

Modeling in ABAQUS for Experimental Investigation of Multi-linear Bond Slip Properties in Reinforced Concrete

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Abstract—Integrity of R.C.C. solely depends on bond between concrete and rebar. Most of the times, bond-slip properties are modeled as indirect parameters in numerical analysis. This indirect approach fails to capture true bond slip character especially in sensitive areas like connections. To understand behavior of RCC in connection region it is felt essential to model true bond slip between concrete and rebar.

Direct bond slip approach is usually avoided by researchers due to increased number of elements and difficulties in curvature contact modeling. Multi-linear or exponential nature of bond slip curve makes it even more complicated to model for numerical analysis..

This work is an attempt to mathematically model experimentally evaluated constitutive bond slip properties of onsite material in ABAQUS. Bond slip properties are mathematically modeled in ABAQUS using cohesive properties and damage evolution option. The geometry of rebar is slightly modified in order to reduce number of elements and to improve curvature contact parameters. Detailed procedure to obtain multi-linear damage evolution is also described. Experimental and numerical results are compared to establish efficacy of mathematical model.

Keywords—Abaqus, Bond-Slip, CDP model, cohesive surface, constitutive properties, experimental, multi-linear damage evolution, on-site material.

I.INTRODUCTION

Performance of RC structure depends on composite action of Rebar and Concrete. This composite action can be ensured only through adequate bond between these materials. Geometrical form of RC frame is ensured through rigidity of the connections. When subjected to seismic excitation, severe bond demands are generated at connections[1]. In order to understand behavior mechanics of connection, proper numerical modeling of bond slip properties is essential. Modeling direct bond-slip properties is tedious and complex. Generally CDP model is with tension stiffening with progressive damage characteristics is adopted for the purpose [2]. Rebar is modeled as wire/truss element and perfect embedment of rebar is assumed. Indirect bond slip is achieved through cracking and subsequent tension hardening/softening[3]. For macroscopic study of rcc element as a whole this approach provides reasonable results. How-ever, for microscopic study of connections, this approach may not provide correct picture of connection behavior. In such cases modeling direct bond slip properties is essential.

Bond slip properties are dependent on the constituent material properties of concrete and rebar. Thus, to model bond slip it is imperative to determine those properties. Properties of site manufactured material differ greatly from those in laboratory conditions. Material specimen were sourced at site conditions and tested to obtain constituent properties of concrete in uniaxial compression, Rebar in uniaxial tension and monotonic bond slip properties for moderate embedment lengths.

Material property results obtained; are processed on basis of literature available for modeling CDP and Rebar to generate input data for ABAQUS.[4]

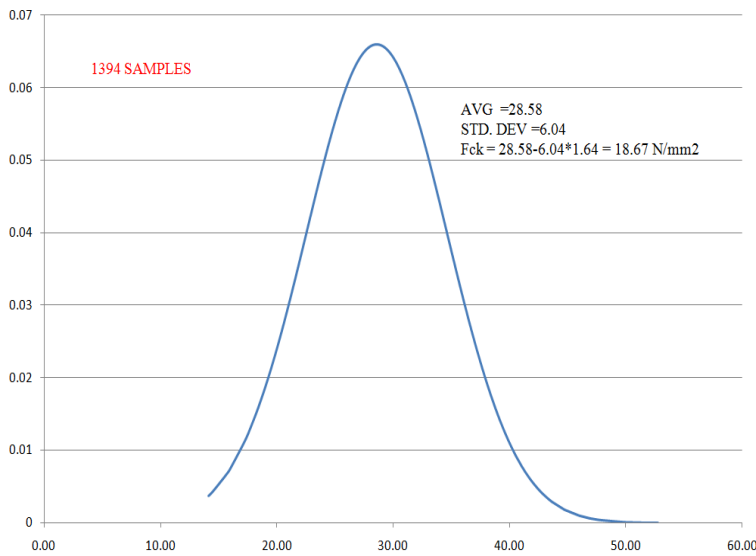
To model bond-slip phenomenon, cohesive surface option with damage evolution is considered. In order to improve curvature contact properties minor modifications are made in rebar cross section geometry. Numerical and experimental results obtained are compared to evaluate mathematical modeling.

II. CONSTITUTIVE PROPERTIES

2.1 Concrete Damaged Plasticity Model

It was decided to obtain on field data for concrete cubes instead of depending on secondary data available in literature. For reliability of data large sample base of concrete testing was required. Data from various authentic concrete testing labs from western Maharashtra was collected. In all data for 1394 site sourced blocks was collected. Normal distribution

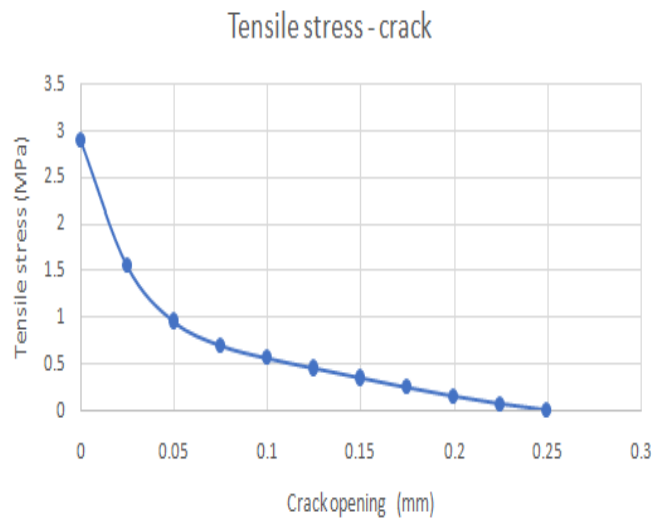
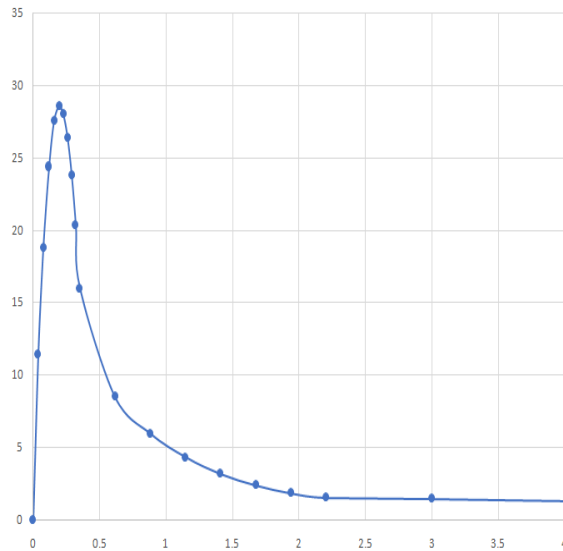
curve was plotted in order to get F_{ck} and F_u values for blocks. Normal distribution curve and relevant values are shown in Fig.1.



Dilatation angle	36^0
Eccentricity	0.1
Ratio bi- /uni-ax	1.16
K	0.667
Viscosity	1e-5
Table 1	

Fig. 1 normal distribution curve for 1394 concrete blocks

F_{ck} for sample size of 1394 Blocks works out to be 18.67 and F_u is 28.58. In absence of multi-axial test data, CDP[3] model modified by Drucker–Prager[5] is referred for preparing constitutional graphs. To obtain compression properties of concrete, EC2[6] is referred up to ultimate strain. For post peak behavior sinusoidal descending branch as per Pavlovicis used. Tension behavior is based on cornessilon curve as defined by Quereshi and Lam. An excel chart was prepared to obtain various properties and damage evolution curves for F_{ck} and F_u . The obtained curves are shown in Fig.2. Numerical values to be used in ABAQUS are given in Table 2. Other relevant data to define CDP parameters was collected from the literature and ABAQUS manual. This data is shown in Table 1.



Concrete compression (total strain vs stress) Fig.2 Tension (crack opening vs stress)

Tension stiffening[3] is used to model stress-strain response between concrete and rebar after cracking. Tension stiffening defines how load is transferred to rebar from the concrete as it cracks. Damage variables are treated as non-decreasing material quantities and correspond to reduction in stiffness.

Table 2. input values for concrete properties.

COMPRESSION			TENSION		
Stress	inelastic strain	damage	damage dt	displacement	yield stress
σ_c (Mpa)	ϵ_c^{in}	dc	0.0000	0.000E+00	2.103758
	$\epsilon_c - \epsilon_{oc}^{el}$	1-sc/fcm	0.4626	3.261E-02	1.130501
0	0	0	0.6706	6.522E-02	0.692919
11.432	0	0	0.7599	9.784E-02	0.505213
18.81253	0.000155	0	0.8071	1.304E-01	0.405891
24.39008	0.00037	0	0.8443	1.631E-01	0.327625
27.56777	0.000665	0	0.8805	1.957E-01	0.251469
28.58	0.001031	0	0.9158	2.283E-01	0.177168
28.02737	0.001354	0.019336	0.9483	2.609E-01	0.108779
26.42161	0.001711	0.075521	0.9765	2.935E-01	0.049379
23.83555	0.002101	0.166006	0.9980	3.261E-01	0
20.33544	0.002521	0.288473			
15.98167	0.00297	0.440809			
8.508462	0.005868	0.702293			
5.941496	0.008603	0.79211			
4.295022	0.011308	0.849719			
3.161929	0.013995	0.889366			
2.376291	0.016671	0.916855			
1.848713	0.019339	0.935314			
1.523458	0.021999	0.946695			
1.429	0.029953	0.95			
0.4	0.099987	0.986004			

TABLE 2.

2.2 Rebar model

15 numbers Rebar of diameter 16 mm 12 mm and 20 mm were sourced from site. Specimen were subjected to find out average proof and ultimate strength. Ramberg-osgood coefficients and MMPDS-01, equation 9.8.4.1.2(b) were referred to obtain engineering and true stress strain graphs in excel spread sheet. Input data of stress strain parameters is as illustrated in Fig 3.

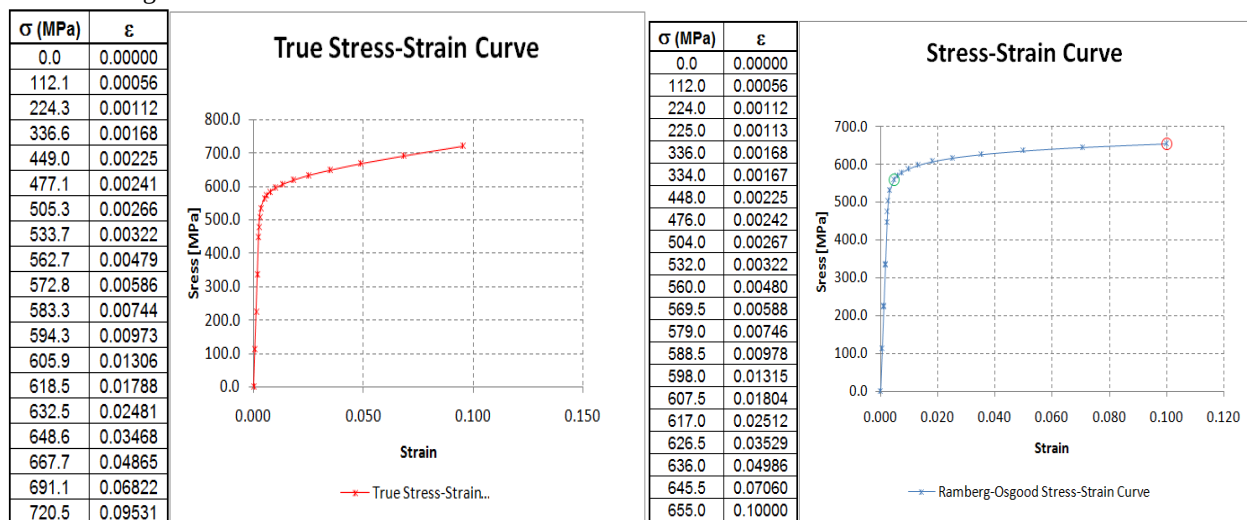


Fig 3. Input values for rebar material in Abaqus

2.3 monotonic bond slip

The bond stress (τ) vs. slip (S) relation for monotonic loading is defined piecewise by a set of five polynomial functions [7], as illustrated below, based on experimental observations. Up to 40% of peak strength (τ_{max}), bond stress increases linearly with slip. Non linear hardening behavior is represented by a fourth-order polynomial, followed by a plateau at τ_{max} . The bond strength degradation is described by a linear descending branch. When slip equals the clear rib spacing for bar (S_R), a residual bond stress equal to 25 to 40 % of τ_{max} is assumed. This value remains constant for further slip.

The expression for monotonic envelope is provided below. In terms of three parameters, Maximum bond strength ($\tau_{\max}$), Slip at which $\tau_{\max}$ is attained (s_{peak}), and clear spacing between ribs (s_R). Equations for multi-segmented bond slip law for monotonic loading are as follows,

$$\tau(s) = \begin{cases} 4 \frac{\tau_{\max}}{s_{\text{peak}}} s & s < 0.1 s_{\text{peak}} \\ \tau_{\max} \left[1 - 0.6 \left(\frac{s - s_{\text{peak}}}{0.9 s_{\text{peak}}} \right)^4 \right] & 0.1 s_{\text{peak}} \leq s < s_{\text{peak}} \\ \tau_{\max} & s_{\text{peak}} \leq s < 1.1 s_{\text{peak}} \\ \tau_{\max} \left[1 - 0.75 \frac{s - 1.1 s_{\text{peak}}}{s_R - s_{\text{peak}}} \right] & 1.1 s_{\text{peak}} \leq s < s_R \\ 0.25 \tau_{\max} & s \geq s_R \end{cases}$$

Graphical presentation of the polynomials is shown in Fig. 4

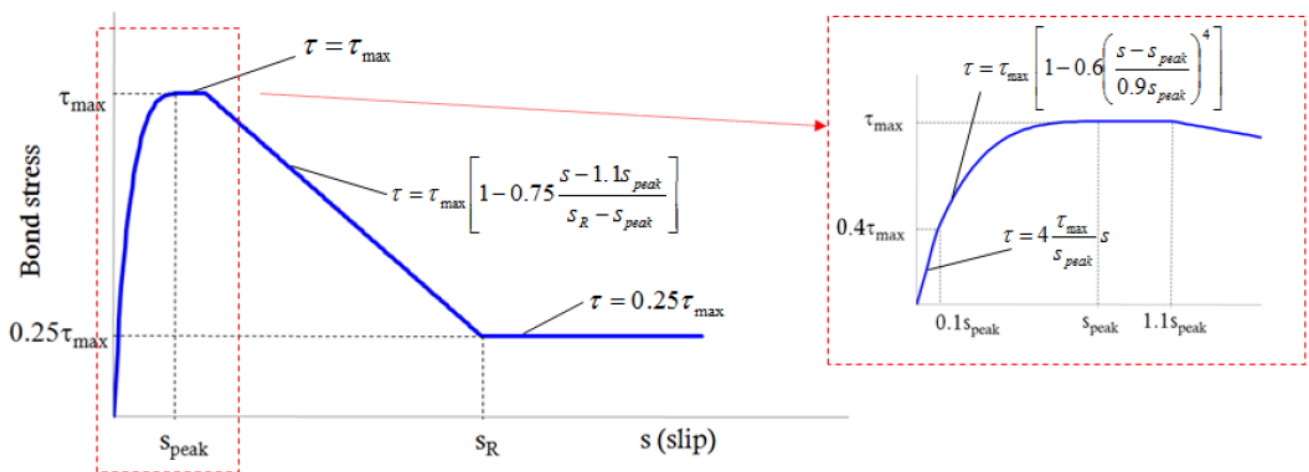


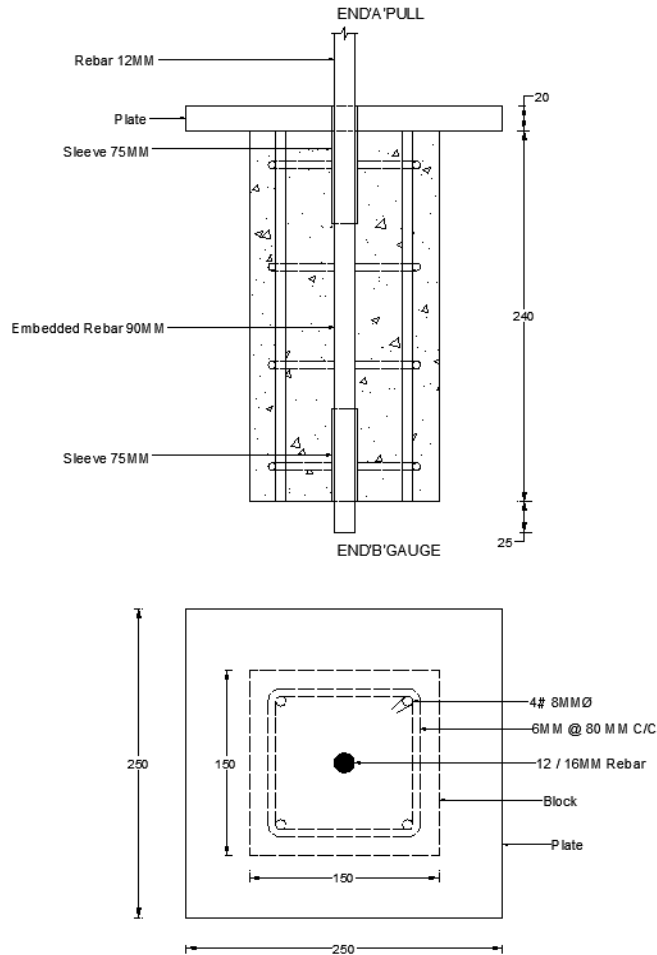
Fig. 4 Monotonic bond slip

2.4 Experimental investigation

A concrete block of size 150x150x240 mm was adopted. Block was reinforced with 4 bars of 8 mm dia. as longitudinal reinforcement. 6 mm dia. 4 no. of links were used as confining reinforcement[8]. 12 mm dia. bar was embedded in central part of block for 90 mm length. Ends of bar were kept un-bonded from concrete by means of PVC pipes and thermo-coal. Specimen were placed in UTM with concrete block held against middle cross head and pull subjected to end 'A' as shown in Fig.5. A digital dial gauge was attached to end 'B' to measure the slip. Average values of F_{ck} , s_R , $\tau_{\max}$, and s_{peak} are as described in Table 3. The graphical presentation is as shown in fig 6.

Table 3. experimentally obtained values of bond slip relation

Bar Dia.	F_{ck}	$s_{1 \text{ peak}}$	$s_{2 \text{ peak}}$	s_R	$\tau_{\max}$
12	19.2	1.2	2.18	8	11.9
16	19	1.1	2.8	10	12.1



Pull out specimen

Fig.5

bar with sleeve and separator

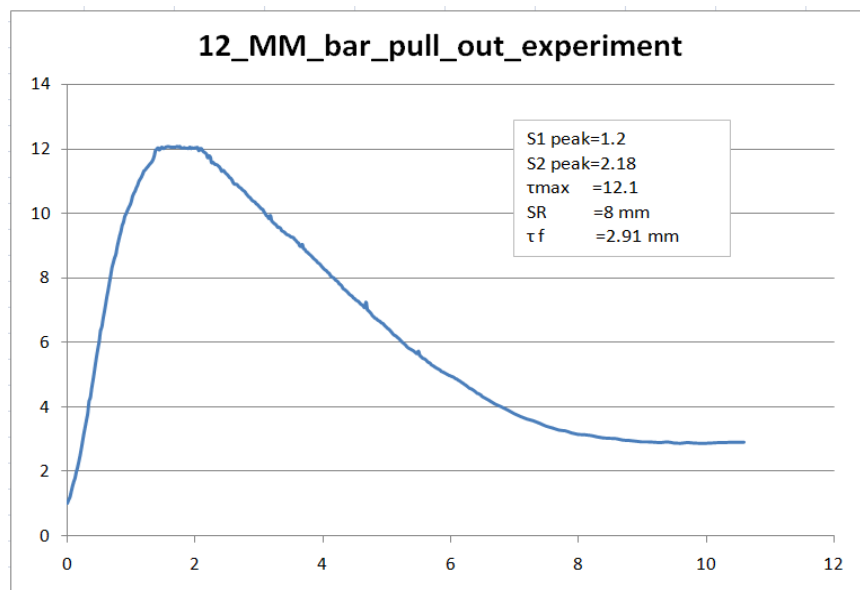


Fig.6 Graph of bond slip obtained in experiment.

3. NUMERICAL MODEL

3.1 Numerical data for bond-slip.

If experimental data is not available then secondary data sourced from literature may be used as follows [9]. The clear rib spacing (S_R) is a measured geometric property of rebar, and is usually between 40 to 60% of the bar diameter. Since bond strength depends on many factors, no theoretical formulae are available to accurately determine τ_{max} , and S_{peak} . However, referring to CEB-FIP 2000 values of τ_{max} , and S_{peak} may be used from Table 4.

Table 4. Bond parameters as per CEB-FIP 2000

Confinement status	S_{1Peak}	S_{2peak}	S_R	τ_{max}	τ_{Fric}
Unconfined	0.6 mm	0.6 mm	Rib spac.	$2.0\sqrt{F_{ck}}$	$0.15 \tau_{max}$
Good confined	1.0 mm	3.0 mm	Rib spac.	$2.5\sqrt{F_{ck}}$	$0.40 \tau_{max}$

Bond slip behavior as shown fig 4 needs to be idealized in multi-linear format for generating input data for Abaqus. With reference to CEB-FIP-2000 monotonic bond slip is idealized as multi-linear graph shown in Fig. 7. First ascending branch is defined by slope of the line with termination point as τ_{max} value. Horizontal part between S_{1Peak} and S_{2peak} is numerically modeled with a line with very little slope as to ensure convergence. This branch and descending branch is defined as damage evolution in Abaqus.

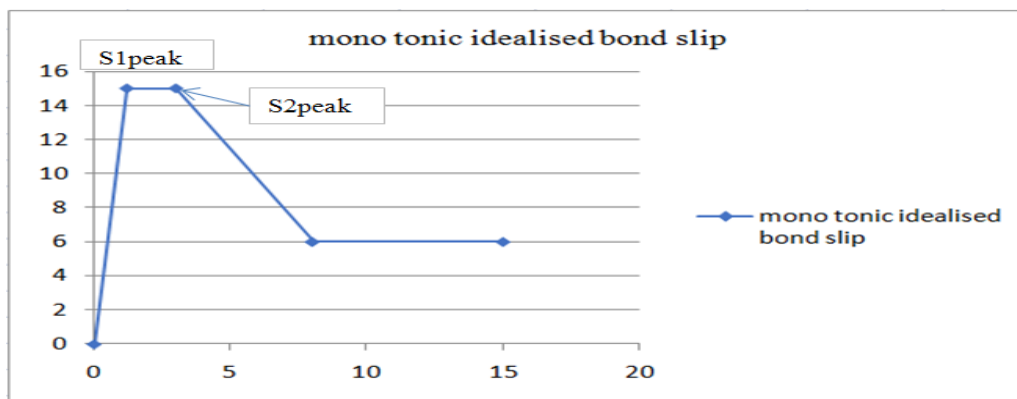
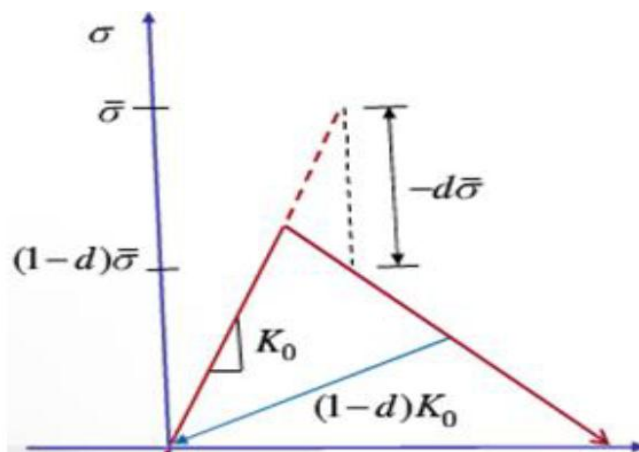


Fig.7 idealized bond-slip curve

Specimen calculations of damage evolution can be seen in Table 5. Key to have proper damage evolution is to understand how value of damage factor 'Df' is calculated. Fig 8. explains basis of 'Df' calculation.



Mathematical model of any curve for damage evolution can be prepared from basic concept ,

$\text{Sigma_bar} = KSS \times \text{Total Slip (without damage)}$

$\text{Sigma} = \text{Expected bond stress for given slip (experimental input data)}$

$Df = 1 - (\text{Sigma} / \text{Sigma_bar})$

Fig.8 calculation of Df.

Table 5. Excel sheet for ' Df 'calculation.

multilinear variation slip_ag_bond						
kss=ktt=11.9 /1.2=		9.91666667				
slip	step factor slip	sigma_expe	step_sigma	sigma_	Df	abs_plastic_slip
1.2	0.001302605	11.9	-0.0001002	14.4	0.173611	0
1.201303		11.8998998		14.41563	0.174514	0.001302605
1.202605		11.8997996		14.43126	0.175415	0.00260521
1.203908		11.8996994		14.44689	0.176314	0.003907816
7.995875		4.80525		95.9505	0.949919	6.795875
7.99725		4.8035		95.967	0.949946	6.79725
7.998625		4.80175		95.9835	0.949973	6.798625
8	0.1	4.8	0	96	0.95	6.8
8.1		4.8		97.2	0.950617	6.9
8.2		4.8		98.4	0.95122	7

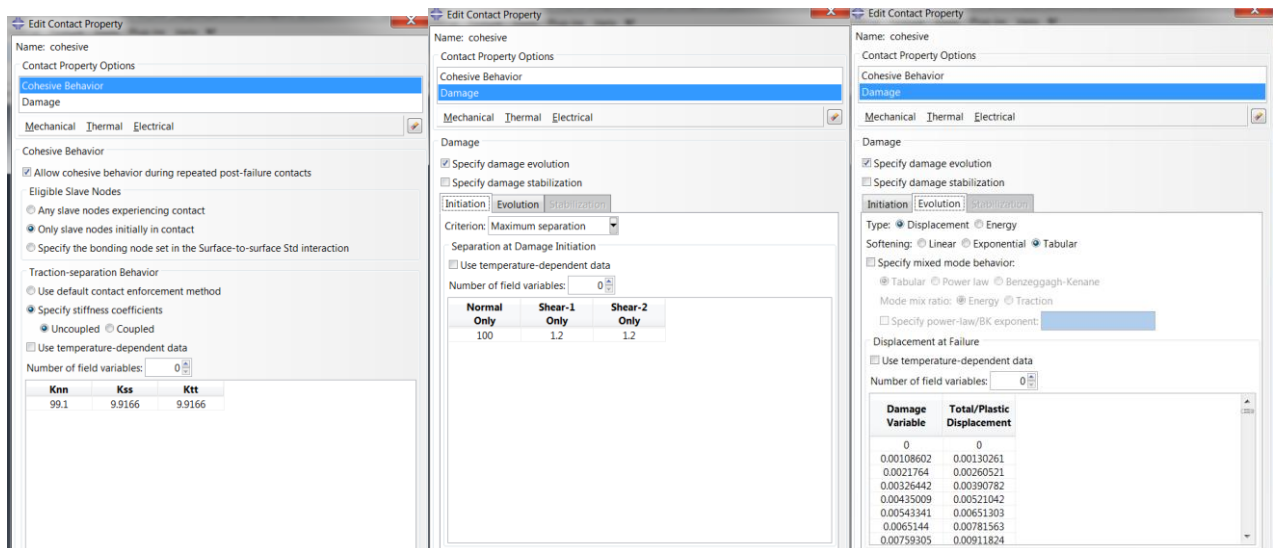
To account for perpetual friction of 0.4 or .25 τ_{max} , damage evolution is suspended at relevant bond stress value and then slips increases further without decrease in τ representing frictional part of bond slip curve. ABAQUS input is shown in Table 6. K_{ss} (Tangential stiffness) in cohesive behavior is slope of ascending line of bond slip curve.

$$: K_{ss} = (\tau_{max} / S_{1Peak})..... \text{Here it is } 11.9/1.2 = 9.9166 \text{ N/mm} \quad (2)$$

K_{nn} is normal stiffness. Exact definition of K_{nn} is not very clear in literature. K_{nn} may be assumed to be resistance of concrete to rebar, crushing concrete at interface. Logically value of K_{nn} can be assumed as,

$$: K_{nn} = (E_{conc} / 2 * \text{radius of bar}) \times 10^3 \text{ N/mm} \quad (E_{conc} = 4500 \sqrt{F_{ck}}) \quad (3)$$

Table 5. cohesive input for Abaqus.

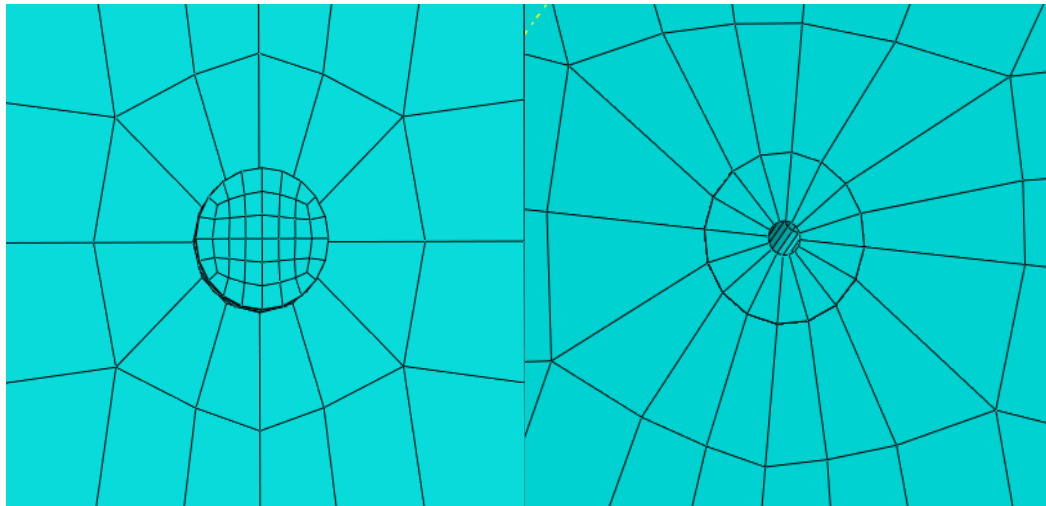


Damage initiation is value of slip S_{1peak} . Slip continues until S_{2peak} without damage as seen in first three terms of damage evolution. Once slip reaches S_{2peak} damage initiates and continues until slip reaches S_R . This is represented by damage parameter 0.6 in table 5. There after slip continues with bond stress remaining constant at $0.4\tau_{max}$.

3.2 Material modeling

Geometrical properties of experimental specimen are replicated in numerical model. Concrete and rebar are modeled as described earlier. Cohesive interaction option in ABAQUS is used to model interface between concrete and rebar to be pulled out. Properties of cohesive bond slip are discussed earlier. Longitudinal and transverse reinforcement in concrete block is modeled using embedded option in ABAQUS. This reinforcement is modeled as wire element B31. Main bar to be pulled out is modeled as 3d solid and C3D8 elements are used to mesh rebar. Ensuring proper contact between rebar and concrete is difficult due to its curved nature. Coarser mesh tends to cause over-penetration between contact surfaces.

Finer mesh increases computational demands. A small hole of 2 mm dia. is introduced coaxially with 12 mm rebar. This improves meshing of rebar surface ensuring proper contact as shown in Fig.9.



Bar without hole(elements 44)

Bar with 2 mm hole (elements 16)

Fig.9. Proper contact formation in part with hole

Introduction of hole reduces area of cross section of bar by 2.78 %. Input values from rebar stress strain graph were modified to account for this reduction in c/s area. Loaded end of bar and supported zone of block were modeled as rigid material in order to avoid local disturbances. Element sizes were adjusted between slave and master elements to ensure proper contact and convergence. Pull out bar was restricted from rotating about longitudinal axis in order to avoid singularity condition. Increments in step size reduced to $1e-5$.

Appropriate boundary conditions were imposed on concrete block and displacement load was applied to rebar in ramp form. Message and output data was checked for over closure and un-bonded elements. The unsymmetrical matrix option was opted for convergence. Graph of slip against bond stress were derived from the results.

4. COMPARISION

Numerically obtained graph is compared to experimentally obtained graph. Both graphs are shown superimposed in Fig.10.

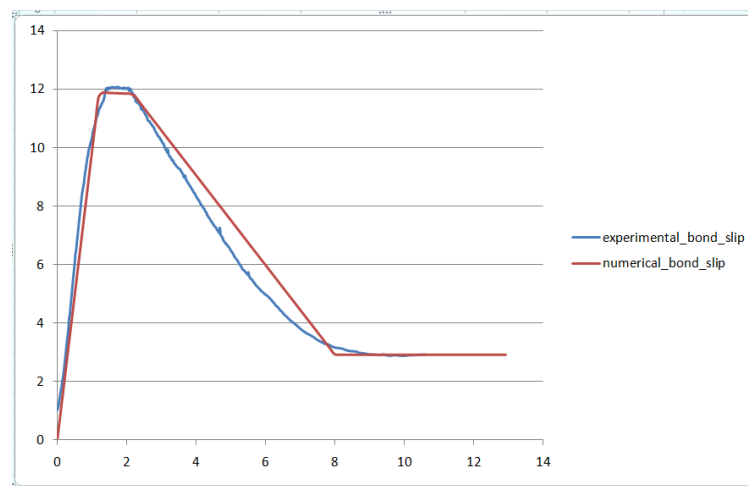


Fig. 10 Experimental and mathematical behavior

It can be observed that mathematical and experimental results match fairly except for descending part of damage evolution curve. This is because of idealized assumptions about curve data input to Abaqus. Modeling current damage

evolution required data generation for 5000 points. A more precise mathematical curve can also be derived with more rigorous damage evolution calculations if required.

5. CONCLUSION

1. Experimentally derived material properties can be mathematically modeled in Abaqus.
2. True bond slip can be modeled in Abaqus. This can eliminate need of approximate interactions like combination of embedded elements and tension stiffening.
3. Judicious modifications in rebar geometry can ensure proper curvature contact control.
4. Experimental and mathematical bond slip distribution fairly agrees with each other.
5. Calibrated model of material properties can be useful in understanding behavior of more complicated and experimentally difficult to establish geometries.
6. Further experimental and mathematical modeling needs to be carried out on calibration of cyclic and reverse cyclic bond slip properties.
7. Illustrated bond slip model can be used to solve problems at microscopic level where theory of fracture mechanics and tension stiffening cannot be used.

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