Proceedings of the 9th International Conference on Structures in Fire (SiF 16)
8-10 June 2016, Princeton University, NJ, USA

Fire Resistance of Reinforced Concrete Columns Subjected to Standard Fire – Comparison of an Advanced and a Simplified Method

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ABSTRACT

For designing concrete columns subjected to a standard fire exposure, the Eurocode permits the use of simplified or advanced calculation methods. For the designer, the question of the respective advantages of these two types of methods arises. Which situations demand the use of an advanced method? When does a simple method provide sufficient accuracy? In this paper, laboratory tests are recalculated using Finite Element Modeling (FEM) as an advanced and Extended Zone Model (EZM) as a simple method in order to investigate these questions. The recalculations indicate that the simple EZM is of sufficient accuracy for symmetric heated columns without restraints. In contrast, the mechanical behavior of columns heated on three sides demands an advanced method such as FEM to be properly described.

INTRODUCTION

Designers who follow the Eurocode EN 1992-1-2 [1] for designing concrete members subjected to a standard fire exposure are left with several options regarding the method to apply. Among the calculation methods, they can opt for simplified methods developed for specific types of members, or for advanced methods, for instance based on Finite Element Modeling (FEM). The objective of this research is to recalculate laboratory tests on concrete columns using an advanced and a simplified method, in order to compare the respective capabilities and advantages of these methods.

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Advanced FEM requires the use of proper material models for simulating the behavior of the materials at elevated temperature. The model given in EN 1992-1-2 [1] for concrete includes the transient thermal strains implicitly, which means that these strains are assumed not to depend on the stress-temperature history. This simplification has been criticized and an advanced material model with an explicit formulation for the transient thermal strains has been proposed [2]. The parameters of the proposed stress-strain curves have been chosen to match the parameters of EN 1992-1-2 under constant compression and monotonously increasing temperature. This model is called “Explicit transient creep model” (ETC). In this paper, FEM with ETC material model is used as the advanced method for the comparative analysis. It is referred to as “ETC method”.

On the other hand, more simplified analysis methods are under development. The Zone Method proposed by Hertz has been extended [3] using the stress-strain curves from EN 1992-1-2, keeping the assumption that thermal strains can be neglected. The proposed method is called “Extended Zone Method” (EZM) and is suitable for the implementation in commercial design software.

APPLIED METHODS

Recalculated laboratory tests

Four columns from TU Braunschweig [4, 5], which have been heated on all sides, are used for recalculation. The pin ended columns have been subjected to a constant load $|N_0|$ with constant eccentricity e_0 and have been heated until failure. The parameters of the columns are given in Figure 1 and Table I.

To study the effect of unequal thermal strains, three tests performed by Anderberg [6] are also recalculated. The columns have been heated on three sides and the deformations of the columns in the mid span have been measured. The parameters of the tests are documented in Figure 2 and Table II.

The concepts of the applied methods are explained briefly in the following paragraphs. Detailed information on the assumptions and limits are given in the literature [2, 3].

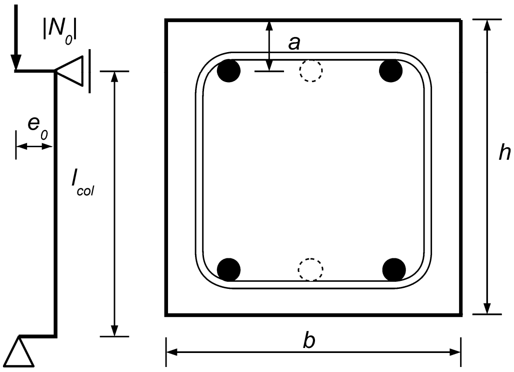

Figure 1. Structural system and cross section for the laboratory tests from TU Braunschweig

TABLE I. PARAMETERS OF TESTS FROM TU BRAUNSCHWEIG

Nr.	l_{col} **(cm)**	$b=h$ **(cm)**	$A_{s,tot}$ **(mm)**	a **(cm)**	f_c **(MPa)**	f_y **(MPa)**	e_0 **(mm)**	$\lvert N_0\rvert$ **(kN)**	t_{exp} **(min)**
SFB5	476	30	6∅20	3.8	37	462	15	740	85
SFB12	376	20	4∅20	3.8	29	487	0	420	58
SFB13	376	20	4∅20	3.8	29	487	0	420	66
SFB46	470	30	6∅20	3.8	38	526	150	465	50

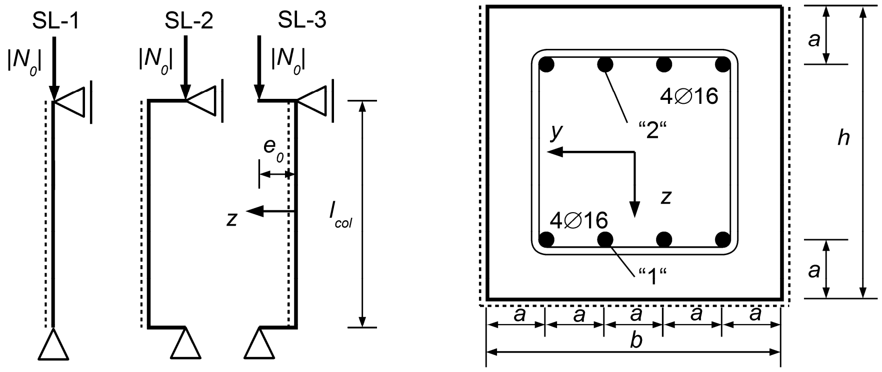

Figure 2. Structural system and cross section for the laboratory tests by Anderberg

TABLE II. PARAMETERS OF TESTS BY ANDERBERG

Nr.	l_{col} **(cm)**	$b=h$ **(cm)**	$A_{s,tot}$ **(mm)**	a **(cm)**	f_c **(MPa)**	f_y **(MPa)**	e_0 **(mm)**	$\lvert N_0\rvert$ **(kN)**	t_{exp} **(min)**
SL-1	200	20	8∅16	4.0	46	453	0	900	52
SL-2	200	20	8∅16	4.0	46	453	-60	600	30
SL-3	200	20	8∅16	4.0	46	453	+60	300	120

"Explicit transient creep model" (ETC)

The stress-strain curves given in EN 1992-1-2 include transient thermal strains implicitly. The "mechanical strains" ε_m considered in the equations consist of the stress related strains ε_σ and transient thermal strains ε_{tr}. In ETC, both components are treated separately. The stress related strains ε_σ are derived from steady-state laboratory tests. Transient thermal strains ε_{tr} are indirectly obtained as the difference in strain between a steady-state test and a transient test. It is assumed that the transient thermal strains can be calculated by:

$$\varepsilon_{tr}(\theta,\sigma) = \phi(\theta)\frac{\sigma}{f_{ck}}\,. \tag{1}$$

The temperature dependent creeping function ϕ is derived from laboratory tests to fit the stress-strain curves of EN 1992-1-2 for a material first-time heated under constant stress. The transient thermal strains are dependent from the load history, hence the corresponding stresses and strains must be traced in the numerical analysis. The ETC model is implemented in the nonlinear finite element software SAFIR® [7], which is used for recalculation.

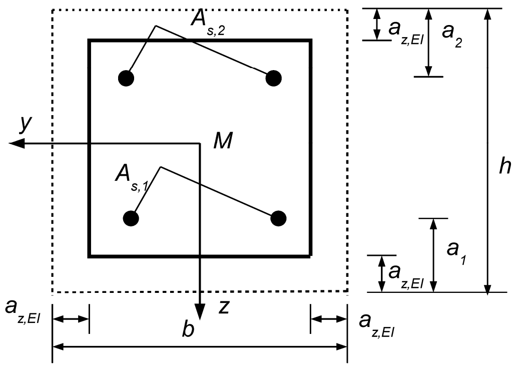

Figure 3. Cross section for the Extended Zone Method

"Extended Zone Method" (EZM)

The basic principle of the Extended Zone Method is to keep as much as possible from the method proposed by Hertz and to introduce modifications only where necessary. The proposed modifications are to use the stress-strain curves for concrete and reinforcing steel given an EN 1992-1-2 and to model the effect of the hindered thermal extension of the compressed reinforcement by a reduced strength. Background information on the validity of these extensions and the assumptions by Hertz are given in detail by Achenbach and Morgenthal [3].

The principles of the Extended Zone Method for a concrete cross section exposed to fire on all four sides, as displayed in Fig. 3, can be described by:

- thermal stains and stresses can be neglected,
- the concrete cross section is reduced by $a_{z,EI}$,
- the concrete is represented with a constant temperature θ_M using the stress-strain curves of EN 1992-1-2,
- the peak strain of the concrete $|\varepsilon_{c1,\theta}|$ is at least 3.5 ‰,
- the stress-strain curves of EN 1992-1-2 are used for the reinforcement,
- the strength of the compressed reinforcement is reduced by $\eta_s(\theta)$.

For a rectangular cross section with $b < h$, the mean strength of the concrete is calculated for a section through the centroid parallel to y:

$$k_{c,m} = \frac{\int_{-b/2}^{b/2} k_c(\theta)\,\mathrm{dz}}{b} \; , \tag{2}$$

with $k_c(\theta) = f_{c,\theta} / f_{ck}$, $f_{c,\theta}$ = concrete strength at temperature θ. The height of the "damaged" zone $a_{z,EI}$ for the compressed cross section is defined by:

$$a_{z,EI} = \frac{b}{2} \cdot \left(1 - \left(\frac{k_{c,m}}{k_c(\theta_M)} \right)^{4/3} \right) \; . \tag{3}$$

The area of the compressed reinforcement is multiplied by

$$\eta_s(\theta) = \begin{cases} 1.0 \text{ for } \theta \leq 100\ °\text{C} \\ 0.5 \text{ for } \theta \geq 400\ °\text{C} \end{cases} \tag{4}$$

to model the effect of the hindered thermal extension, values for 100 °C < θ < 400 °C can be interpolated linearly. The strength of reinforcement is not reduced for rebars under tension.

It is not necessary to trace the load history in EZM, each time step can be solved independently. This is useful in a design situation for a given fire resistance, because only the desired “end point” must be solved.

The proposed method is verified by the recalculation of laboratory tests [8]: the calculated results are close to those of the Advanced Calculation Method given in EN 1992-1-2. The Extended Zone Method is implemented in the computer algebra system Mathcad for this paper, using a transfer matrix method for the calculation of the state of strain.

Parameters for recalculation

The physical properties according to EN 1991-1-2 [9] and EN 1992-1-2 [1] are used for the thermal analysis. The considered parameters are given in Table III.

The yield strength of reinforcement f_{yk} is taken from the measured values for f_y. Hot rolled reinforcement, as documented in the reports [4-6], is taken in the recalculation. Siliceous aggregates are assumed for both test series. The concrete strength f_c at the age of test has been measured using 200 mm cubes. The documented concrete strength f_c is transformed into the corresponding 150 mm cylinder strength f_{ck} according to the recommendations by Schnell and Loch [10]:

$$f_{ck} = k_{150} \cdot k_{cyl} \cdot k_{cure} \cdot f_c = 1.05 \cdot 0.8 \cdot 0.92 \cdot f_c = 0.77 \cdot f_c \tag{5}$$

where: k_{150} = strength of 150 mm cubes / 200 mm cubes, k_{cyl} = strength of cylinders / cubes, k_{cure} = strength of wet cured / dry cured concrete.

For the centrically loaded columns heated on all four sides (SFB 12 and 13), an initial curvature of l_{col} / 2000, as recommended by Haß [11], is applied in the recalculation. It is assumed that all columns are perfectly pin ended.

The thermal strains of concrete and reinforcement are disregarded in EZM. Therefore curvatures, which may be caused by asymmetric heating, must be estimated. In this paper, the differences in thermal strains of the rebars are used for this simple approach. The curvatures κ_{th} are calculated by

$$\kappa_{th} = \frac{\varepsilon_{th,s}("1") - \varepsilon_{th,s}("2")}{h\text{-}2a} \tag{6}$$

with the nomenclature given in Figure 3.

TABLE III. PARAMETERS OF THERMAL ANALYSIS

Parameter	value	unit
α	25 / 4	[W/m²K]
ε	0.7	[-]
ρ	2400	[kg/m³]
u	3	[%]
λ_c	lower limit	[W/mK]

RESULTS OF RECALCULATION

Tests from TU Braunschweig – symmetric heated columns

The calculated times to failure $t_{cal,ETC}$ and $t_{cal,EZM}$ - using the advanced method ETC and the simplified EZM - are given in Table IV. It must be pointed out that the load history is not considered in the implementation of EZM. The results for columns SFB 12 and SFB 13, which have both identical parameters but different experimental times to failure, are dependent from the applied initial curvature.

Comparing the results for both methods reveals that both methods are able to predict the experimental time to failure with comparable deviations. Using the advanced method ETC does not increase the accuracy of the calculated time to failure. But to generalize this statement, a larger database of laboratory tests should be considered to allow a statistical evaluation.

Tests by Anderberg – asymmetric heated columns

Results for the Anderberg tests are plotted in Figure 4-6. The plots show the horizontal deflections at mid-span of the columns calculated with the EZM and ETC methods, as well as the measured ones.

Test SL-1 must be considered carefully. It was reported [6] that the column exploded early, probably due to the high moisture content of u = 6 % and the high level of applied loads. Hence the effect of spalling cannot be fully ignored for SL-1. As shown in Figure 4, the measured deflections in the middle of the column are towards the fire for the first 25 min of the test, which can be explained by thermal curvatures. After 25 min, the column moves away from the fire. This may be caused by the proceeding deterioration of the concrete, which causes a shift of the neutral axis of the cross section. This effect can be explained by EZM, because the cross section is only reduced at the heated surfaces. Both ETC and EZM with simplified curvatures overestimate the deflections towards the fire and the time to failure. It is noted that spalling is not captured by either method.

For SL-2, the calculated deflections for ETC and EZM with simplified thermal curvatures are close to the measured results, as displayed in Figure 5. There are only experimental results for the first 30 min reported, because the test has been interrupted due to a support failure. The thermal strains and the eccentricity of applied loads cause a deflection towards the fire. In this case, the accuracy of the calculated deflections using EZM can be improved with the simple estimation of thermal curvatures given by Eqn. (6).

TABLE IV. RESULTS OF TESTS FROM TU BRAUNSCHWEIG

Nr.	t_{exp} (min)	$t_{cal,ETC}$ (min)	$t_{cal,EZM}$ (min)
SFB5	85	74	89
SFB12	58	49	44
SFB13	66	49	44
SFB46	50	54	51

For SL-3, the eccentricity of the load is partly balanced by the deflections due to unequal thermal strains. This effect is visible in in the measured deflections displayed in Figure 6. The observed deformations can be reproduced with satisfying accuracy using ETC. The limits of the simple EZM become clear for SL-3: disregarding the thermal strains leads to an underestimation of the deflections, while the consideration of simplified thermal curvatures leads to an overestimation.

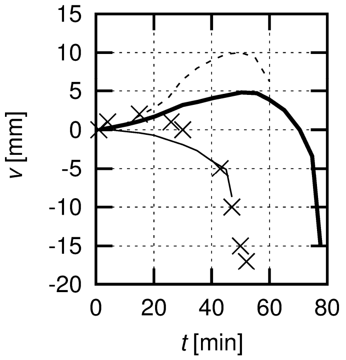

Figure 4. Calculated deflections for SL-1 using ETC (▬), EZM (—), EZM (- - -) with simplified thermal curvatures and measured deflections (×)

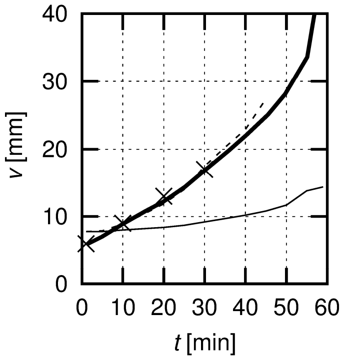

Figure 5. Calculated deflections for SL-2 using ETC (▬), EZM (—), EZM (- - -) with simplified thermal curvatures and measured deflections (×)

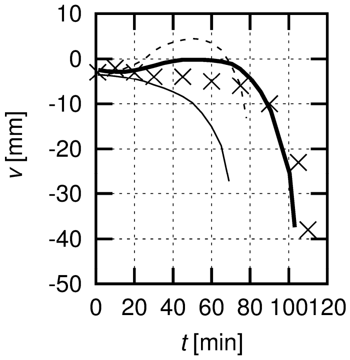

Figure 6. Calculated deflections for SL-3 using ETC (▬), EZM (—), EZM (- - -) with simplified thermal curvatures and measured deflections (×)

CONCLUSIONS

The first series of recalculations indicate that the simplified EZM is of sufficient accuracy for the calculation of unrestrained columns subjected to a standard fire on all four sides. In this situation, which is the standard design situation used in a single member design, the advanced ETC method can also be used but it does not provide any significant improvement in terms of accuracy for the calculated time to failure. The limits of EZM become clear when the effects of non-uniform heating have to be considered. In this case, the advanced ETC is more able to describe the observed behavior of the tested columns. In future, this research will be extended to include a larger database of tests to allow for a statistical evaluation of the different methods.

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