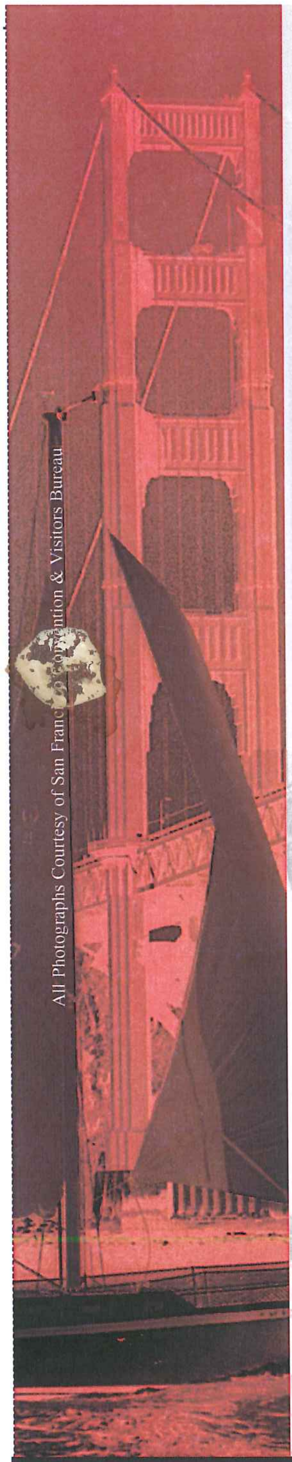
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NUMERICAL EVALUATION OF LOAD INDUCED THERMAL STRAIN IN RESTRAINT STRUCTURES COMPARED WITH AN EXPERIMENTAL STUDY ON REINFORCED CONCRETE COLUMNS

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Abstract

This paper presents a new thermal induced strain model for concrete (TIS-Model) [1]. The non-linear model comprises thermal strain, elastic strain, plastic strain and transient temperature strains as well as load history which means that, as a consequence, the modelling of restrained concrete structures subjected to fire is possible.

Calculations of simple elements, namely columns, were done by FE method using the structural code SAFIR [2] in which the material model using the new transient TIS-Model has been incorporated. This code is suitable to calculate complex structures with different material models.

The behaviour of reinforced columns with a constant load during heating and cooling was calculated. The results are compared with the results of measured data related to different mixtures of siliceous concrete with compression strength lower or equal than 50 MPa.

The calculations showed a good correlation between the TIS-Model and measured data. In addition, a comparison between results using the Eurocode 2 (EC2) material model and the TIS-Model for concrete structures is given. It was shown that there are differences in the results of structure calculations with both models.

The influence of high compressive stresses in concrete section is very high, because the creep strains for transient temperature condition indicates a significant influence of the thermal induced strains. The Eurocode doesn’t consider this behaviour explicitly. According to our results, the time of failure is shorter using the EC2-Model for concrete members under high compressive load or restraint compared to the TIS-Model.

1 Introduction

Calculations to predict the deformation rate and load bearing capacity of concrete structures at high temperatures are often based on material models according to EC2. In Europe most of the 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.

The load bearing capacity of concrete structures can be optimized with models representing a 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 constant external 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 siliceous concrete is given in [1]. This model is called "Thermal-Induced-Strain-Model" (TIS-Model) and transient conditions during the whole calculation routine are taken into account. The transient load and the real temperature development are considered.

Generally the TIS-Model can be used to represent the results of specimens of every type of concrete. This examination is based on ordinary concrete with a siliceous aggregate. A simple structure with a small amount of reinforcement seems appropriate to show the effect of a concrete model considering transient conditions.

In the report we calculate simple structures as columns to show the effect of the TIS-Model compared to calculations according to the EC2 concrete model.

2 Transient model for thermal induced strain

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

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{pl} + \varepsilon_{tr} + \varepsilon_{th} \qquad (1)$$

The thermal strains is a function different aggregates as shown in Figure 1.

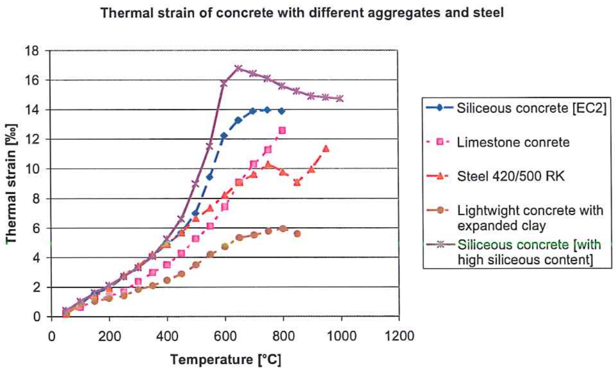


Fig. 1 - Thermal strain of concrete with different aggregates and steel; according to [3; 4].

To calculate the mechanical strain, a load factor is introduced. This factor is calculated as follows:

$$\alpha = \frac{\sigma_{hist}}{f_c(20°C)} \qquad (2)$$

σ_{hist} is the time dependent compression stress due to external loads. In this report the load level α was kept constant during fire exposure. This factor represents the load history and is used for structures which are loaded in the elastic range $\alpha = 0.3$, whereas some researchers adopt $\alpha = 0.4$ as upper limit for the application of this method.

Figure 2 shows the reduction of compressive strength as a function of temperature for different load histories compared to measurements [3]. $f_c(20°C)$ is an experimental result for the ordinary concrete tested and cured under RILEM conditions [5].

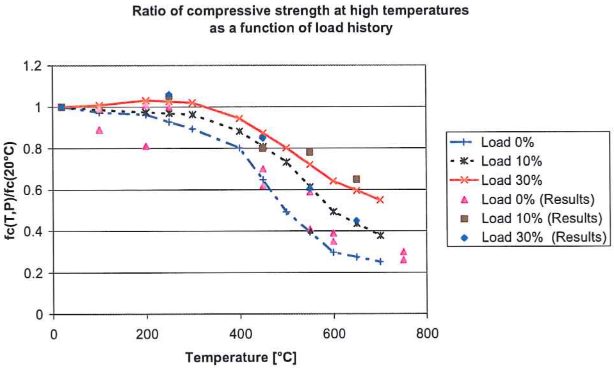


Fig. 2 - High temperature compressive strength of siliceous concrete being loaded or not loaded during heating up – experimental and calculated results, according to [3].

The Young's Modulus as a function of load history and temperature, $E(T,\alpha)$ must be measured according to RILEM [5] or National Codes with respect to the geometry of specimens being used in the high temperature range, see Figure 3.

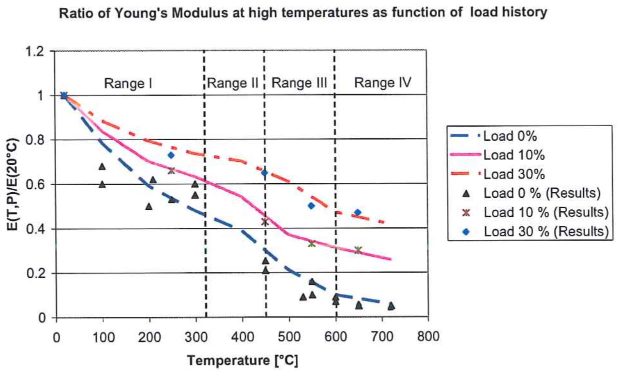


Fig. 3 - Influence of high temperature on the Young's Modulus of siliceous concrete – experimental and calculated results; according to [3].

The ultimate strain of the stress-strain relationship is also a function of temperature and α. The ultimate strain $\varepsilon_u(T,\alpha)$ is calculated as follows [10]:

$$\varepsilon_u(T,\alpha) = \varepsilon_u(20°C) + \Delta\varepsilon_u(T) * f(\alpha) \qquad (3)$$

with $\varepsilon_u(T,\alpha) \leq 7.8 * 10^{-3}$ as an upper limit for all cases (α=0).
where:

$$\varepsilon_u(20°C) = 2.2 * 10^{-3} \qquad (4)$$

$$\Delta\varepsilon_u(T) = \left[4.2 * 10^{-6} + (T-20) * 5.4 * 10^{-9}\right] * (T-20) \qquad (5)$$

$f(\alpha)$ is a function of load history. A linear interpolation is applied for intermediate values of load factor α:

$$f(\alpha) = 1\ (\alpha = 0),\ f(\alpha) = 0.227\ (\alpha = 0.1),\ f(\alpha) = 0.066\ (\alpha = 0.2),\ f(\alpha) = -0.095\ (\alpha = 0.3)$$

Two parts of the stress induced strains at high temperatures i.e. elastic and plastic strains can be included in a stress-strain relationship according to the following equations:

$$\sigma(t) = f_c(T,\alpha) * \frac{\varepsilon(\sigma(t))}{\varepsilon_u(T,\alpha)} * \frac{n}{(n-1) + \left(\frac{\varepsilon(\sigma(t))}{\varepsilon_u(T,\alpha)}\right)^n} \qquad (6)$$

where: n=3 for ordinary concrete, according to [1; 6]

with $\varepsilon_{pl}(T,\alpha) = \varepsilon\{\sigma(t), \varepsilon_u(T,\alpha), T, \alpha\} - \varepsilon_{el}\{\sigma(t), T, \alpha\}$.

Eq. 7 is used to calculate the thermal induced creep strain:

$$\varepsilon_{tr}(T,\alpha) = \frac{\varphi * \sigma(t)}{E(T)} - \varepsilon_{pl}(T,\alpha) - \Delta\varepsilon_{el}(T,\alpha) \qquad (7)$$

with: $\Delta\varepsilon_{el}(T,\alpha) = \varepsilon_{el}(T) - \varepsilon_{el}(T,\alpha)$ (8)

$\varepsilon_{tr}(T,\alpha)$ is called “thermal induced creep strain“ but the definition is different compared to [6]. The pure transient creep will not be calculated numerically within the proposed calculation procedure described above, but the exact extended relationship is given in equation (7).

The φ-function is calculated by the equation (9). It utilizes new parameters as shown in Table 1, those were obtained by recent scientific results [7; 8] based on ongoing research.

$$\varphi = C_1 * \tanh\gamma_w * (T-20) + C_2 * \tanh\gamma_0 * (T - T_g) + C_3 \qquad (9)$$

Tab. 1 - Parameters for transient creep functions of structural concretes; according to [4].

Parameter	Dimension	Quarzit concrete	Limestone concrete	Lightwight concrete
C_1	1	2.50	2.50	2.50
C_2	1	0.70	1.40	3.00

C_3	1	0.70	1.40	2.90
γ_0	°C^{-1}	7.5*10^{-3}	7.5*10^{-3}	7.5*10^{-3}
T_g	°C	800	700	600

The moisture content of concrete is taken into account using equation (10).

$$\gamma_w = 0.3*10^{-3}*w^{0.5} + 2.2*10^{-3} \text{ with } \gamma_w \leq 2.8*10^{-3} \quad (10)$$

w is the moisture content of concrete in % by weight whereby 1% < w < 4.5% [4].
Figure 4 shows the φ-function for siliceous concrete. The equation (9) above is similar to the equation for creep strain at room temperature. That is why the φ-function is called „transient creep function“ in RILEM literature [9], although it was known that φ contains in addition small parts of plastic and elastic strains [9].

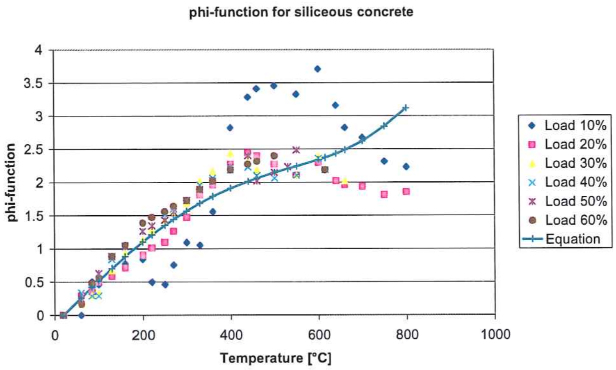


Fig. 4 - Transient creep function for siliceous concrete; according to [4].

3 FAILURE MODEL

To calculate the specimens in a concrete model with FE analysis we need a model to find the failure point. That's why the following assumption was used in the calculation.

The failure of concrete starts due to crack opening in compression, if $\frac{\sigma(t)}{f_c(T)} > 0$. On the other hand the failure of concrete may occur due to pure tensile stresses. In reality the whole stresses are transferred to the reinforcement steel and the specimens will not fail due to tensile failure of concrete. Without reinforcement the whole concrete structure fails under tension in this case. As long as we consider concrete as basic material the cracking is a dominant factor.
Cracks start directly due to the release of tensile strain and plastic deformation energy exceeding the surface crack energy. The failure may be estimated by the following criteria [10]:

- Temperature: $T_{\max} \geq T_{critical}(\alpha)$
- Deformation rate: $v(\dot{\varepsilon}_{tot}) \geq v(\dot{\varepsilon}_{critical})$

- Maximum deformation: $\varepsilon_{tot} \geq \varepsilon_{critical}$

In the case of high temperatures, concrete under different constant load fails during heating up, as shown in Figure 5.

Note that the maximum of critical concrete temperature is in the range of 850 to 950°C for loaded structures. The upper level of fatigue load at this temperature range is $\alpha = 0.1$. That means, if you heat up the concrete specimen continuously with a load factor of $\alpha = 0.1$ the specimen fails at about 900°C.

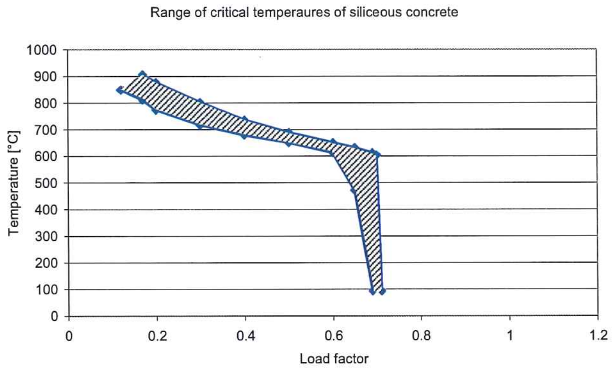


Fig. 5 - Critical concrete temperatures of siliceous concrete with constant load during heating up; according to [11].

From the test results for the total deformation strains ε_{tot} one may conclude, that the deformation rate $v(\dot{\varepsilon}_{tot})$ plays a dominant role during the simulation of transient load history. If the maximum deformation rate is exceeded, the concrete fails (range of failure see Figure 5, after [7]). That means in this case the ratio $\frac{\sigma(t)}{E(T,\alpha)}$ during heating can not be larger than the results of deformation ratio per every second. The deformation rate is shown in Figure 6. The limit of failure curve in Figure 10 presents the failure of concrete, if the deformation rate is larger than the limit curve based on the range of failure according to [7]. The observed failure rates $v(\dot{\varepsilon}_{tot})$ range from $5*10^{-4}$ ‰/s to $35*10^{-4}$ ‰/s depending on the load level and the test temperature. The failure rates are based on the crack development in concrete.

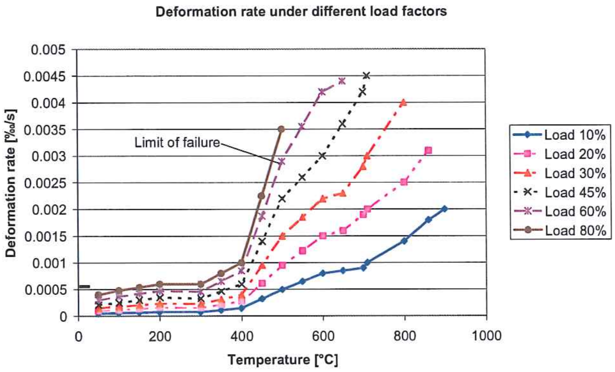
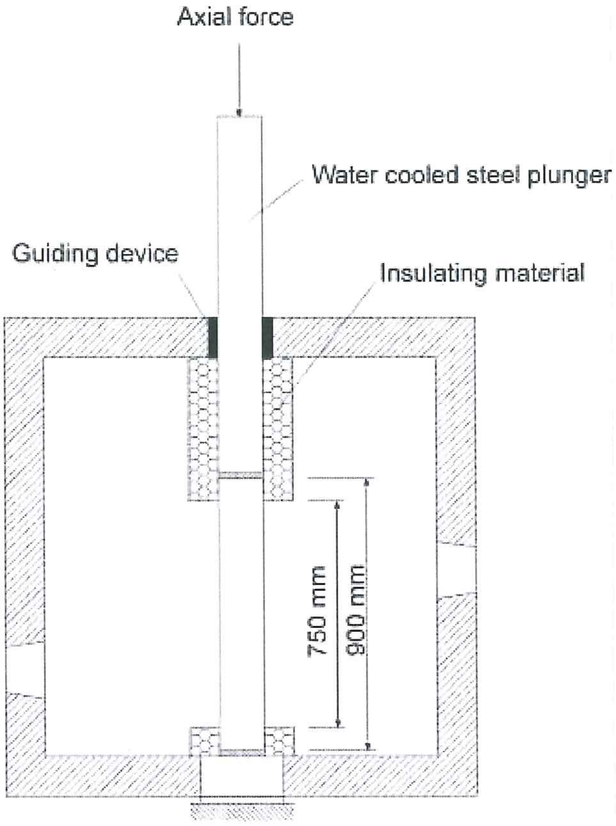


Fig. 6 - Deformation rate under different load factors during heating up; according to [6].

Cracks develop in physical-chemical conversion by thermal destruction of CSH phases in cement mortar and of crystal conversion of aggregates respectively. This phenomenas are considered to decrease the compressive strength and the critical temperature. Furthermore cracks are influenced by the kinetic parameters, such as activation energy, reaction rate of dehydration products and reaction rate of concrete aggregates which leads to the time and temperature dependent loss of strength [12]. Drying of concrete at high temperatures is also responsible for cracks [13]. In our model the shrinkage strain during heating is included in the transient thermal strain part which depends on the type of concrete (see Figure 1) [4]. The ultimate strain of ordinary concrete is considered as a function of load factor α and temperature in chapter 2. It was observed that relating the ultimate strain of loaded specimens at high temperatures just to the ultimate strain at 20°C is not sufficient. A part of the larger deformation properties is compensated by the transient creep. The ability of concrete for plasticizing at high loads is depleted, that's why the ultimate strain is unexpected low [14], whereas the total strains under failure conditions are very high.

4 Principal calculations and experimental settings

A centric loaded column was calculated with the new TIS-Model. Measured data were taken from [15] to compare the measured strains over the total length of centrically loaded columns. This is a simple model without considering the accidental excentricity of the load as recommended by EC2 for calculation of columns. But it is usable to show the effect of a calculation with the TIS-Model. The results were obtained using the test equipment shown in Figure 7 and 8.



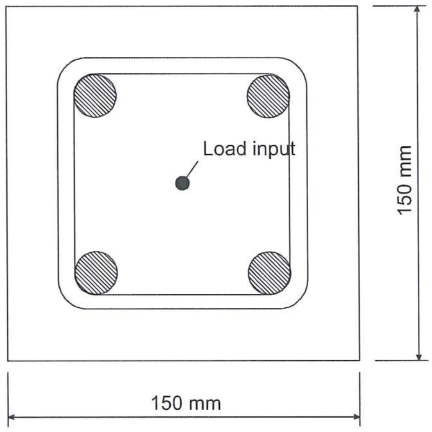


Fig. 7: Sectional drawing testing equipment

Fig. 8: Cross section of specimens

In these examples calculations based on fire exposure test in accordance to the Time / Temperature Curve ISO 834 according to [16], as shown in Figure 9.

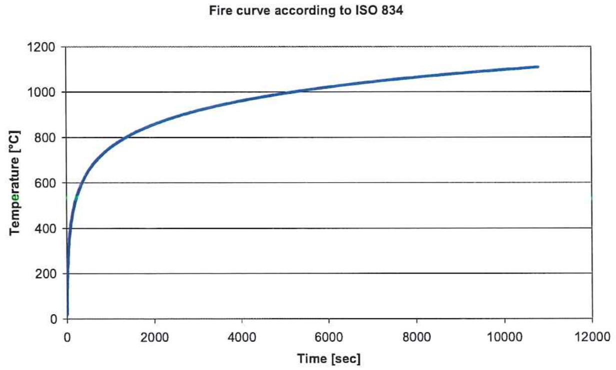


Fig. 9: Fire curve according to ISO 834 according to [16]

The measured data of thermo couples across the cross section showed reasonable results according to the fire curve. The surface of the specimens showed a temperature of 1000°C after 60 minutes. In the centre of the column the temperature reached 300°C as a maximum. The thermal analysis of the specimens with FE calculations reasonably reproduced these results, see Figure 10.

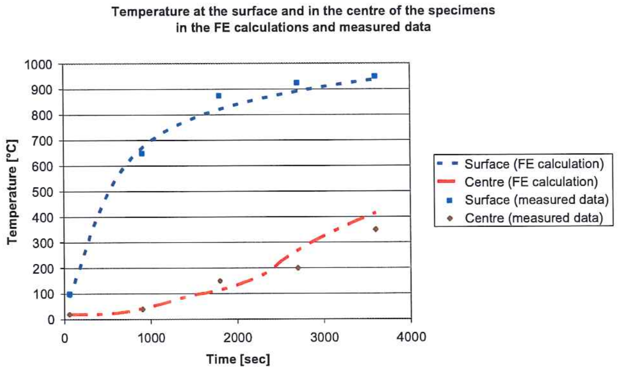


Fig. 10: Temperature curve at the surface and in the centre of the specimen

Five different specimens were tested using siliceous concrete mixtures with the following material properties (Reinforcement: 4 bars ∅ 20 mm, yield strength = 500 MPa, Stirrups ∅8 mm, Cover 20 mm). In Table 2 the mixture parameters are shown in kg/m³. Table 3 shows the material properties and the test parameter of the load.

Table 2: Mixture parameters of concrete for the mixtures 1 to 5

	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Cement content	320	320	320	320	320
Sand 0-2 mm	480	480	480	480	480
Gravel 2-8 mm	480	480	480	480	480
Gravel 8-16 mm	960	960	960	960	960
Plasticizer	10	10	14.2	10	10
Water	170	170	170	170	170
Dispersed silica	10	10	10	-	10
Dispersed micro silica	-	1.0	2.0	2.0	2.0

Table 3 shows the properties of the different concrete mixes according to standard material test at ambient temperature.

Table 3: Material properties and load during heating of the mixtures 1 to 5

	Material properties						Test parameter
Mixture	Density [g/cm³]	$f_{c,cube,dry}$ [MPa]	f_{ck} [MPa]	E_{c0m} [MPa]	E_{cm} [MPa]	Moisture [% by mass]	Load [kN]
1	2.377	66	50	36762	34251	3.6	609.2
2	2.357	60	45	35776	32963	3.7	599.4
3	2.355	59	45	35606	32745	4.1	628.6
4	2.352	46	35	33234	29821	3.2	451.9
5	2.344	55	42	34910	31865	4.0	540.8

For the tangent modulus (the modulus at zero strain) we used [8]:

$$E_{c0m} = 9500 * \left(f_{ck} + 8\right)^{\frac{1}{3}}$$

and for Young's Modulus we used:

$$E_{cm} = \left(0.8 + 0.2 * \frac{f_{ck} + 8}{88}\right) * E_{c0m} \text{ with } E_{cm} \leq E_{c0m}$$

The concrete mixtures 1 to 5 were altered using a different content fine dispersed micro silica in the mix. The model for ordinary concrete used in our investigation was developed for ordinary concrete without any modifications by addition of small amounts of dispersed silica.

5 Results

In the following figures we compare the calculation results obtained by TIS-Model, the EC2-Model (ENV with recommended and maximum value of the peak stress strain) and measured data taken from [15]. The results show the transient longitudinal strain ε_{tot} of the specimens. Between the three calculation models significant differences are observed. Note that the results show the transient longitudinal strain ε_{tot} are influenced by different thermal strains of the concrete tested compared to the TIS-Model and EC2-Model (see Figure 1). The TIS-Model considers the influence of external load during heating on the stress-strain-relationship of concrete and the transient creep effect (see Figure 2 and 3). Due to the TIS-stress-strain model the concrete indicate a wide range of compressive strains at failure, whereas the EC2-Model shows a more or less brittle type of failure.

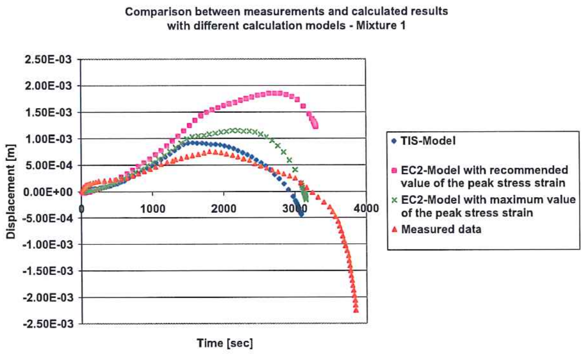


Fig. 11: Calculation results compared to measured data - Mixture 1

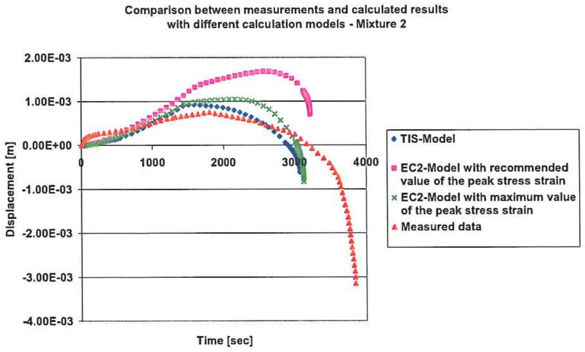
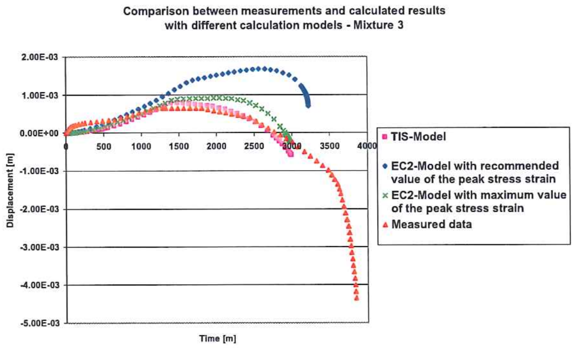


Fig. 12: Calculation results compared to measured data - Mixture 2



Picture 13: Calculation results compared to measured data - Mixture 3

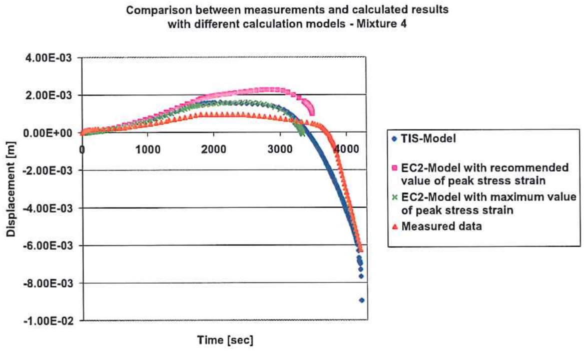


Fig. 14: Calculation results compared to measured data - Mixture 4 (without silica)

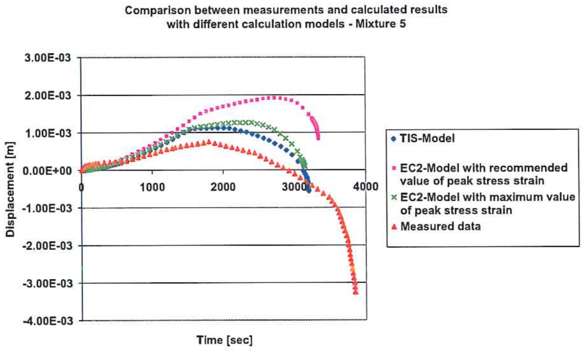


Fig. 15: Calculation results compared to measured data - Mixture 5

The measurements started after loading the columns and the calculated results were adapted to the level of deformation at that time. The result of mixture 4 gave the best approximation with respect to the measured data. For this test specimen no silica was used and the Young's Modulus is less than 30,000 MPa. The specimen with silica indicated a Young's Modulus higher than 32,000 MPa, i.e. the modulus is higher than for ordinary concrete. Generally there is a good agreement between measured and calculated results in long time behaviour of the columns.

It was found that for mixtures with higher Young's Modulus the failure in the calculation starts at a time of about 50 minutes. The simulation considers the creep part of the deformation up to this time. It should be noted that the model of concrete was originally developed for ordinary concrete with a Young's Modulus less than 30,000 MPa. With higher Young's Modulus the results of the calculation approximated the measured strains very well up to the time of 50 minutes, but the failure of the specimen starts earlier than the deformations from our material model. The current model doesn't consider the specific reduction of the compression strength of high performance concrete and uses a φ-function for the transient thermal creep strain according to ordinary concrete. Nevertheless we have obtained a very high accuracy in our calculations with the TIS-Model for ordinary concrete compared to existing structural tests of concrete with higher Young's Modulus.

The calculation with the average value of ultimate strain according to Eurocode 2 predicts a much higher strain of concrete columns compared to the measured data and the calculations with the TIS-Model. The failure behaviour of concrete with Young's Modulus higher than 32,000 MPa is close to the EC2-Model. The failure point and ultimate strain of mixture 4 is nearly identical to the calculation with the TIS-Model. Generally it is seen that the strain prediction of the EC2 is less accurate then the calculated data using the TIS-Model.

6 Outlook

The results of the simulation of loaded concrete structures subjected to fire depend significantly of the material model being used. The strain results of the TIS-Model are closer to measured data than the EC2-Model. The EC2-Model doesn't consider the transient creep of concrete. That's why the EC2-model cannot account for the total load bearing capacity of the material during the failure of specimen. It was observed that the TIS-Model provides less safety reserve than the EC2-Model with respect to the time of failure but it clearly indicates the high strain potential of the material under fire.

The results of the calculation with the TIS-Model for ordinary concrete lead to a comparatively good approximation to measured data. The tests of columns with micro silica concrete indicated a shorter fire duration compared to the calculation results of EC2-Model and TS-Model. Generally a brittle failure was observed. For concrete with higher Young's Modulus leading to earlier failure the TIS-Model worked astonishing good and it seems to us that it is possible to adopt the model easily for applications in the field of high strength concrete.

The calculation with the TIS-Model has a high potential for optimizing concrete structures, more than the EC2-Model [17] because this Model is not able to determine the total strains with high accuracy.

The TIS-Model will be applied to complex structures in further research. For instance calculations of tunnel cross sections are part of our permanent work.

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