12th International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-12
B.L.A. Pichler, Ch. Hellmich, P. Preinstorfer (Eds)

https://doi.org/10.21012/FC12.1341
MS09-1:3

ON THE SUITABILITY OF EUROCODE 2 STRESS-STRAIN MODEL WITH IMPLICIT TRANSIENT STATE STRAIN FOR PREDICTING FRACTURE AT ELEVATED TEMPERATURE

HITESH LAKHANI* **AND JAN HOFMANN***

* University of Stuttgart, Institute of Construction Materials (IWB)
Pfaffenwaldring 4, 70569 Stuttgart, Germany
e-mail: hitesh_lakhani06@rediffmail.com, www.iwb.uni-stuttgart.de

Key words: Implicit transient strain, Concrete, Elevated Temperature, Eurocode2

Abstract: The strain components needed to correctly predict the deformation behavior of concrete at elevated temperature are extremely complex given the interdependence of these strain components and hence the difficulties in uniquely defining each of these strain components independently. The Load Induced Transient Strain “LITS” is known to be the most complex and important component for concrete exposed to elevated temperature. This component has been considered in a simplified way in the current design provision by implicitly including it in the uniaxial stress-strain law. This simplification simplifies the complexities for the designer. However, it leads to certain limitations which have already been highlighted in literature based on structural level simulations of reinforced concrete. But its suitability for predicting the deformation and fracture behavior of concrete at elevated temperature remains unanswered. The paper presents results of a numerical investigation aimed at investigating the suitability of the Eurocode 2 stress-strain model for predicting the macroscopic response of concrete under compression at a geometric scale corresponding to material testing level. Different tests from literature on cylinders with varying loading histories and exposed to elevated temperatures are simulated. Based on the simulation results, the paper comments on the macroscopic response at material level which can/cannot be captured using the Eurocode 2 model.

1 INTRODUCTION

Simulating concrete fracture at ambient condition has always been a numerically challenging task not only in terms of predicted failure loads but the cracking. The associated complexities increase further at elevated temperature given the hygro-thermo-mechanical phenomenon taking place at micro and meso- scales which causes damage/cracking in concrete. The total deformation experienced by concrete at elevated temperature under compression is known to consist of a) instantaneous strain associated with external loading; b) thermal strain due to change in temperature, which also includes effects due to change in volume of concrete due to physical changes and chemical reactions; c) shrinkage strain due to loss of water and d) transient creep strains due to heating (transient state) and loading which otherwise cannot be accounted. These strain components constituting the total strain in concrete at elevated temperature have been known as early as 1969 as reported by Anderberg and Thelandersson in 1973 [1]. These strain components at elevated temperature are extremely complex given the interdependence of these strain components and hence, difficulties in uniquely defining each of these strain components independently.

In literature, the creep and transient strain together are also referred as “transient-creep-strain", or "Load-Induced-Thermal-Strain" (LITS) due to their dependency on the applied load. The explanation of the phenomenon responsible for "LITS" strain components is outside the scope of this paper but can be found in literature [2].

For design purposes, to consider the LITS component in a simplified way, it is considered implicitly in the stress-strain model for concrete at elevated temperature in Eurocode 2 (EN1992-1-2 [3]). Because of this simplification the stress-strain response becomes artificially less stiff. Some limitations of Eurocode 2 stress-strain model, as found in literature [4–7], are viz., it leads to higher predicted axial deformation and longer time to failure for reinforced concrete columns, and possible recovery of LITS in case of unloading and cooling scenarios. Since the application limits of Eurocode 2 stress-strain model are not specifically laid-out and it's easy to use. The model is extensively used for different modelling approaches ranging from beam elements to 3D solid elements.

The paper presents results of a numerical campaign aimed at systematically investigating the suitability of the Eurocode 2 stress-strain model for predicting the macroscopic response of concrete under compression at material testing level. Different tests from literature on cylinders with varying loading histories and exposed to elevated temperatures are simulated. Based on the simulation results, the paper comments on the macroscopic response at material level which can/cannot be captured using the Eurocode 2 model.

2 NUMERICAL INVESTIGATIONS

Anderberg and Thelandersson in 1976 [8] reported test results of various test series aimed at determining the deformation characteristics of concrete at elevated temperature. The test series consisted of different combinations of loading and temperature histories. In this paper test conducted with constant preloads loads (5 levels) and two cases with variable loads (once load increased during exposure and once load decreased during exposure) exposed to a heating rate of 5°C per minute and a stabilization period of 2 hrs.

The results are based on sequentially coupled 3D thermomechanical analysis performed using commercially available general purpose Finite Element software Ansys® [9].

2.1 Geometric details and boundary conditions

The concrete cylinder had an outer diameter of 75 mm and a height of 150 mm. The cylinder had a 10 mm through hole at its center which was used for measuring the deformation on the top and bottom face of the cylinder.

In numerical investigations only one fourth of the geometry was modelled using symmetry boundary conditions as shown in Figure 1.

For thermal analysis only the outer surface of the cylinder is exposed to elevated temperature. The heat transfer from surrounding to the concrete surface is modelled using convection and radiation boundary conditions.

For mechanical analysis the cylinder was assumed to be resting on a hard surface with compression only support at the bottom end and the load was applied on the top face of the cylinder.

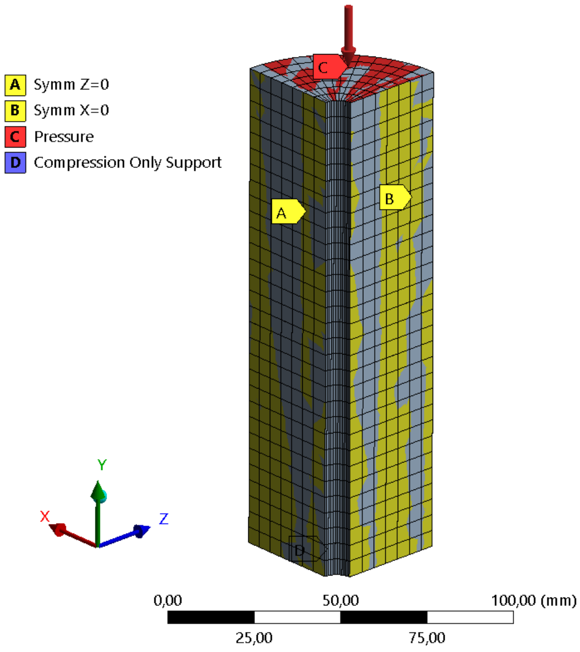


Figure 1: Meshed quarter model with respective boundary conditions.

2.2 Material model and properties

The thermal properties for concrete viz., density, specific heat and conductivity were taken as recommended in EN1992-1-2 [3]. The concrete was assumed to be dry (for selecting the specific heat) and lower bound conductivity was used based on the sensitivity study performed by Lakhani et al. [10].

Concrete is modelled using Drucker-Prager model under compression and Rankine's tension yield surface. The temperature dependent constitutive stress-strain relationship under compression as recommended by Eurocode 2 with exponential softening after reaching a stress level of 85% in the post peak range. The tensile strength degradation given in Eurocode 2 is modified to have a tensile strength of 10% (of ambient value) at and above 600°C. The tensile fracture energy was assumed to be independent of temperature.

Since the cylinders were tested at different ages and sometimes were also cased in different batches. The compressive strength was taken as the average of all the strengths tested in the series (A5 to A9 tests as referred in the original reference [8]). The concrete was made using quartzite aggregates. The mean 150 mm cube strength is calculated as 58 MPa and the strength of the cylinder specimen simulated is taken as 0.75 the cube strength i.e., 43.5 MPa. The factor 0.75 was reported by Anderberg and Thelandersson [8] based on experimental results. The tensile strength is taken as 3.4 MPa (as per [11]) and the tensile fracture energy is assumed to be 0.06 N/mm. The fracture energy is assumed to be independent of temperature.

3 RESULTS AND DISCUSSION

3.1 Thermal analysis

Experimentally temperatures inside the cylindrical specimen were reported at 10 mm and 30 mm from the center. The measured temperatures are compared with the simulation results in Figure 2. The simulation results are in good agreement with the measured temperature.

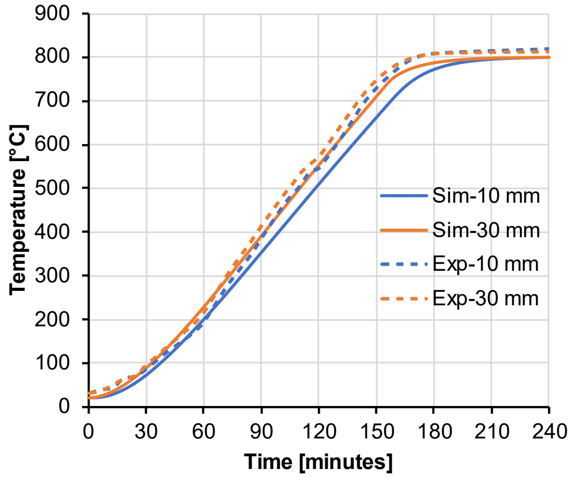


Figure 2: Comparison between measured and simulated temperature results.

3.2 Mechanical analysis

Mechanical response of cylinder loaded with 5 different loaded levels, viz., 0%, 22.5%, 35%, 45% and 67.5% of the ambient capacity of the cylinder are shown in Figure 3. The load was applied before the cylinders were exposed to elevated temperature and was maintained constant throughout the exposure.

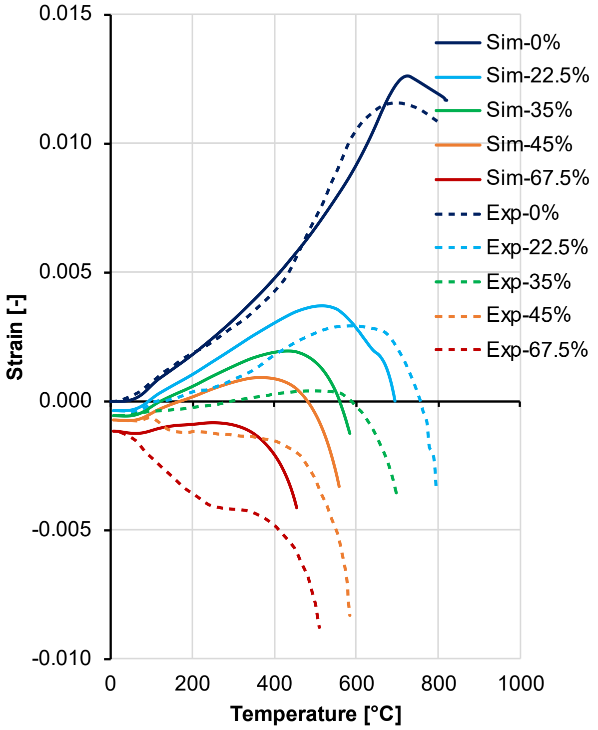


Figure 3: Deformations predicted for specimens with constant load history using EN1992-1-2 stress-strain relationship.

It should be noted that the temperature on the x-axis is at 26 mm from the center as reported in the original reference [8]. The strain on the Y-axis is calculated as the difference of the mean surface deformations on the bottom and top of the surface of the cylinder divided by the total length of the cylinder (150 mm).

As seen in Figure 3 the predicted axial expansion is larger than those measured in experiments by Anderberg and Thelandersson [8]. This difference increases with an increase in load level. This observation can lead to conclusion that the transient creep components are underestimated in Eurocode 2 (based on the current recommended strain values at peak stress) especially for higher load levels.

To further investigate this observation additional simulations were performed with variable loading histories during thermal exposure. The two specimens D5 and D8 (tested by Anderberg and Thelandersson [8]) were specifically selected since the load on specimen D5 was increased in steps during thermal exposure and decreased in steps on specimen D8 as shown in Figure 4. The results of the specimens D5 and D8 are shown in Figure 5 (a) and (b) respectively.

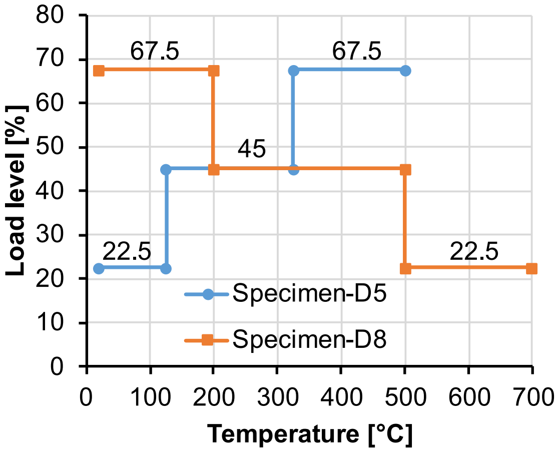
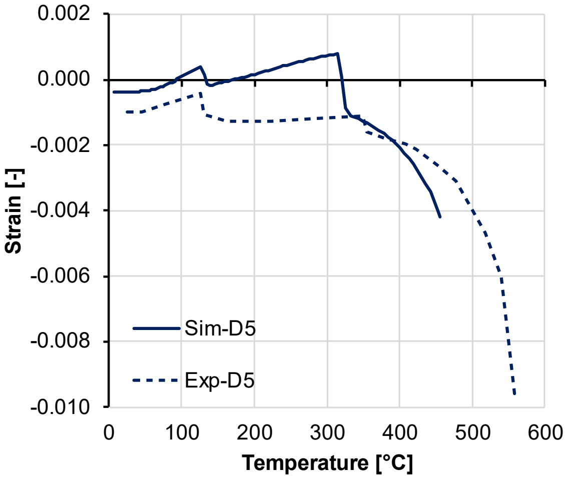


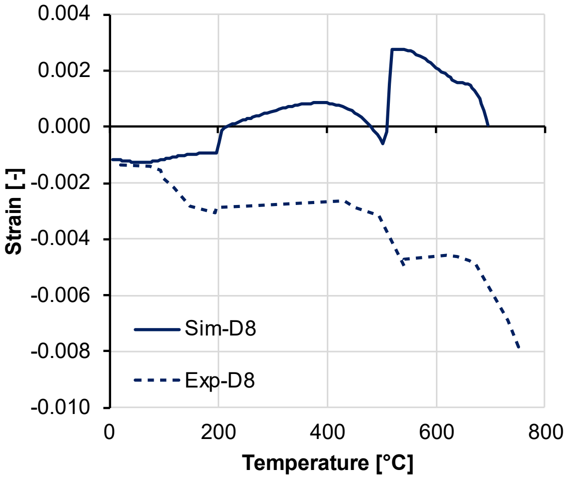
Figure 4: Loading history for specimen D5 and D8

Based on the results shown in Figure 5, the following can be concluded:

1. For the case with increase in load levels the deformation pattern agrees reasonably with the experimental observations, but the deformations themselves are underestimated (larger expansions are predicted),
2. For the case with decreasing load levels in steps, the deformation pattern and values both deviates from the experimental observations. It should be noted that numerically there is recovery of strain components with reduction in load levels which is not observed in experiments.



(a) Specimen: D5 (Load increased in steps during thermal exposure)



(b) Specimen: D8 (Load decreased in steps during the thermal exposure)

Figure 5: Deformations predicted using EN1992-1-2 stress-strain relationship for specimen loaded with variable load history.

4 CONCLUDING REMARKS

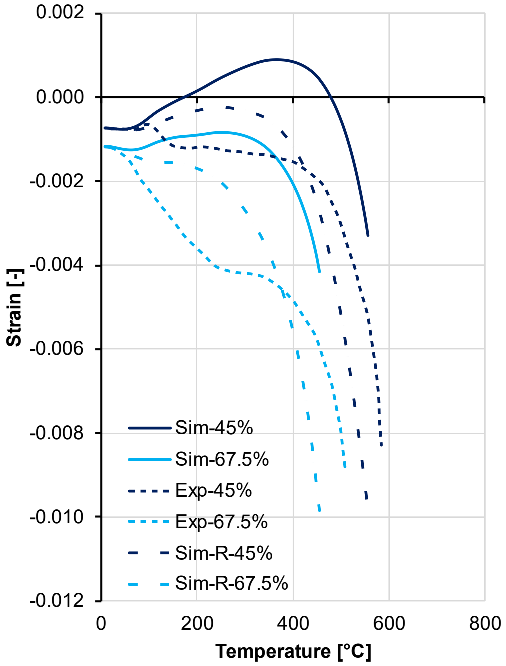
The paper presented results of numerical study using the implicit transient strain formulation for uniaxial compression stress-strain relationship proposed by Eurocode 2 (EN1992-1-2 [3]). The numerical investigation was aimed at assessing the suitability of these strain-strain relationships in predicting the deformation behavior of concrete at elevated temperature. As shown in this paper the deformations (compressive/contraction) of loaded concrete are not correctly captured by the current Eurocode 2 stress-strain constitutive law. The differences between the measured and calculated deformations are significant for load levels of 45% (of ambient strength) and higher. Furthermore, it was observed that with decrease in load levels during temperature exposure (can also be referred as unloading of concrete) the recovery in axial contraction is too large. This recovery is axial contraction is not seen in the experimental observations. This strain recovery can be attributed as an effect caused due to pseudo reduction in the stiffness (E-Modulus) of concrete caused due to the way Eurocode 2 implicitly considers the transient strain (i.e., increasing the strain values at peak stress).

It should be noted that the strain values at peak stress in the prEN1992-1-2:1995 [12] (draft version of current EN1992-1-2) were increased in the final version of the EN1992-1-2 citing that lower strain valued leads to too large elongations of reinforced concrete columns because of underestimation of the transient creep strains [13]. Hence, as a possible solution to improve the Eurocode 2 stress-strain model using the same approach (further increase the strain values at peak stress). Some simulations were repeated with an (further) increased strain value on an ad-hoc basis. The revised strain values for siliceous aggregate concrete used for the second set of simulations are given in Table 1 and its effect in terms of predicted deformations for specimens with different load histories are shown in Figure 6 (a), (b) and (c).

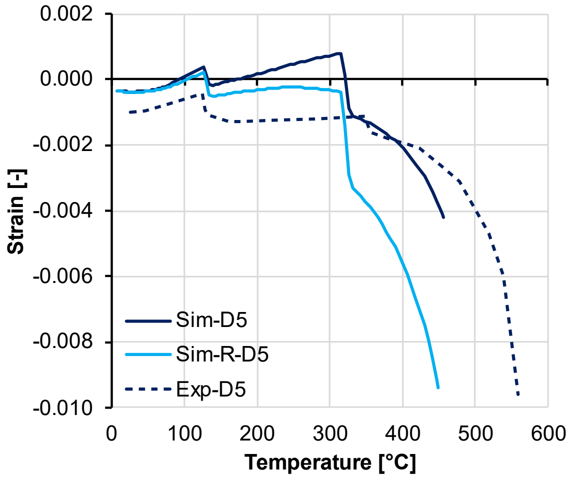
Although the revised strain values significantly improved the predicted deformations for constant load and increase in load histories but the case with decrease in load history (or unloading) still shows unreasonable recovery in axial strain. Hence, further validations at material level and structural level are needed to clearly define the area of applicability of current (or improved) uniaxial stress-strain relationship with implicit transient state strain for concrete at elevated temperature.

Table 1: Revised (R) strain values at peak stress used for simulation along with values as per EN 1992- 1- 2

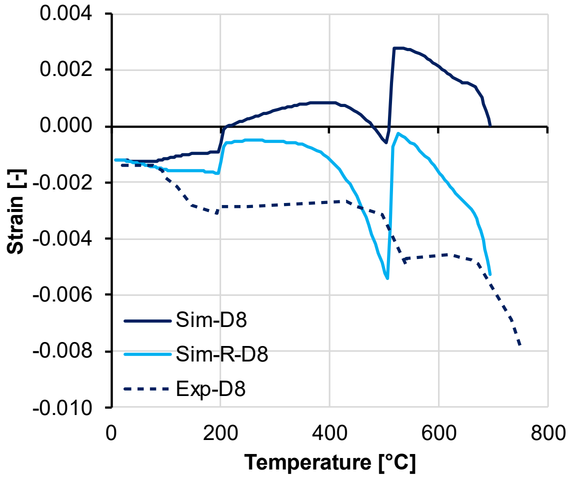
Temp (θ)	ε_{c1}	
°C	EN 1992-1-2	Revised (R)
20	0.0025	0.0025
100	0.0040	0.0050
200	0.0055	0.0070
300	0.0070	0.0100
400	0.0100	0.0150
500	0.0150	0.0250
600	0.0250	0.0350
700	0.0250	0.0350
800	0.0250	0.0350
900	0.0250	0.0350
1000	0.0250	0.0350
1100	0.0250	0.0350



(a) Constant load - 45% and 67.5% load levels



(b) Variable load history - Specimen: D5



(c) Variable load history - Specimen: D8

Figure 6: Deformations predicted using EN1992-1-2 and revised (R) proposal for strain at peak stress.

REFERENCES

[1] Anderberg Y, Thelandersson S, 1973. Stress and Deformation Characteristics of Concrete at High Temperatures. 1. General Discussion and Critical Review of Literature, Bulletin 34. *Lund Institute of Technology*.

[2] Torelli G, Mandal P, Gillie M, Tran V-X, 2016. Concrete strains under transient thermal conditions: A state-of-the-art review. *Engineering Structures* **127**:172–188.

[3] EN1992-1-2, 2004. Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design. *European Committee for standardization,* Brussels.

[4] Bratina S, Čas B, Saje M, Planinc I, 2005. Numerical modelling of behaviour of reinforced concrete columns in fire and comparison with Eurocode 2. International Journal of Solids and Structures 42:5715–5733

[5] Bratina S, Saje M, Planinc I, 2007. The effects of different strain contributions on the response of RC beams in fire. *Engineering Structures* **29**:418–430.

[6] Gernay T, 2012. Effect of Transient Creep Strain Model on the Behavior of Concrete Columns Subjected to Heating and Cooling. *Fire Technology* **48**:313–329.

[7] Kodur VKR, Alogla SM, 2017. Effect of high-temperature transient creep on response of reinforced concrete columns in fire. *Materials and Structures*. **50(1)** https://doi.org/10.1617/s11527-016-0903-8.

[8] Anderberg Y, Thelandersson S, 1976. Stress and Deformation Characteristics of Concrete at High Temperatures. 2. Experimental Investigation and Material Behaviour Model, Bulletin 54, *Lund Institute of Technology*.

[9] Ansys® Academic Student Mechanical, Release 2024R1.

[10] Lakhani H, Kamath P, Bhargava P, Sharma UK, Reddy GR, 2013. Thermal analysis of reinforced concrete structural elements. *Journal of Structural Fire Engineering* **4**:227–244.

[11] EN1992-1-1:2004 Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. *European Committee for standardization*, Brussels.

[12] prEN1992-1-1:1995 -draft- Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. *European Committee for standardization*, Brussels.

[13] Gernay T, Franssen J-M, 2012. A formulation of the Eurocode 2 concrete model at elevated temperature that includes an explicit term for transient creep. *Fire Safety Journal* **51**:1–9.