Creep analysis and time-dependent concrete material models in OpenSees
– Manual –

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1. INPUT FOR TDCONCRETE(EXP) AND TDCONCRETEMC10(NL) MODELS

This section explains the input parametrs for the TDC models. An Excel sheet (**TDC_Input.xlsx**) is also developed to facilitate calculating input parameters.

1) TDConcrete

The first material to be explained is TDConcrete. It models concrete as linear in compression, linear until tensile strength in tension with nonlinear tension softening after cracking and with ACI 209R-92 [1] shrinkage and creep models.

The syntax for assigning TDConcrete is:

```
uniaxial material TDConcrete $matTag $fc $ft $Ec $beta $tD $epsshu $psish $Tcr $phiu $psicr1$psicr2 $tcast
```

The argument are explained in detail in Adam Knaack's thesis [2], here they are mentioned briefly.

$fc is the cylinder compressive strength (this is a dummy parameter since compression behavior is linear) (input negative)

$ft is the tensile strength (splitting or axial tensile strength should be input, rather than the flexural)

$Ec is the modulus of elasticity (preferably at time of loading if there is a single loading age)

$beta is a tension softening parameter (see [2]) – higher beta means more softening (tending towards brittle cracking) – in sheet „**s-e Lin**" of **TDC_Input.xlsx**, by varying cell D1, the effect of changing beta (***β***) can be seen. The value recommended by Tamai et al. [3] for deformed bars is 0.4.

$$\sigma_t = f_t \cdot \left(\frac{\varepsilon_{tm}}{\varepsilon_m}\right)^{\beta} \tag{1}$$

where ε_{tm} is the mechanical strain at cracking (f_t/E_c) and ε_m is the tensile strain.

$tD is the analysis time at initiation of drying (in days)

$epsshu is the ultimate shrinkage strain $\varepsilon_{sh,u}$, as per ACI 209R-92 [4] (input as negative)

This value should include the ultimate shrinkage strain and all correction coefficients (curing, humidity, size, slump, fine aggregate, cement, entrained air) as per ACI 209R-92 [4]. A detailed account can also be found in the Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete [1].

This value can be corrected by any other global correction factor.

$psish is the fitting parameter within the shrinkage time evolution function as per ACI 209R-92 [4]

$$\beta_{sh}(t,t_D) = \frac{t-t_D}{\psi_{sh}+(t-t_D)} \tag{2}$$

According to [1], $psish should be calculated as 26.0exp($1.42\cdot10^{-2}\cdot$V/S) (in SI units) where V/S is the volume/surface ratio of the member or cross-section.

$Tcr is the creep model age in days

$phiu is the ultimate creep coefficient φ_u, as per ACI 209R-92 [4]

This value should include the ultimate creep coefficient and all correction coefficients (loading age, humidity, size, slump, fine aggregate, entrained air) as per ACI 209R-92 [4]. A detailed account can also be found in the Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete [1].

This value can be corrected by any other global correction factor.

$psicr1 is a fitting constant within the creep time evolution function as per ACI 209R-92 [4]

$psicr2 is a fitting constant within the creep time evolution function as per ACI 209R-92 [4]

$$\beta_{cr}(t,t_D) = \frac{(t-T_{cr})^{\psi_{cr1}}}{\psi_{cr2}+(t-T_{cr})^1} \tag{3}$$

According to [1], $psicr2 should be calculated as 26.0exp($1.42\cdot10^{-2}\cdot$V/S) (in SI units) where V/S is the volume/surface ratio of the member or cross-section, $psicr1 should be taken as 1.0.

$tcast is the analysis time corresponding to concrete casting in days (note: concrete will not be able to take on loads until the age of 2 days).

The calculation of input parameters is provided in the „**ACI**“ sheet of **TDC_Input.xlsx**.

If experimental results need to be input, then simply values $epsshu and $psicr should be replaced by measured values of the shrinkage strain and creep coefficient, respectively, but divided by the time evolution function’s value at the point when measurements were made (since the input values should be *ultimate* values). For example, if shrinkage was measured as –0.6‰ at 1000 days and the time evolution function’s value (Eq. (2)) at 1000 days is 0.92, then $epsshu should be input as –0.6/0.92 = –0.652‰.

2) TDConcreteEXP

The input for TDConcreteEXP will not be discussed here since it is very similar to TDConcrete and is explained in [2].

The main difference is that the ultimate creep coefficient $psicr is replaced with the ultimate creep strain $epscru and experimental applied creep stress $sigCr. This makes the model unnecessarily difficult to use since it is easier to simply calculate $phicr and use TDConcrete.

3) TDConcreteMC10

The next material to be explained is TDConcreteMC10. It models concrete as linear in compression, linear until tensile strength in tension with nonlinear tension softening after cracking and with Model Code 2010 [5] shrinkage and creep models.

The syntax for assigning TDConcreteMC10 is:

```
uniaxial material TDConcreteMC10 $matTag $fc $ft $Ec $Ecm $beta $tD $epsba $epsbb $epsda $epsdb $phiba $phibb $phida $phidb $tcast $cem
```

The argument list is explained below:

$fc is the cylinder compressive strength (this is a dummy parameter since compression behavior is linear) (input negative)

$ft is the tensile strength (splitting or axial tensile strength should be input, rather than the flexural)

$Ec is the modulus of elasticity (preferably at time of loadingif there is a single loading age)

$Ecm is the modulus of elasticity at 28 days – necessary for calculating creep strain as per Model Code 2010 [5] ($\varepsilon_{cc} = \varphi \cdot \sigma_c / E_{cm}$)

$beta is a tension softening parameter (see [2]) – higher beta means more softening (tending towards brittle cracking)

In sheet „**s-e Lin**“ of **TDC_Input.xlsx**, by varying cell D1, the effect of changing beta ($\boldsymbol{\beta}$) can be seen. **Default value is 0.8**, see Eq. (1).

$tD is the analysis time at initiation of drying (in days)

$epsba is the ultimate basic shrinkage strain, $\varepsilon_{cbs,0}$, as per Model Code 2010 [5]

This value can be corrected by any other global correction factor.

$epsbb is the fitting parameter within the basic shrinkage time evolution function as per Model Code 2010 [5] and prEN1992-1-1:2017 [6]

$$\beta_{bs}(t) = 1 - \exp\left(-0.2 \cdot \text{\$epsbb} \cdot \sqrt{t}\right) \tag{4}$$

$epsda is the product of $\varepsilon_{cds,0}$ and β_{RH}, as per Model Code 2010 [5]

This value can be corrected by any other global correction factor.

$epsdb is the fitting parameter within the drying shrinkage time evolution function as per Model Code 2010 [5] and prEN1992-1-1:2017 [6]

$$\beta_{ds}(t, t_D) = \left(\frac{t - t_D}{\$epsdb + (t - t_D)}\right)^{0.5} \tag{5}$$

where

$$\text{\$epsdb} = 0.035 \cdot h_0^2 \cdot \xi_{cds,2} \tag{6}$$

where h_0 is the notional thickness and $\xi_{cds,2}$ an arbitrary fitting parameter as per [6]

$phiba is the parameter for the effect of compressive strength on basic creep $\beta_{bc}(f_{cm})$, as per Model Code 2010 [5]

This value can be corrected by any other global correction factor.

$phibb is the fitting parameter within the basic creep time evolution function as per Model Code 2010 [5] and prEN1992-1-1:2017 [6]

$$\beta_{bc}(t, T_{cr}) = ln\left(\left(\frac{30}{t_{0,adj}} + 1\right)^2 \cdot \frac{(t - T_{cr})}{\text{\$phibb}} + 1\right) \tag{7}$$

where

$$\text{\$phibb} = \xi_{bc,2} \tag{8}$$

and $\xi_{bc,2}$ an arbitrary fitting parameter as per [6]; and $t_{0,adj}$ is the adjuste loading age:

$$t_{0,adj} = t_0 \cdot \left[\frac{9}{2 + t_0^{1.2}} + 1\right]^{\$cem} \tag{9}$$

$phida is the product of $\beta_{dc}(f_{cm})$ and $\beta(RH)$, as per Model Code 2010 [5]

This value can be corrected by any other global correction factor.

$phidb is a fitting constant within the drying creep time evolution function as per Model Code 2010 [5]

$tcast is the analysis time corresponding to concrete casting in days (note: concrete will not be able to take on loads until the age of 2 days).

$cem is the coefficient dependent on the type of cement: –1 for 32.5N, 0 for 32.5R and 42.5N and 1 for 42.5R, 52.5N and 52.5R.

The calculation of input parameters is provided in the „**MC10**“ sheet of **TDC_Input.xlsx**.

If experimental results need to be input, then simply values $epsbb, $epsdb, $phibb, $phidb and $phidc should be replaced by measure values if both basic and drying components of creep and shrinkage were measured. If only total creep and shrinkage were measured than experimental values should be entered as $epsdb, $phidb and $phidc, whereas $epsbb and $phibb should be entered as 0.0.

4) TDConcreteMC10NL

The last material to be explained is TDConcreteMC10NL. It models concrete as nonlinear in compression with a parabolic banch until f_c (at strain ε_{c0}), a linearly decreasing branch until f_{cu} (at strain ε_{cu}), and a horizontal branch afterwards, linear until tensile strength in tension with nonlinear tension softening after cracking and with Model Code 2010 [5] shrinkage and creep models.

The relationship in compression is taken from OpenSees material Concrete02:

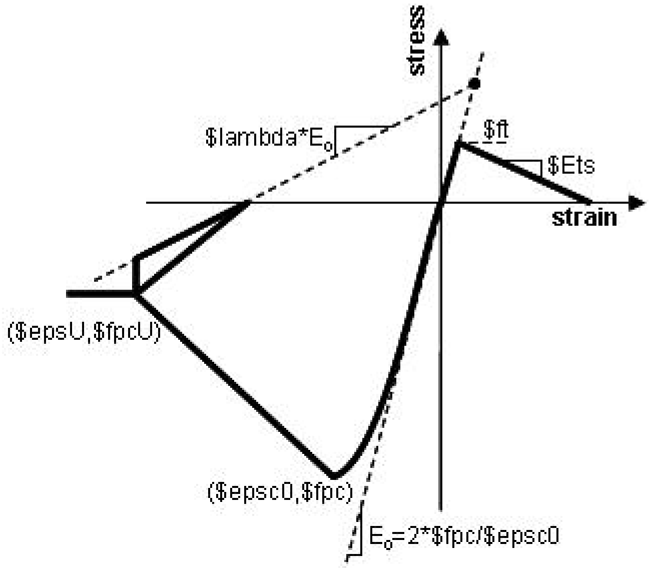

Fig. 13. Stress–strain relationship of material Concrete02 (compressive behavior is copied)

The syntax for assigning TDConcreteMC10NL is:

```
uniaxial material TDConcreteMC10NL $matTag $fc $fcu $epscu $ft $Ec $Ecm $beta $tD $epsba $epsbb
$epsda $epsdb $phiba $phibb $phida $phidb $tcast $cem
```

The argument list is explained below only for new parameters compared with TDConcreteMC10:

$fcu is the concrete crushing strength (to be adopted as wished) (input as negative)

$epscu is the concrete strain at crushing (to be adopted as wished) (input as negative)

In sheet „**s-e NLin**" of **TDC_Input.xlsx**, by varying cells B1, B2, B3 and B5, the stress–strain diagram in compression can be seen.

2. OUTPUT FROM TDCONCRETE(EXP) AND TDCONCRETEMC10(NL) MODELS

All TDC models use the recored CreepStressStrainTangent for output.

The .tmp are created for each fiber and output:

analysis time

stress

total strain – sum of (total) creep strain, mechanical strain and (total) shrinkage strain

tangent stiffness

creep strain (in the case of MC10 models *basic* then *drying*)

mechanical strain

shrinkage strain (in the case of MC10 models *basic* then *drying*)

A MATLAB script can then be used to plot the development of strains over time or their distribution over the height of a cross-section.

3. EXAMPLE MODEL FILES USING TDCONCRETEMC10NL

Example model files are provided of beam B1-a from the experimental program by Gilbert and Nejadi [7]. The beam in question is a 3.5-m span simply supported beam loaded in four-point bending after 14 days with the load maintained for 380 days. The details of the experiment are provided in reference [7].

To run the analysis, the the version of OpenSees compiled with the TDConcrete source files should be copied into the folder „Gilbert and Nejadi - Ba1". Once it is started, the user only needs to enter the command:

„source driver.tcl"

The Driver.tcl file sources the B1Param.tcl and CreepBeam.tcl files.

The B1Param.tcl file contains the variables defining the loading age (tPrime), imposed load (totalLoad), the number of fibres for discretizing the elements (nFibres), number of time steps for the shrinkage analysis (nShrink), number of time steps for the creep analysis (nCreep), and the time of analysis end (tFinal). All units are in N-mm.

The CreepBeam.tcl file contains the main commands for generating the model, assigning material properties, fibre discretization, analysis and output commands. First, the Variables.tcl file is sourced.

Lines 17–60 define the beam, dividing it into 21 nodes, as well as the boundary conditions.

Lines 62–72 define the assignment of material properties: TDConcreteMC10NL for concrete and Steel01 for reinforcement.

Lines 74–106 define the fibre disretization – the entire beam is discretized the same way, 40 fibres across the cross-section height and two additional fibres for reinforcing bars.

Lines 108–127 define the node connectivity using dispBeamColumn elements.

Lines 129–149 define the recorders – displacement of the mid-span, reinforcement stress and strain, and concrete component strains (using the CreepStressStrainTangent command).

Lines 153–213 define the analysis and load application. First, the beam is initialized at the end of drying (here coinciding with the age at loading) and the global Creep variable is set on („setCreep 1"). Then, uniformly distributed load of the beam and reinformcenet self-weight is applied in a Static analysis step. A creep analysis is performed from the end of drying to the time of applying the imposed load (here coinciding). The imposed load is applied in thirds of the span as nodal forces and a Static analysis is performed. Finally, a creep analysis is performed from the age at loading (tPrime) until the end of analysis (tFinal). For each creep analysis, the start and end time, as well as the number of steps are defined.

All the creep analyses are performed by sourcing the TimeAnalysis.tcl file.

The Variables.tcl file sourced in the beginning of CreepBeam.tcl reads the MatParameters.txt and CreepParameters.txt files, defines the the age at end of drying (tDry) and the tension softening parameter $beta.

The MatParameters.txt file contains parameters for TDConcreteMC10NL $fc, $fcu, $epscu, $fct, $Ec, $Ecm and the unit density of concrete $WGT for calculating dead load.

The CreepParameters.txt file contains parameters for TDConcreteMC10NL $espba, $epsbb, $epsda, $epsdb, $phiba, $phibb, $phida, $phidb, $cem.

The TimeAnalysis.tcl file sets time steps between creep analysis times in a logarithmic progression with a limitation on the maximum time step and a procedure for switching between solution algorithms if any of them should not converge.

The results are populated in the output folder.

References

[1] ACI 209.2R-08, Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete, American Concrete Institute, Farmington Hills, MI, 2008.

[2] A.M. Knaack, Sustainable concrete structures using recycled concrete aggregate: short-term and long-term behavior considering material variability, University of Notre Dame, 2013.

[3] S. Tamai, H. Shima, J. Izumo, H. Okamura, Average stress-strain relationship in post yield range of steel bar in concrete, Concr. Libr. JSCE. 11 (1988) 117–129.

[4] ACI 209R-92, Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures, American Concrete Institute, Farmington Hills, MI, 1992.

[5] FIB, fib Model Code for Concrete Structures 2010, International Federation for Structural Concrete (fib), Lausanne, 2013. doi:10.1002/9783433604090.

[6] PT1prEN1992-1-1, Eurocode 2: Design of concrete structures – Part 1-1: General rules, rules for buildings, bridges and civil engineering structures, CEN, Brussels, 2017.

[7] R.I. Gilbert, S. Nejadi, An experimental study of flexural cracking in reinforced concrete members under sustained loads, Kensington, 2004.