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Calculation of a Tunnel Cross Section Subjected to Fire

with a New Advanced Transient Concrete Model for Reinforced Structures

U. Schneider, M. Schneider, J.-M. Franssen

The paper presents the structural application of a new thermal induced strain model for concrete – the TIS-Model. An advanced transient concrete model (ATCM) is applied with the material model of the TIS-Model. The non-linear model comprises thermal strain, elastic strain, plastic strain and transient temperature strains, and load history modelling of restraint concrete structures subjected to fire.

The calculations by finite element analysis (FEA) were done using the SAFIR structural code. The FEA software was basically new with respect to the material modelling derived to use the new TIS-Model (as a transient model considers thermal induced strain). The equations of the ATCM consider a lot of capabilities, especially for considering irreversible effects of temperature on some material properties. By considering the load history during heating up, increasing load bearing capacity may be obtained due to higher stiffness of the concrete. With this model, it is possible to apply the thermal-physical behaviour of material laws for calculation of structures under extreme temperature conditions.

A tunnel cross section designed and built by the cut and cover method is calculated with a tunnel fire curve. The results are compared with the results of a calculation with the model of the Eurocode 2 (EC2-Model). The effect of load history in highly loaded structures under fire load will be investigated.

A comparison of this model with the ordinary calculation system of Eurocode 2 (EC2) shows that a better evaluation of the safety level was achieved with the new model. This opens a space for optimizing concrete structure design with transient temperature conditions up to 1000 °C.

Keywords: Material model, transient thermal strain, thermal creep, tunnel, concrete, fire.

1 Introduction

Calculations to prédict the deformation rate and load bearing capacity of concrete structures at high temperatures are often based on material models according to the model of Eurocode 2 (EC2-Model). In Europe, most calculations of structures are based on this model. The model is very usable and provides a high level of safety for members under bending and standard fire test conditions. It has not been tested for natural fire conditions which include decreasing temperature conditions.

The load bearing capacity of concrete structures can be optimized with models representing transient material behaviour. Models which are approximated by transient data are more realistic. The following investigation describes the potential when using a new transient concrete model. This model considers thermal induced strain with external load or internal restraint load during heating up. For this model, a realisation of all components of concrete strain is needed. The concrete behaviour is influenced by transient temperature and load history.

A material model for calculation of siliceous concrete is given in [1]. This new model is based on the Thermal-Induced-Strain-Model (TIS-Model) and is called the Advanced Transient Concrete Model (ATCM). Transient conditions during the whole calculation routine are taken into account. The transient load and the real temperature development are considered. Generally, an ATCM can be used for all types of concrete; only some parameters have to be changed. This examination is based on ordinary concrete with siliceous aggregates.

The general calculation method is divided into thermal and mechanical analyses, which are normally nonlinear. Using this model, Finite Element Analysis (FEA) is applied to the calculation [2]. In order to determine the time / temperature curves within the concrete, the thermal equation is solved with the inclusion of heat transfer through thermal analysis [3]. Mass transports can also be included, because during fire exposure many phase transitions of the cement stone matrix and aggregate appear [4, 5]. These thermally conditioned physico-chemical variables can have influences on the mechanical model [6, 7, 8]. The mechanical analysis is based on these results. There are numerous models available for determining the behavior of ordinary concrete at high temperatures [9, 10, 11]. In regard to this, there is also high dependency on the type of concrete, used as studies for ultra-high performance concrete have shown (UHPC) [12, 13].

In a first step, the behaviour of small cylinders with siliceous concrete is calculated. The results are obtained using an ATCM, which determines all local stresses and mechanical strains considering the whole cross section. These results are based on measured results according to [14]. In addition, a calculation of restraint stresses is given. The FEA considers different material behaviour which allows all results obtained with the new model to be compared with the results of calculations obtained with the EC2-Model, which is widely used in Europe.

The two concrete models, the EC2-Model and ATCM based on material properties according to TIS-Model (see equation (1), show a very different behaviour for deformation and restraint stresses during calculation. The influence of the load during heating is essential.

The calculations with simple structures show a good approximation between calculation results and measured data [15].

The good adaptation of the new ATCM to measured data gives hope for a good adaptation in the calculation of complex structures. A cut and cover rectangular-shape reinforced concrete tunnel is calculated with the new model in the following sections.

2 Generals and calculation results with concrete models

2.1 General TIS-Model

It is generally agreed that the total strain ε_{tot} comprises the following parts:

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{pl} + \varepsilon_{tr} + \varepsilon_{th}, \tag{1}$$

where ε_{tot} total strain, ε_{el} elastic strain, ε_{pl} plastic strain, ε_{tr} total transient creep strain, ε_{th} thermal dilatation.

It is therefore convenient to write for the pure mechanical strain:

$$\varepsilon_{m} = \varepsilon_{el} + \varepsilon_{pl} + \varepsilon_{tr} = \varepsilon_{tot} - \varepsilon_{th}. \tag{2}$$

During an isothermal creep test the following types of deformation occur, see Fig. 1.

According to [17], in this case the term is called "load inducted thermal strain". It consists of transient creep (transitional thermal creep and drying creep), basic creep and elastic strains. The shrinkage during the first heating is accounted for by the observed thermal strain (load 0 %).

Fig. 2 shows a general evolution of the total strain for specimens under different constant loads during heating up, based on the TIS-Model. The high influence of load during transient heating is to be seen. The elastic strain is very small at temperature $T = 20$ °C compared to the high deformation at high temperatures.

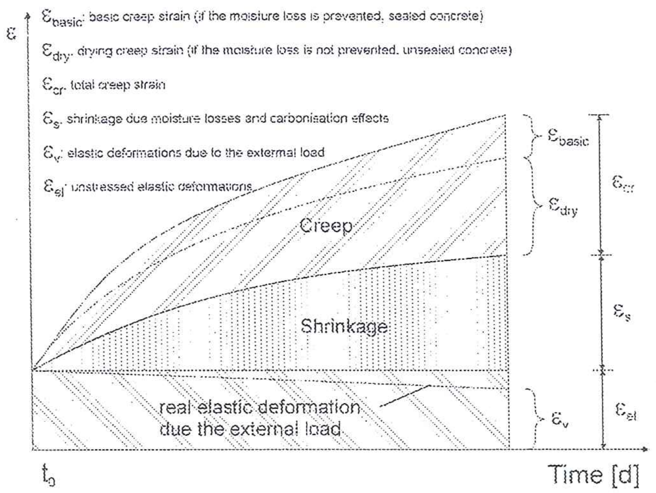

Fig. 1: Deformations of concrete at ambient temperatures subjected to a constant compressive load, according to [16]

It is concluded that the irreversible character of the main material properties must be incorporated in a calculation model to ensure a realistic consideration of the behavior of concrete.

2.2 Calculation of total strains with the ATCM and EC2 Method

2.2.1 Model parameters for calculation of total strains with the EC2 and ATCM Method

The specimens are cylinders 80 mm in diameter and 300 mm in height. The heating rate is 2 K/min. The compressive strength at 20 °C is 38 MPa. The moisture content is

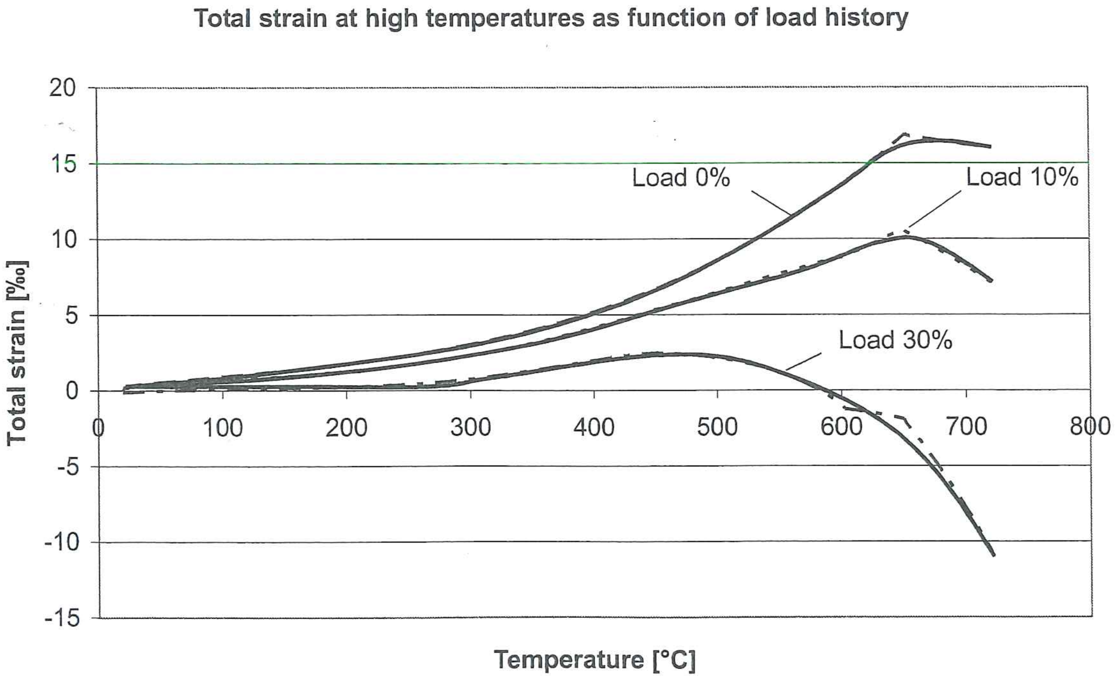

Fig. 2: Total strain at high temperatures as a function of load history

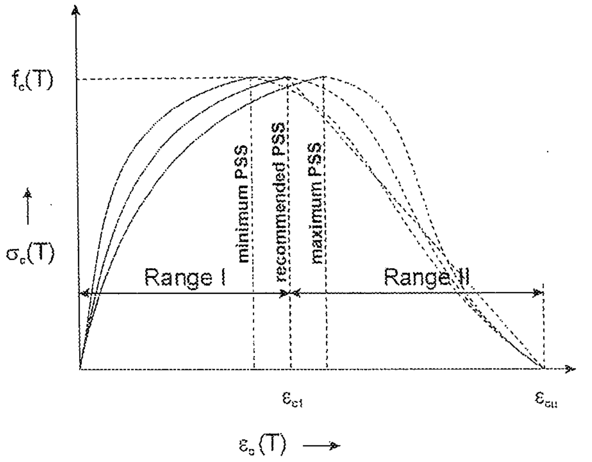

Fig. 3: Stress strain relationship subjected to fire, according to EC2 [18]

$w = 2$ %. The results are obtained from heated specimens under different stress-time relationships [14].

In the advanced transient concrete model (ATCM), the TIS-Model is used. The FEA uses a model taken from Eurocode 2 with a stress-strain constitutive model with minimum, recommended and maximum values of the peak stress strain. The minimum value of the peak stress strain (PSS) is nevertheless not considered further, because the results are at a very negative side compared to the other models. Fig. 3 shows the different peak stress strain values.

The concrete behaviour shows a different Young's Modulus during heating: the higher the PSS, the smaller the Young's Modulus. The practical relationship according to the measured data is not shown in Eurocode 2. The stress-strain relationship in Eurocode 2 is also used for a normative temperature condition, according to ISO 824 (ISO fire curve).

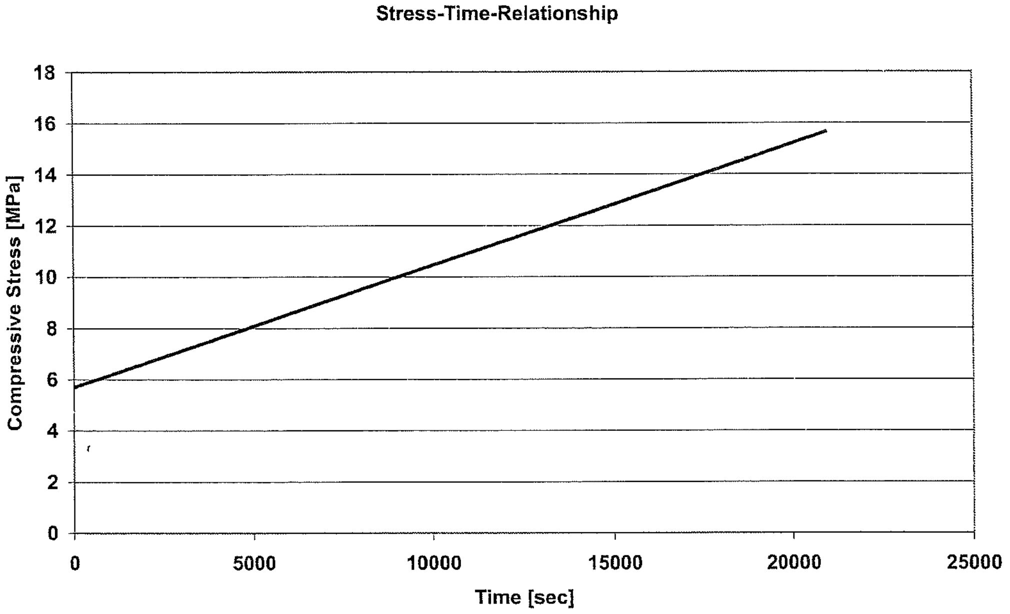

Fig. 4: Stress-Time Relationship with constantly increasing load

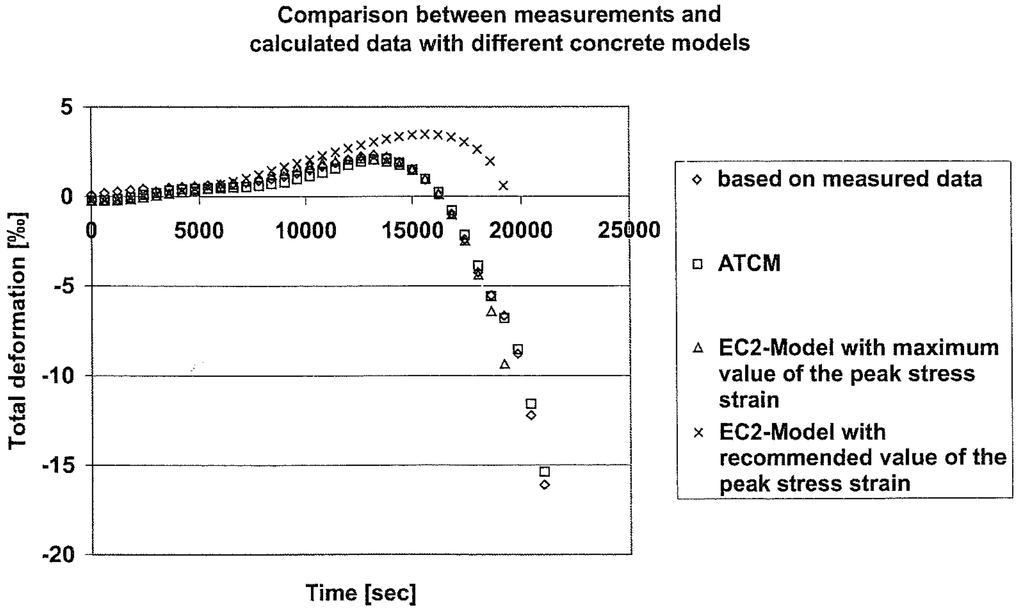

Fig. 5: Comparison of measured and calculated total strains under an applied load function according to Fig. 4

2.2.2 Results of measurements and calculations of total strains with an ATCM and EC2 Model

The calculation is done with different load functions during heating. The ATCM method is also well approximated for the mechanical strain according to measured data according to [14]. Fig. 4 shows the load function as stress-time relationship of a constant increasing load. A comparison between the ATCM method and the EC2 calculation is shown in Fig. 5.

The ATCM with the TIS-Model are very well approximated with the measured based data. The result of the calculation with the EC2 Model with the maximum PSS value is generally as good as the value approximated by ATCM. The calculation with the recommended value of PSS is totally different above 3.5 h.

Fig. 6 shows the evolution of stress as a function of time that has been considered, with a linear increase until 15000 seconds and a linear decrease thereafter. Fig. 7 shows the results of the comparison.

The EC2 Model with the maximum value of PSS and the FEA with the ATCM approximated very well, as did the result of the calculation with EC2-Model considering the maximum value of PSS. The calculation with the EC2 Model with the recommended value of PSS generally has more deformation than the other calculations.

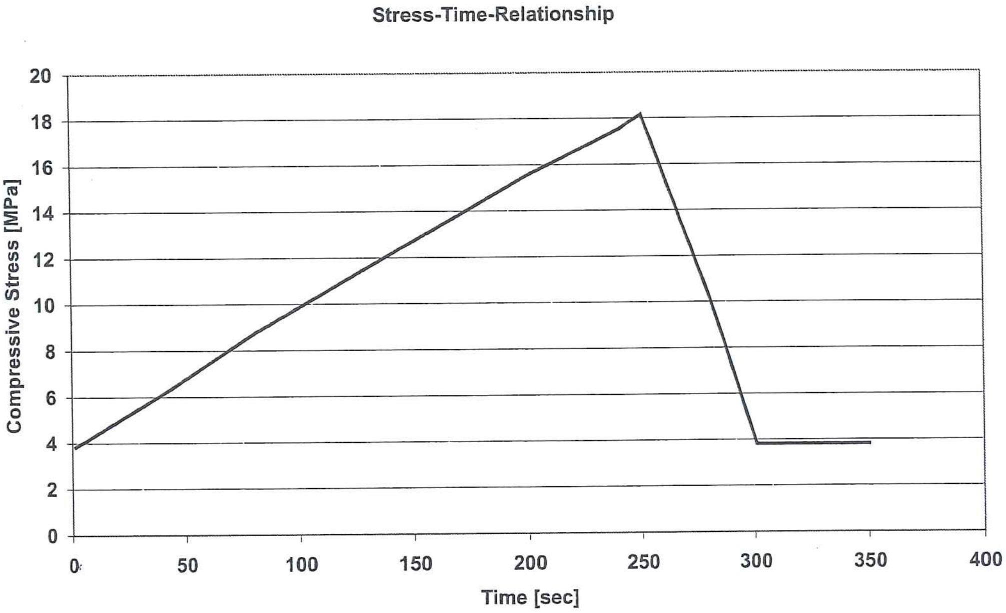

Fig. 6: Stress-Time Relationship with continuously increasing load with continuous decreasing above 15000 seconds

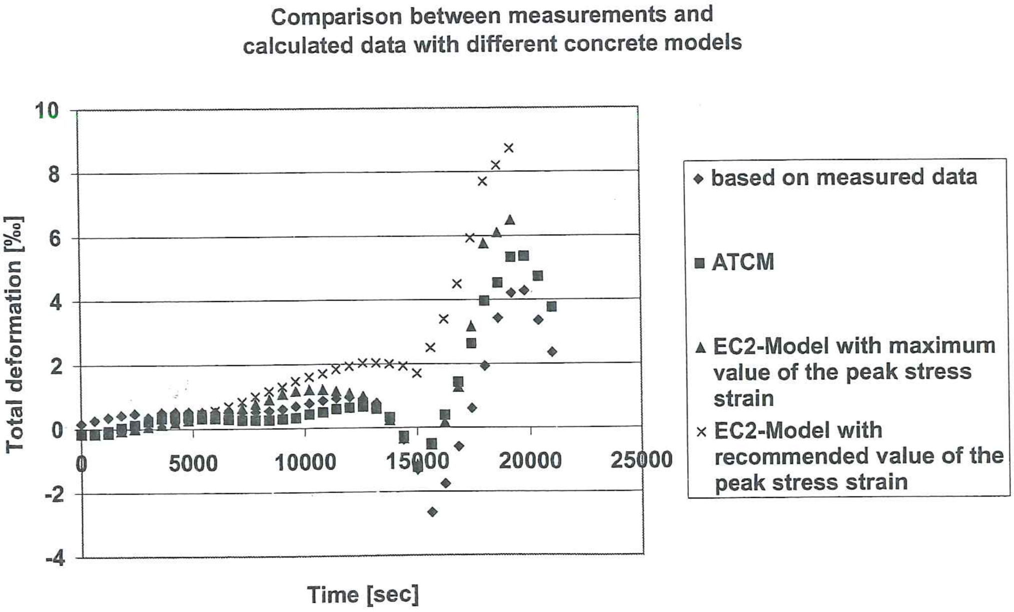

Fig. 7: Comparison of measured and calculated total strains under an applied load function according to Fig. 6

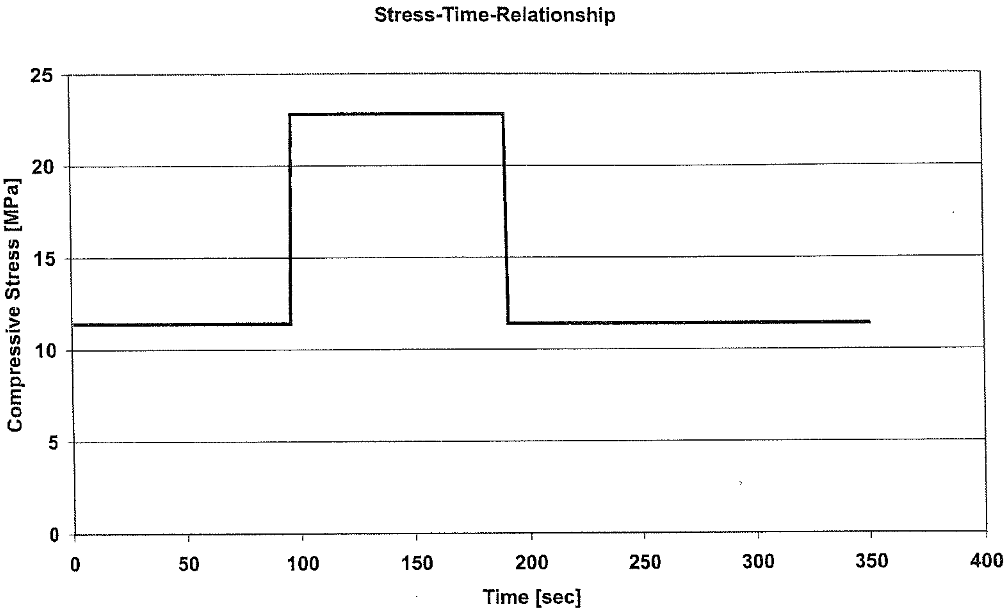

Fig. 8: Stress-Time Relationship with a sudden increase of the load and a sudden decrease till the origin

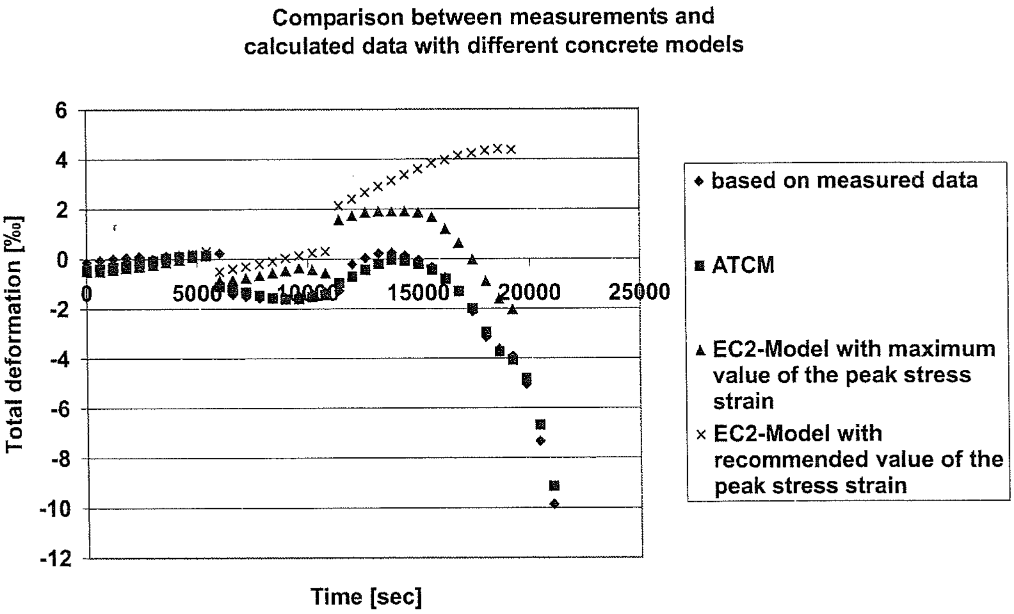

Fig. 9: Comparison of measured and calculated total strains under an applied load function according to Fig. 8

The load function as a stress-time relationship with stepwise application of the load and stepwise unloading is given in Fig. 8. A comparison between the different models is shown in Fig. 9.

The approximation between the two compared calculation methods with the ATCM is comparatively good. However, a much higher difference between the total strains calculated with the ATCM and the EC2 Model with the maximum PSS value is observed. The result of the calculation with the EC2 Model with the recommended value of PSS is significantly different from the calculations with the ATCM and from the test results.

Fig. 10 shows the load function as a stress-time relationship with 3 increasing load steps and 3 decreasing load steps. Fig. 11 shows a comparison between the different calculation models.

The differences generally increase between the calculations with the EC2 Model and ATCM. The calculations with the ATCM are a good approximation of the test results. The EC2 models, whatever value of PSS is chosen, do not allow deformations to be calculated under a load function with a complex stress-time-relationship. For this calculation, ATCM must be used.

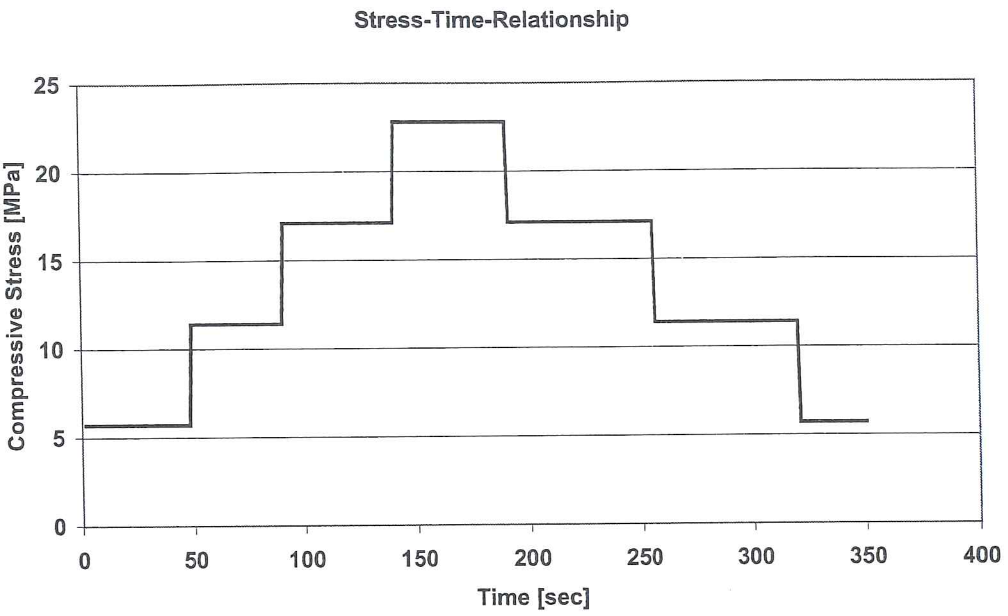

Fig. 10: Stress-Time Relationship with 3 sudden increases in load and 3 sudden decreases till the origin

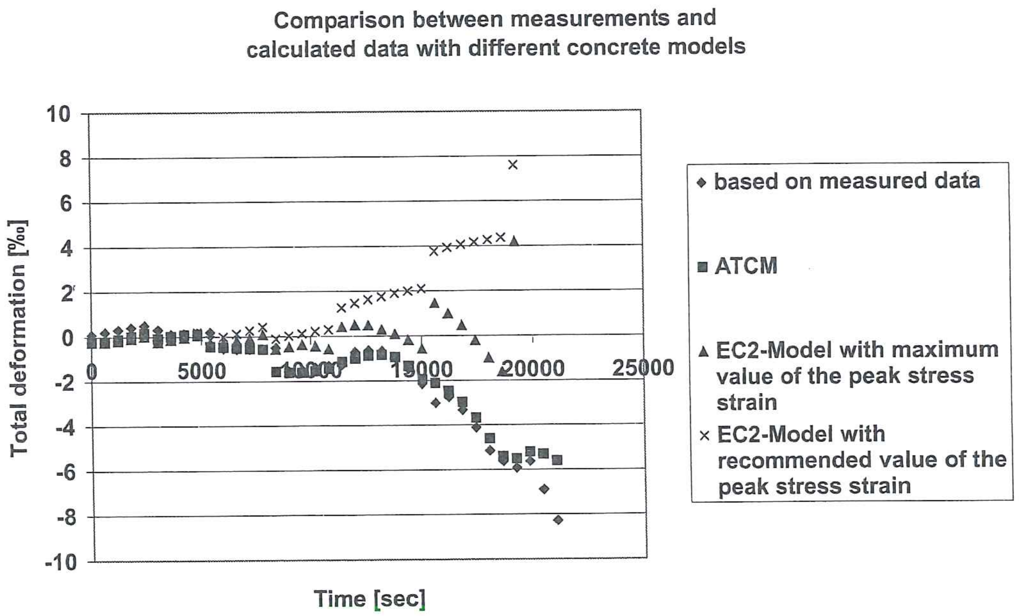

Fig. 11: Comparison of measured and calculated total strains under an applied load function according to Fig. 10

2.3 Calculation of restraint axial force of a specimen under restraint condition

2.3.1 Model parameters calculation of restraint axial force under restraint condition

The specimens are calculated with the ATCM and the EC2 Model under restraint conditions and with a heating rate of 2 K/min. The restraint deformation applied at the beginning of the calculation is kept constant during heating up.

The specimens are cylinders 80 mm in diameter and 300 mm in height. The cube compressive strength of the siliceous concrete at 20 °C is 20 MPa and it has a moisture content of $w = 2$ %.

2.3.2 Calculation results of restraint axial forces for a heated specimen which is fully restrained

The following figures compare the results of the calculation with the ATCM with measured data taken from [14]. Fig. 12 shows the restraint axial forces during heating with a load factor of 0.3. The measured data is based on different storage conditions during curing.

The curve of the ATCM is below the data of 105 °C dried concrete specimen till 300 °C and near the standard cured concrete ($w = 2$–4 %). Above a temperature of 300 °C, the curve of the ATCM is close to the curve of the water stored specimen. The curve of ATCM lies in the confidence interval of all curves. Fig. 13 shows the ratio of restraint axial force di-

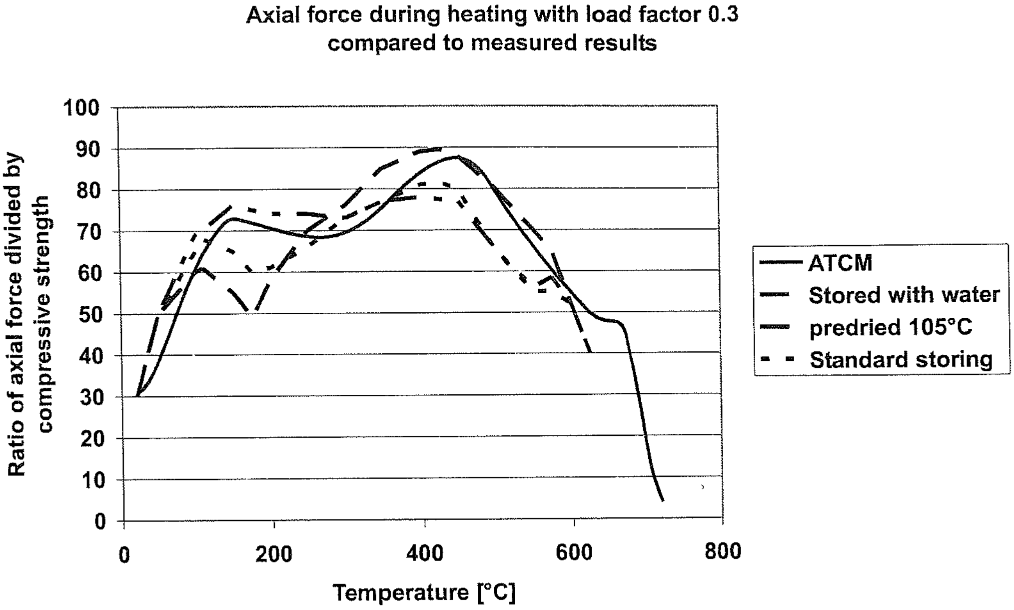

Fig. 12: Restraint axial force during heating with a load factor 0.3 compared to measured results

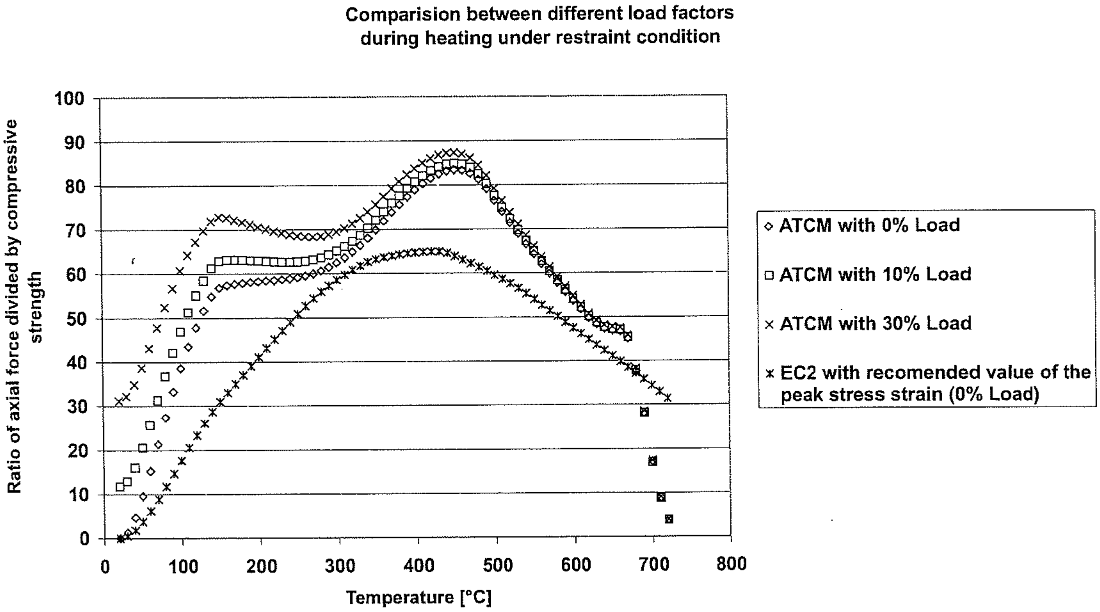

Fig. 13: Comparison of restraint forces for different load factors

vided by compressive strength. The figure compares the restraint axial forces under different load conditions. The EC2 Model is a stress-strain constitutive model without considering the load factor, i.e. it does not yield a good simulation result for restraint.

At a temperature less than 420 °C the different load conditions indicate different restraint axial forces. Above 420 °C the curves are nearly identical. The higher the load level, the higher are the restraint axial forces.

The lines of the calculation with the EC2 Model do not give a good approximation to the results of the ATCM. From the experimental result of Fig. 12 we come to the conclusion that EC2 Model simulations do not give a good approximation of the measured values. The restraint axial forces are significantly lower than the measured data.

Since the axial stress has a significant effect on the fire resistance of building elements according to [19], a realistic simulation is important for loaded structures.

2.4 Calculation of a tunnel cross section

2.4.1 Model of the calculation of a tunnel cross section

In general, calculation methods have two separate arithmetic steps: a thermal analysis and a mechanical analysis. For further information, please see the references [17, 20, 21]. The calculation model was divided into the following parts of the structure, see Fig. 14.

- ground plate
  - BEAM 01 = symmetric axis of the cross section at node 1
  - BEAM 12 = mid-point between BEAM 01 and BEAM 20 at node 20
  - BEAM 20 = corner between ground plate and wall at node 41
- wall
  - BEAM 23 = corner between wall and ground plate at node 41
  - BEAM 36 = point of maximum bending moment at node 75
  - BEAM 49 = corner between ceiling and wall at node 97
- ceiling
  - BEAM 49 = corner between wall and ceiling at node 97
  - BEAM 60 = mid-point between BEAM 49 and BEAM 71 at node 120
  - BEAM 71 = symmetric axis of the cross section at node 143

In the following example, a single-bay frame is calculated. It is a model of a tunnel taken from a research project, shown in Fig. 14 [22].

The simulation calculates a tunnel cross section with an exposition of a HCI curve [23].

Derived from the Hydrocarbon curve, the maximum temperature of the HCI curve is 1300 °C instead of the 1100 °C standard HC curve. Fig. 15 shown the time-temperature relationship. Such fires may occur in accidents involving tank trucks [7, 24].

The arithmetic model is based on a section 1 meter in width [25]. General calculations utilize the semi-probabilistic concept of Eurocode 1 [17, 26].

The bedding is considered with the help of a spring component under every beam element of the ground plate [27]. The material used here is ordinary siliceous concrete C25/30 and steel BSt500.

The heating is calculated for transient heating. Before the structure is subjected to fire, the basic combination must be used to determine the amount of reinforcement that is to be used for comparison purposes during the fire exposure. It is assumed that no spalling occurs during the fire.

2.4.2 *Results of the calculation of a tunnel cross section*

Figs. 16 to 17 show the results of the deformation with the EC2 Model with the maximum PSS value, and with the ATCM.

The various displacements demonstrate how the whole structure responds during heating. The stiffness of the system changes as a function of time [28, 29].

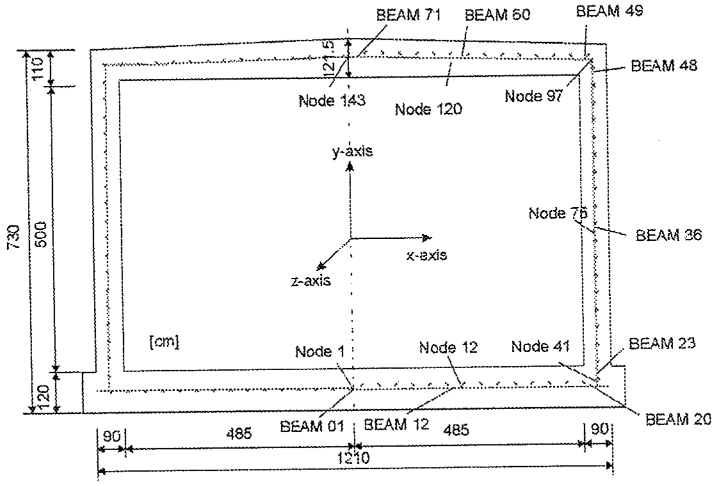

Fig. 14: Principle sketch of the tunnel; according to [22]

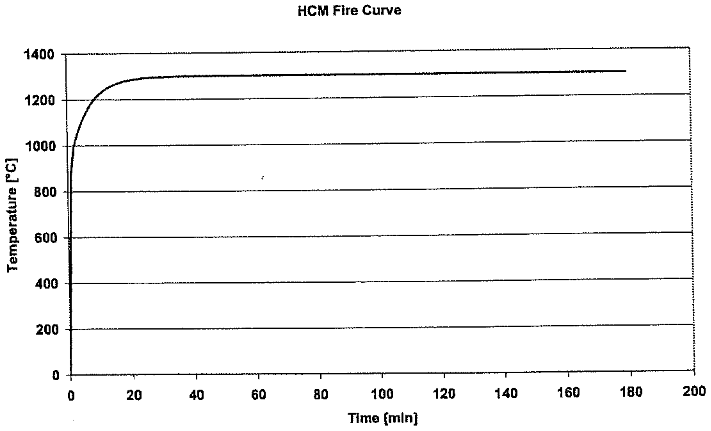

Fig. 15: Hydro Carbon Increased fire curve according to [7]

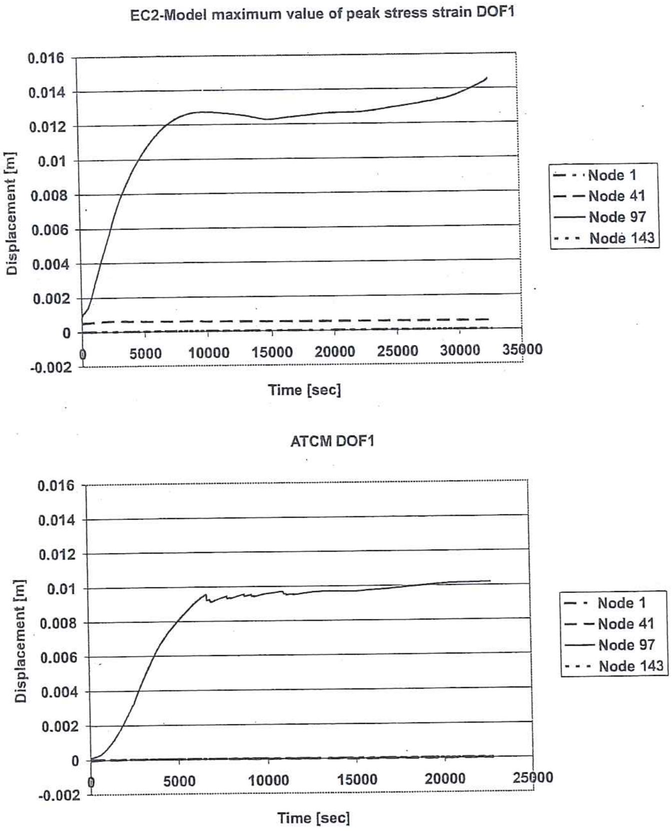

Fig. 16: Displacement in the *x*-axis in various nodes

Most of the deformations show a lower deformation with ATCM. Only in node 1 is the deformation in y-axis slightly larger with ATCM than with the EC2 Model. These results show the effect of the higher load utilisation of the new model. Without considering the load history, the influence of the load under temperature exposure is not sufficiently reflected in the calculation of the deformation of the structure. The next figures show the mechanical properties of the strucure with respect to the axial forces and the bending moments.

Figures 18 to 23 show a comparison between the mechanical results.

The axial forces of the ground plate, the wall and the ceiling are generally higher according to simulations with the EC2 Model compared to simulations with ATCM. Due to the lower deformation in ATCM, lower axial forces occur. An insignificant difference between the two models is seen in the calculation of the bending moment. Positive bending moments are lower with ATCM than with the EC2 Model. Negative bending moments are higher with ATCM than with the EC2-Model.

3 Discussion of the results

To calculate the load bearing capacity and the behaviour of structures subjected to fire, new material equations for the most important material properties of ordinary concrete have been developed [1, 15]. This model was developed to supplement the existing concrete model of EC2 with respect to the transient thermal creep and the effect of the load history. With this new model we can consider the load history in all phases of thermal exposure. With this complex model, we can calculate the total strain, taking into account a wide range of variations of load history and temperatures. Different parts of deformations are approximated with discrete equations inter-

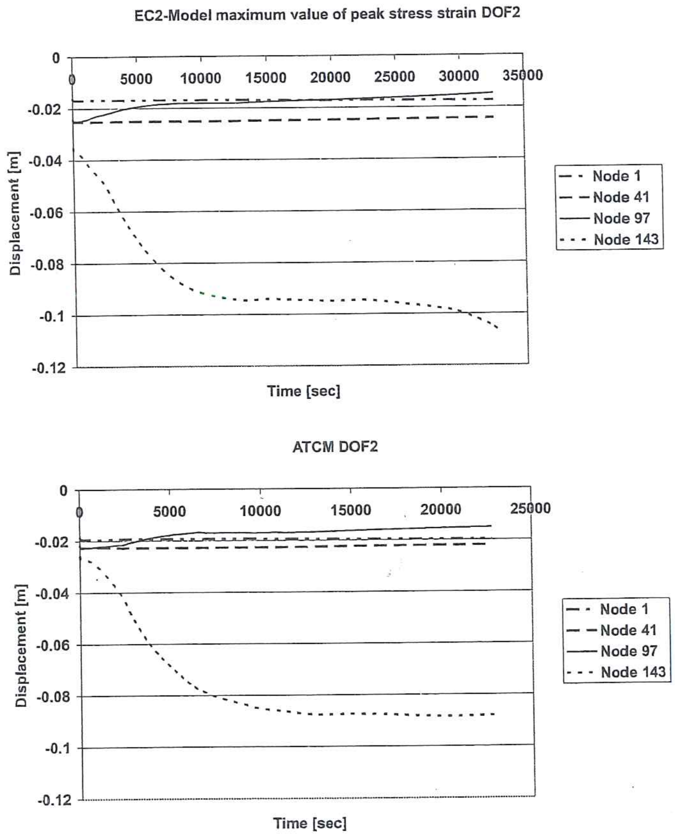

Fig. 17: Displacement in the *y*-axis in various nodes

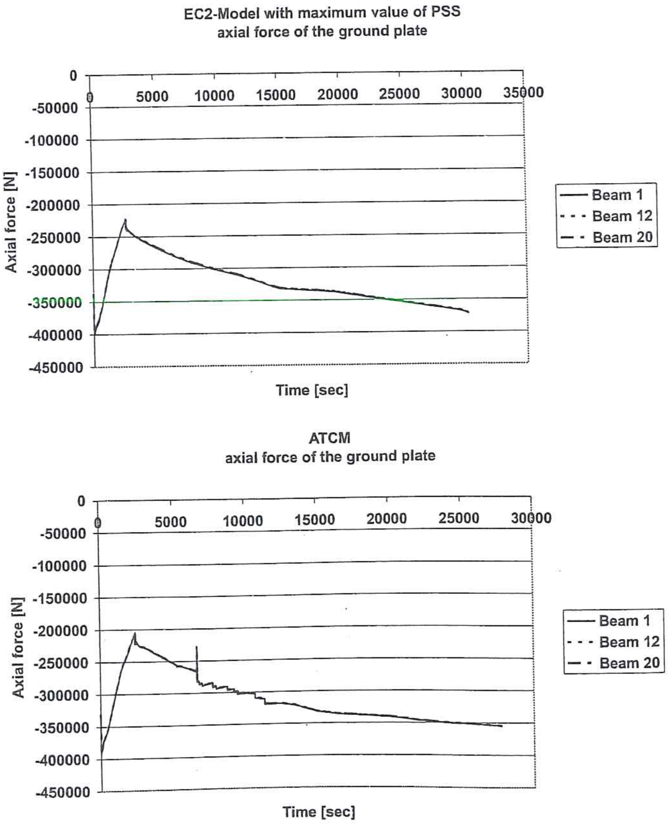

Fig. 18: Axial forces in various beams in the ground plate

acting in the new concrete model. This technique can be used for realistic calculations of the behaviour of structures [30, 31, 32], especially in the case of restraint.

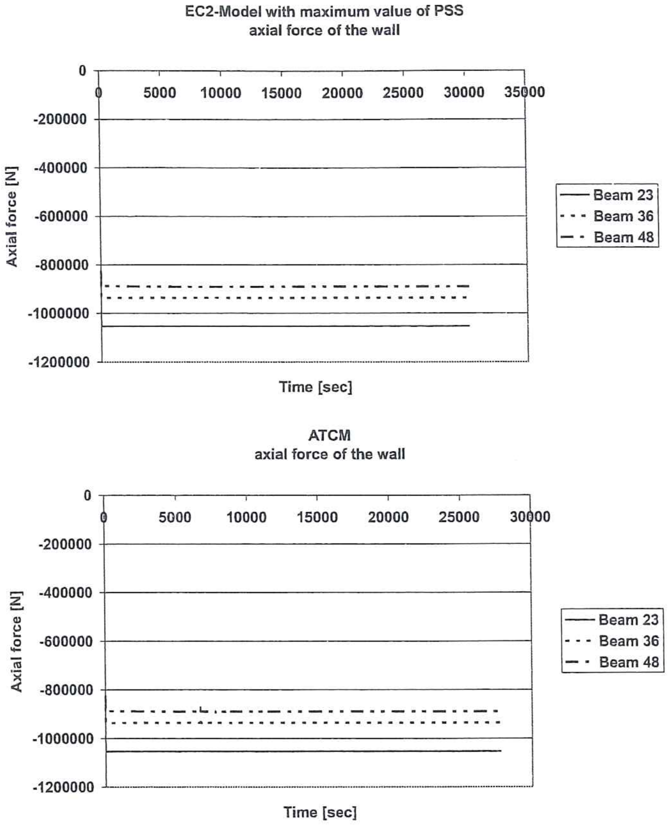

Fig. 19: Axial forces in various beams in the wall

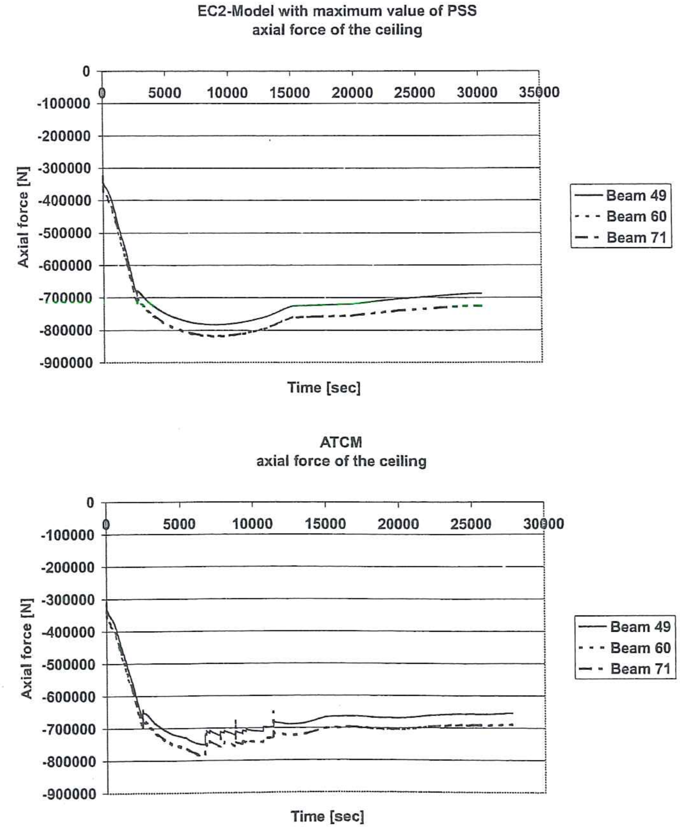

Fig. 20: Axial forces in various beams in the ceiling

By considering the load history during heating up, an increasing load bearing capacity due to higher stiffness of the concrete may be obtained in several cases. With this model,

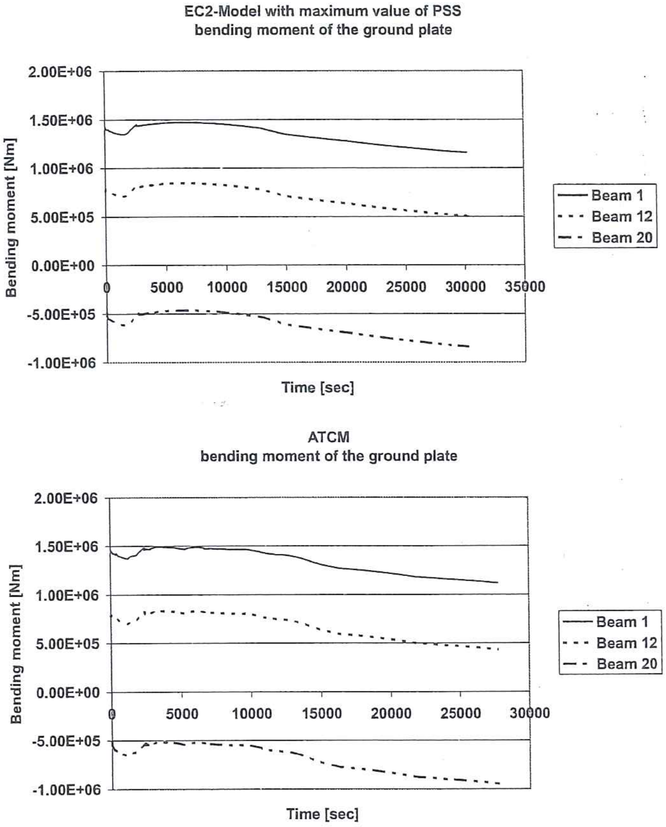

Fig. 21: Bending moments in various beams in the ground plate

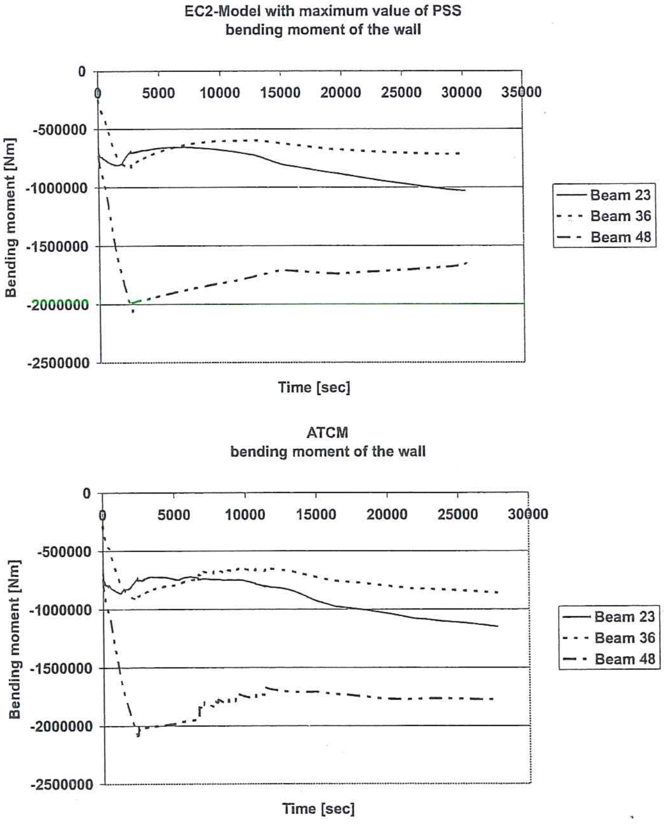

Fig. 22: Bending moments in various beams in the wall

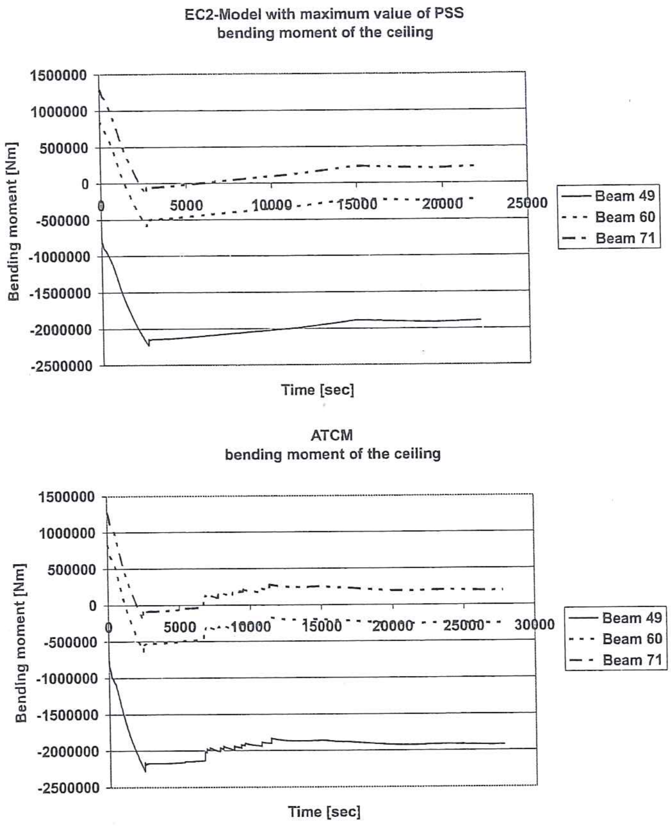

Fig. 23: Bending moments in various beams in the ceiling

we can consider the thermal-physical behaviour of material properties for the calculation of reinforced concrete structures. Application of this model, instead of the calculation system of EC2, will lead to a better evaluation of the safety level. This opens a space for optimizing reinforced concrete structures under temperature exposure.

A calculation of a tunnel cross section of a cut-and-cover single bay frame was performed and presented above. Lower deformations are calculated in all parts of the structures using the new Advanced Transient Concrete Model (ATCM). Due to this lower deformation, there is a lower axial force during heating.

The results of the calculation of the bending moments show a lower moment on the inside of the tunnel surface and a higher bending moment outside of the tunnel, if we compare the results of ATCM with those of the EC2 Model. The differences between the calculations are very small. Here we do not observe a significant difference in this structure when using the new model of concrete.

4 Conclusion

It has been shown that the recommended model of EC2 does not calculate realistic values of deformations of concrete structures under high temperature, when compared with the results of the Advanced Transient Concrete Model (ATCM), which is based on measured data. A maximum value of peak stress strain is necessary for a relatively realistic description of the behaviour of the structure. For calculation of tunnels with concrete with siliceous aggregates, the EC2 Model should be taken with the maximum value of the peak stress strain. For calculating a higher load bearing member, ATCM should be applied. Note that the full concrete behaviour is used in the structure only with the TIS-Model with the equations of ATCM.

Calculation with ATCM has a high potential for optimizing concrete structures, higher than the EC2 Model. The reliability of the load bearing capacity is higher with ATCM, because the deformations are lower than with the EC2 Model. The calculated axial forces with ATCM are with the EC2 Model are close to each other.

A potential is observed for more detailed calculations of complex structures. In the concept of structures it may be applied with lower safety factors, i.e. lower excess charges may be used in the design.

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Ulrich Schneider
e-mail: ulrich.schneider+e206@tuwien.ac.at

Martin Schneider b,
e-mail: e0527948@student.tuwien.ac.at

University of Technology Vienna
Karlsplatz 13/206
1040 Wien, Austria

Jean-Marc Franssen
e-mail: jm.franssen@ulg.ac.be

University of Liège
1, Ch. des Chevreuils, 4000, Liège, Belgium