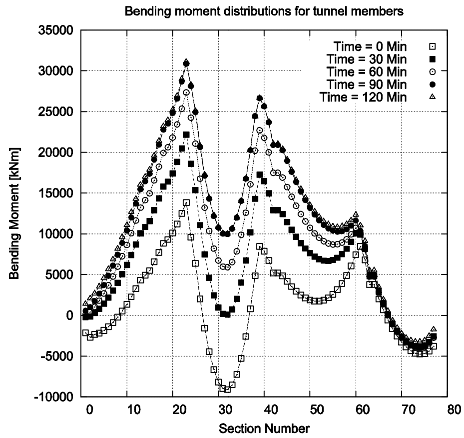

FIGURE 19 – CONCRETE TUNNEL BENDING MOMENT DISTRIBUTION AT GIVEN TIME INCREMENTS.

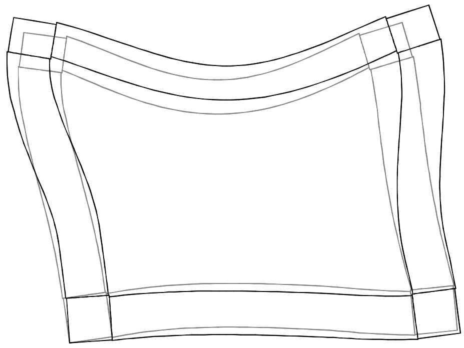

FIGURE 20 – AMPLIFIED DEFORMED MODEL SHAPE AT ROOM TEMPERATURE AND AFTER 120 MINUTES OF FIRE EXPOSURE.

CONCLUSIONS

An efficient, design oriented, approach is proposed within the present work to describe complex physical phenomena such as the evolution of structural response under fire exposure for reinforced concrete tunnels. Starting from the application of a normalized fire curve in the time domain, proper thermal and mechanical properties are assigned to steel and concrete, in order to capture a realistic response.

Numerical simulation can be considered as the most effective way to handle fire design tasks for general geometries. Scale models are difficult to set up for these problems and analytical correlations, useful for design, are therefore limited. International standards are becoming, on the other hand, very demanding on analysis of increasing complexity and rigorous models must be created to be fully compliant to code requirements.

The results obtained can be considered as a starting point towards strength optimization procedures for new tunnels and at the same time they offer a time effective tool for a fire certification of existing structures. Furthermore, for revamping of existing tunnels, the developed procedure can be useful to minimize the cost related to the installation of protective layers.

ACKNOWLEDGMENT

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