MODELLING OF TIME-DEPENDENT BEHAVIOR OF SHCC BY USING MULTI-LAYERED MICROPLANE MODEL

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ABSTRACT: The time-dependent behavior of strain hardening cementitious composites (SHCC) is modelled by using multi-layered microplane model. The rate of total creep and shrinkage is considered the main source to influence the constitutive relation of SHCC as the creep strain could cause a structure to deform larger than expected if the load is sustained for a period of time. The formation of new cracks and time-dependent fiber pull-out are considered as the significant source of time-dependent deformation of SHCC. This mechanism is formulated and simulated by using multi-layered microplane model. The simulated results are compared with experimental data.

KEY WORDS: SHCC, Creep, Shrinkage, Multi-layered model, Cracking creep strain, Pullout

1. INTRODUCTION

Strain-hardening cementitious composites (SHCC) are the material which exhibit strain hardening, quasi-ductile behavior with a tensile strain capacity of up to 5%. Due to the favorable mechanical properties, it has become an alternative building material. This pseudo-ductility is achieved by the formation of fine closely spaced cracks which do not widen significantly during the strain hardening phase resulting in its capability to use for durable structures.

The long-term behavior of SHCC has recently received an attention as the mechanical behavior of cement-based material is highly time-dependent. The creep is a well-known phenomenon in terms of continued deformations under sustained load. It has been determined that three main causes of macroscopic tensile creep of SHCC are the matrix creep, time-dependent fiber pull-out and the formation of additional multiple cracks over time. It has also been found that time-dependent fiber pull-out causes cracks widening under sustained loading.

The time-dependent single fiber pull-out experiments were carried out to investigate the sources and mechanism of tensile creep. The specimens for the production of test samples were cast following Katz and Li and the test set up for single fiber pull-out tests is based on Kanda and Li. The results of these experiments may be helpful to understand the phenomenon of cracking creep strain. The cracking creep strain is considered the additional and significant source of time-dependent deformation that is associated with formation of new cracks over time. The mechanism of creep in SHCC is also studied and a model for creep of SHCC is proposed by Zijl. This model has been shown to realistically capture rate-enhanced tensile resistance as well as tensile creep fracture.

This phenomenon of formation of new cracks and widening of cracks under tensile sustained loads need to be analytically quantified and simulated for durability design models of structures. The phenomenon of creep and creep fracture has been investigated in a computational framework for SHCC. This has been done at a macro-level using a homogeneous material model incorporating nonlinear creep for the behavior of SHCC.

To study the mechanical time-dependent behavior of SHCC, the experimental work has been done in the recent past. The first step in this regard was the tensile creep, drying shrinkage and the rate dependence characterization on uncracked SHCC specimens. The results of these experiments revealed the identification of new sources of time-dependent tensile strain that encourages the researchers to do more experiments on cracked SHCC to precisely model the phenomenon of time-dependent crack initiation and fiber pull-out creep.

In the present study the time-dependent behavior of SHCC is modelled by using multi-layered microplane model. The multi-layered model is an efficient tool to
simulate the multiple cracking behavior of SHCC along with phenomenon of widening of cracks over time at micro-level as well as the time-dependent change of crack spacing and number of cracks. The simulation of tensile creep and shrinkage behavior is the main target of the present study which has been characterized on each layer of microplane and the constitutive relationship of SHCC can be developed.

In the microplane model, the constitutive properties are characterized separately on small planes of various orientations within the material, called microplanes. Kinematic constraint is used on these microplanes, i.e., the total strain vector on each microplane (crack) is assumed to be resolved component of the macroscopic strain tensor while the fibers are assumed to be directed to normal to each microplane. The effect of fiber orientation may be considered by introducing a coefficient of fiber orientation. The state of each microplane is described by normal deviatoric and volumetric strain and by shear strain (further split into two orthogonal components) as shown in Fig. 1. The concrete creep has been incorporated into microplane model M4 for nonlinear triaxial behavior of concrete, including tensile fracturing and behavior under compression. The continuous relaxation spectrum has been determined for Maxwell chain, based on the solidification spectrum for ageing creep of concrete.

In the present study, the normal component of strains and stresses will be considered because the tangential stiffness is assumed negligible due to flexible nature of synthetic fibers. The constitutive relationship of SHCC is modelled by considering multi-layered microplanes. The position of these multi-layered microplanes on the sphere is shown in Fig. 2(a).

The main advantage of the multi-layered model is that the phenomenon of multiple cracking can be well explained by using the multi-layered microplane model for small sized specimen equal to about the size of one element used in FEM for simulation of larger structures. For this purpose the computational time for each simulation is very less, i.e., within minutes while for the same simulation of fiber and matrix interaction at cracking, the computational time is within hours.

2. MULTI-LAYERED MICROPLANE MODEL

Multiple cracking behavior can be modelled by expressing total strain by summation of strains in the uncracked part and those in the cracked part

\[
\Delta \varepsilon = \sum_{i=1}^{N_c} (\Delta \varepsilon_i)
\]

\[
\Delta \varepsilon_i = \Delta \varepsilon_{\text{un}} + \Delta \varepsilon_{\text{cr}}
\]

where \(N_c\) is the maximum number of active (open) cracks, \(\Delta \varepsilon_{\text{un}}\) and \(\Delta \varepsilon_{\text{cr}}\) are the strain increments for uncracked and cracked part respectively. The multiple cracking system is shown in Fig. 2(b) where \(L_{un}\) and \(L_{cr}\) are the lengths of uncracked part and cracked part at \(i\)-th crack respectively. The total strain, then, can be obtained by the substitution of the equations for strain increments of uncracked and cracked parts in Eq.[2].

2.1 Assumptions for multiple cracking under short-time loading

The following assumptions are used for the multi-layered model based on multiple cracking system.

1. \(P_i = P_{i0}\) where \(P_i\) and \(P_{i0}\) are the loads in \(i\)-th uncracked and cracked part respectively.

2. \(\sigma_{i0} < \sigma_{i1}\) where \(\sigma_{i1}\) is the fiber pullout stress in bridging fibers at \(i\)-th crack and \(\sigma_{i0}\) is the maximum bridging stress of fibers.

3. A bilinear relationship for the bridging (pullout) stress–fiber pullout displacement is assumed as shown in Fig. 3.

4. The total number of cracks is estimated from the
Fig. 3 Bilinear relationship of bridging stress-pullout displacement of fibers

\[ X'_0 = \frac{1}{2} \left( L_r - \sqrt{L_r^2 - 2\pi L_r x'} \right) ; x' = \frac{V_m}{V_f} \frac{\sigma_{mu} d_f}{4\tau_0} \]  

where \( L_r \) is the length of fiber, \( V_m \) and \( V_f \) are the volume of matrix and fiber respectively, \( \sigma_{mu} \) is the matrix ultimate strength, \( d_f \) is the diameter of fiber and \( \tau_0 \) is the frictional (bond) strength.

2.2 Assumptions for multiple cracking under sustained loading

The following assumptions are used for the multi-layered model for sustained loading based on multiple cracking system.

(1) Each time-dependent crack width depends on number of bridging fibers.

(2) Initially, all of the time-dependent cracks are assumed to appear as potential cracks. Then, those cracks change into active cracks over time.

(3) The number of fibers bridging each potential crack is assumed to be the same over time.

3. NUMERICAL MODEL FOR SHORT-TIME BEHAVIOR OF SHCC

Due to spatial distribution of short fibers, the material properties have a certain amount of statistical variation concluding that \( V_f \) is the principal independent parameter. The statistical distribution of the fiber volume fraction \( V_f \) is assumed to follow the uniform distribution with mean \( m_{V_f} \), the standard deviation \( \sigma_{V_f} \), and the coefficient of variation \( w_{V_f} \). It is assumed that cracking sequence is in the increasing order of tensile strength of SHCC.

At \( i \)-th crack \( \sigma_i = f_i \), where \( \sigma_i \) and \( f_i \) are the stress applied and the tensile strength of material at \( i \)-th crack respectively. To apply assumption (1), the following relationships are considered.

\[ P = \sigma A \ (A = bh) \]  
\[ P_j = \sigma_j A_j \ (A_j = N_j A_{j0}) \]  

where \( P \) is load passing through uncracked part, \( \sigma \) is the stress, \( A \) is the cross-sectional area of uncracked part with width \( b \) and height \( h \), \( P_j \) is the load passing through bridging fibers, \( A_j \) is the area of fibers, the number of bridging fibers is \( N_j \), \( A_{j0} \) is cross-sectional area of single fiber, and \( \sigma_j \) is bridging stress of fiber.

The equation to calculate the total displacement at \( i \)-th crack stage for \( N_i \); maximum number of cracks can be expressed as follows.

\[ (w)_T = \sum_{j=1}^{i} w_j + g_i \]  

where \( (w)_T \) is the total crack width at \( i \)-th crack stage and \( w_j \) is the crack width of \( j \)-th crack that can be evaluated as

\[ w_j = \frac{A_{ij}}{k_{ij} A_{ij}} \]  

where \( k_{ij} \) is the stiffness of bridging fibers per unit area of fiber at \( j \)-th crack and \( f_{ij} \) is the tensile strength at \( j \)-th crack. In Eq.[6], \( g_i \) is the sum of all crack openings due to increase of load beyond the initial cracking load at each crack stage, i.e.,

\[ g_i = \sum_{j=1}^{i} \left( \frac{P_{ji}-P_{ji-1}}{k_{ij} A_{ij}} \right) + \sum_{j=1}^{i} \left( \frac{P_{ji-1}-P_{ji}}{k_{ij-1} A_{ij-1}} \right) \]  

where \( P_{ji} \) is the load at \( j \)-th crack stage and \( P_{ji-1} \) is the load at \( j-1 \) crack stage. In Eq.[8], the summation is taken place while the upper limit is larger than the lower limit and last term is for \( j = i \). Hence the strain at \( i \)-th stage of cracks for cracked part is \( \varepsilon_{cri} \) that can be calculated in terms of stiffness of fiber by using Eq.[9].

\[ \varepsilon_{cri} = \frac{(w)_T}{L_0} \]  

where \( L_0 \) is the original length of specimen.

4. MODELLING OF TIME-DEPENDENT BEHAVIOR OF SHCC

Following the same formulation of multi-layered microplane model, the incremental macroscopic time-depen-
dent stress-strain relationship can be represented as

$$\Delta \sigma_{ij} = C_{ijm} (\Delta \varepsilon_{ij} - \Delta \varepsilon_{ij}^{\text{creep}} - \Delta \varepsilon_{ij}^{\text{shr}})$$  \hspace{1cm} \text{[10]}$$

where $\Delta \sigma_{ij}$ and $\Delta \varepsilon_{ij}$ are the macroscopic stress and strain increments, $\Delta \varepsilon_{ij}^{\text{creep}}$ and $\Delta \varepsilon_{ij}^{\text{shr}}$ are the strain increments for tensile creep strain and shrinkage strain, and $C_{ijm}$ is the stiffness tensor which can be evaluated as

$$C_{ijm} = \frac{3\pi}{2} \int n_i n_j n_k C_{ik} F(n) \, ds$$  \hspace{1cm} \text{[11]}$$

$$\Delta \varepsilon_{ij}^{\text{creep}} = n_i n_j (\dot{\varepsilon}_{ij}^{\text{creep}} + \ddot{\varepsilon}_{ij}^{\text{creep}}) \Delta t$$  \hspace{1cm} \text{[12]}$$

$$\Delta \varepsilon_{ij}^{\text{shr}} = n_i n_j \varepsilon_{ij}^{\text{shr}} \Delta t$$  \hspace{1cm} \text{[13]}$$

where $C_{ij}$ is the incremental normal secant modulus for current loading for a microplane. $F(n) = 1$ which is a weight function of the normal direction that can introduce anisotropy in its initial state and $n$ with subscripts $i,j,r,s$ are the direction cosines.

In Eq.[12], $\dot{\varepsilon}_{ij}^{\text{creep}}$ is the rate of tensile matrix creep strain and $\ddot{\varepsilon}_{ij}^{\text{creep}}$ is the rate of creep cracking strain. The tensile matrix creep component can be evaluated as

$$\dot{\varepsilon}_{ij}^{\text{creep}} = a_i a_j (t - t_0) \sigma_N^{a_i - 1}$$  \hspace{1cm} \text{[14]}$$

where $t$ is current time, $a_i a_j$ are the constants that can be adjusted by identification with test data for creep, $t_0$ is time at loading and $\sigma_N$ is the normal stress acting on a microplane.

$\varepsilon_{ij}^{\text{shr}}$ is the rate of shrinkage strain. $\Delta t$ is the time increment at each loading stage. The shrinkage strain component can be calculated as, using the power law,

$$\dot{\varepsilon}_{ij}^{\text{shr}} = b_i b_j (t - t_1) h_i^{-1}$$  \hspace{1cm} \text{[15]}$$

where $t_1$ is time at drying. $b_i b_j$ are the constants that can be adjusted by identification with test data.

### 5. TIME-DEPENDENT CRACK WIDTH MODEL

The creep cracking strain is dependent on time-dependent fiber pullout displacements. These time-dependent fiber pullout displacements can be attributed to the time-dependent crack widths at each cracking stage. If sufficient data of fiber pullout creep is available, then the rate of cracking creep strain can be calculated as

$$\dot{\varepsilon}_{ij}^{\text{creep}} = \frac{1}{L_0} \sum_{i=1}^{N_c(t)} w_{ij}(t)$$  \hspace{1cm} \text{[16]}$$

where $N_c(t)$ is the maximum number of active cracks, $L_0$ is the original length of specimen and $w_{ij}(t)$ is the rate of time-dependent crack width. The time-dependent fiber pull out displacement can be calculated as power function of difference of time at initial loading and current loading as follows

$$w_{ij}(t) = c_{1i} (t - t_0)^{c_{2i}} = w_{ij}(t)$$  \hspace{1cm} \text{[17]}$$

where $w_{ij}(t)$ is the time-dependent fiber pull out displacement at $i$-th crack. $w_{ij}(t)$ is the time-dependent crack width of $i$-th crack. $c_{1i}, c_{2i}$ are the parameters that can be adjusted by identification with experimental data for each time dependent crack. The rate of time dependent crack width at $i$-th crack stage can be given as

$$w_{ij}(t) = c_{1i} (t - t_0)^{c_{2i}} - 1$$  \hspace{1cm} \text{[18]}$$

where $w_{ij}(t)$ is the rate of time-dependent crack width. Hence cracking creep strain can be formulated for each crack by using Eq.[16]. The total crack width is obtained by Eqs.[14], [15] and [16].

### 6. ALGORITHM FOR CALCULATIONS

Eq.[10] represents the macroscopic constitutive incremental relationship for short time and time-dependent behavior. The relationship is sufficient to simulate time-dependent behavior of SHCC for drying shrinkage and tensile creep. The step-by-step algorithm for calculation of simulations is given below.

1. The macroscopic strain increments are imposed at the first step for normal strains for uniaxial tensile loading. These increments are updated at each stage of loading.

2. These macroscopic normal strains are transformed into strain at each microplane by multiplying direction cosines, i.e., the global normal strain is transformed into local normal strain.

3. Based on the local normal strain, the normal secant modulus is calculated for single multi-layered microplane as shown in Fig. 2(b) as exponential function. This function is then integrated over 21 integration points on the spherical surface. This numerical integration formula is based on the work of Ref.[14] in which the comparison of microplane models for different integration point formula is reported. For the present study, the 21-point formula is used.

4. After calculating global stiffness tensor, the incremental macroscopic stress is calculated by using Eq.[10] without time-dependent strains. These
steps are followed if strain hardening is observed before applying the sustained load. In the present case, no strain hardening and multiple cracks are observed. Hence stress–strain relationship is elastic before applying sustained load for tensile creep.

(5) The sustained load for tensile creep is applied in the absence of drying shrinkage as practically drying shrinkage is measured separately by using different set up. Therefore drying shrinkage and tensile creep are calculated separately and then added to get total time–dependent behavior if required.

(6) When sustained load starts to apply, the stress increments become zero as now stress becomes constant. All of the potential cracks appear at the start of application of sustained load. The applied stress is usually a certain percentage of static first cracking strength of the material to practically reduce the chances of static cracking strain to be appeared. In this case, the left hand side of Eq.[10] becomes zero.

(7) For right hand side of Eq.[10], the stiffness tensor cannot be zero. Therefore, the term within brackets become zero which gives the strain equal to strain due to tensile creep or drying shrinkage or total time–dependent strain.

(8) Then the creep matrix strain and creep cracking strain are calculated in the absence of drying shrinkage as drying shrinkage is separately simulated for sealed creep specimens.

(9) The both components of tensile strain are calculated by imposing time increments as rate functions. The material parameters for matrix creep are adjusted by identification with experimental data. The time function is a scalar parameter so that it is universal in all directions. The strain field is also assumed uniform. Therefore coordinate transformation is enough and summation over the microplanes is not required for time–dependent strains.

(10) For the creep cracking strain, the time–dependent number of cracks is taken from the experimental data and time–dependent crack widths are calculated from Eq.[18]. If sufficient data for time–dependent fiber pull–out displacements is not available, then the data for time–dependent crack width can be simulated directly as time–dependent displacements are attributed to time–dependent crack widths.

(11) For simulation of drying shrinkage, Eq.[15] is used. The parameters are adjusted by identification with experimental data.

(12) The results are plotted for tensile creep, drying shrinkage and time–dependent crack widths and compared with experimental data.

7. RESULTS AND DISCUSSIONS

7.1 Drying Shrinkage

The drying shrinkage is measured separately for the same properties of dumbbell shape specimens with material properties in Table 1. The value of shrinkage strain is significant for SHCC and it cannot be ignored to model the time–dependent behavior of SHCC as drying shrinkage is expected to occur in SHCC. For that purpose two unloaded and unsealed specimens were tested by Boshoff et al[5]. The shrinkage specimens are kept in the same controlled climate as the creep specimens. The age of SHCC at loading or drying is 14 days. The relative humidity during the test is 65 % and the temperature is 23 °C. The test setup for drying shrinkage is shown in Fig. 4. The average shrinkage of two specimens is reported and it is used to compare with the simulated results. The model parameters have been adjusted by identification with test data and given in Table 2. The analytical results show a good agreement with the experimental data as shown in Fig. 5.

7.2 Tensile Creep

The tensile creep is simulated in the present study by using two different test data. The tensile sustained load is applied on the pre–cracked specimens. The material properties are given in Table 1 for two different tests data. This kind of test data is fully representative
Table 2 Model parameters of analysis

<table>
<thead>
<tr>
<th>Test data</th>
<th>Model parameters</th>
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<tbody>
<tr>
<td>Drying shrinkage</td>
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<tr>
<td></td>
<td>$b_1$ 0.007</td>
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<tr>
<td></td>
<td>$b_2$ 0.15</td>
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<tr>
<td>Tensile creep</td>
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<td></td>
<td>$a_1$ 0.015</td>
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<tr>
<td>Tensile creep</td>
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<tr>
<td></td>
<td>$a_2$ 0.36</td>
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<tr>
<td>Time-dependent crack width</td>
<td>$c_1$ 0.035</td>
</tr>
<tr>
<td></td>
<td>$c_2$ 0.25</td>
</tr>
</tbody>
</table>

Fig. 5 Comparison of analytical results of drying shrinkage (for unloaded, unsealed specimens) with experimental data

Fig. 6 Test setup for tensile creep

of the model presented here as the mechanism of time-dependent fiber pull-out and widening of cracks over time is significantly observed in the specimens. The simulation is done by following the algorithm explained in the previous section. The model parameters are adjusted by identification with test data.

This experimental data is resulted by measuring tensile creep for the pre-cracked dumbbell shaped specimens of dimension given in Table 1. These specimens are notched from the center to focus the cracks in the notched area. The creep test setup has been designed and built to apply the creep load with free hanging weights acting on the specimen with a lever arm as shown in Fig. 6. For the proposed model such kind of data has been considered the most appropriate as the potential cracks are assumed in this model to be appeared initially for tensile creep. The experimental conditions are explained in Ref.[2] as the age of SHCC at loading or drying is 14 days and the relative humidity during test is 65 %. The temperature during test is 23 °C. The applied sustained stress in this case is 60 % of the static tensile stress which gives value equal to 1.94MPa. The creep is measured for 16 days. The drying shrinkage in this case is measured separately for the same mix proportion of specimen that gives a value of shrinkage deformation equal to 0.04mm.

As compared to the total tensile creep strain value about 2 %, the drying shrinkage is considered almost negligible. The analytical results show a good agreement to experimental data as shown in Fig. 7. Fig. 8 shows the tensile creep model verification for another test data. The analytical results show a good agreement to experimental data. For this case, the creep is measured with completely sealed specimens by applying Sikagard 63N sealant.

For tensile creep data of Fig. 8, the sustained load is applied as 70 % of the static tensile load on the specimen. The value of applied sustained load is 1.87MPa. The experimental conditions are explained in Ref.[5] as age of SHCC at loading or drying is 14 days while the loading rate up to maximum stress for creep is 0.1mm/sec. The relative humidity during the test is 65 % and the temperature is 23 °C. The test setup is shown in Fig. 6 for measuring tensile creep for the dumbbell shaped specimen of dimensions given in Table 1. The comparison results show a good agreement at early age and at later stage of times as well. The experiments have also been done for single fiber creep to distinguish fiber creep from the pull-out creep deformation. These experiments resulted in the fact that the contribution of single fiber creep itself is insignificant. As a result the single fiber creep is considered as negligible in the present model.

The time-dependent constitutive relationship resulted in the tensile creep strain curve that is shown in
The results show the start of creep at 60% of the static tensile load. After that, the creep strain phenomenon occurs and load becomes constant.

7.3 Time-dependent Crack Width

The time-dependent crack width data is available that is a result of work by Boshoff et al.\(^2\). The number of cracks has been observed over time. These observations were done by taking pictures of notched area using an 8 Mega pixel digital camera connected to a microscope. Photos were taken at suitable interval for tensile creep tests. These photos have been used to evaluate the crack patterns, crack distributions and number of cracks. A scale has been set to the photos in order to measure the crack widths optically. Because of this kind of data, it becomes possible to fully depict the mechanism of creep cracking strain and to model them successfully. A very few such kind of test data is available. It is the recent focus of researchers these days. The simulation is done for average values of crack width by dividing maximum displacement of cracks by the number of cracks over time. The number of bridging fibers and \(c_1, c_2\) are considered the same for each crack in the present model for simplicity. Hence model parameters are considered the same for all active cracks. The analytical results are shown in Fig. 10 along with number of cracks at each development of average crack width over time. The model parameters are given in Table 2 while material properties are shown in Table 1.

Fig. 10 represents the analytical results compared with test data for crack widths. For this case, the number of cracks over time was also reported in the reference. Based on these available test data values, it became easier to implement the presented model.
to simulate time-dependent crack width. The results show a good agreement with test data.

8. CONCLUSIONS

The conclusions of the present study are summarized below.

(1) The time-dependent mechanism of strain hardening cement-based composites is fully interpreted by incorporating all the possible mechanisms for the tensile creep including matrix creep and fiber pull-out creep.

(2) The time-dependent constitutive relationship for strain hardening cement-based composites is established at each microplane (crack) which is a good interpretation of the practical sources of tensile creep and drying shrinkage.

(3) The results for the tensile creep and drying shrinkage of the presented analytical study show a good agreement with the experimental data. Although a very few such kind of data is available for SHCC but still the results are satisfactory.

(4) The numerical model of time-dependent cracking strain is based on time-dependent fiber pull-out displacements while the experimental data was available for the time-dependent crack widths. Therefore, the simulation is done by considering the fact that the time-dependent fiber pull-out is attributed to the time-dependent crack widths. This assumption resulted in satisfactory comparison with experimental data.

(5) The creep cracking strain is dependent on magnitude of sustained loading applied. The creep cracking strain become more significant when the percentage of the static tensile stress applied as sustained stress is increased. At lower sustained stress values, smaller number of time-dependent cracks are formed. Therefore, the contribution of the creep cracking strain in the total tensile creep of the specimen will be less at smaller magnitude of sustained loading as percentage of static tensile load.

(6) Given sufficient test data, the present model will be extended to be used for developing new SHCC materials for multiple cracking for given mix proportions and fiber information. The fiber characteristics and mix proportion information are used as input to estimate number of cracks. The prediction of stress-strain relationship or strain-time relationship with multiple cracking information is output of the present model.

REFERENCES:


