USER BULLETIN 5

DETERMINATION OF MATERIAL PROPERTIES

1. INTRODUCTION

Correctly defining concrete and rebar properties are important for any nonlinear finite element analysis. The parameters input such as concrete strength, rebar yield strength and ultimate strength are used to construct a stress-strain curve which will be used in the nonlinear analysis. However, sometimes material properties are not available in the construction drawings or academic research papers, thus making it difficult to model structures correctly. Reasonable assumptions must be made for the concrete and reinforcement properties. This bulletin will illustrate how to logically assume reinforcement parameters when only yield strength is known, as well as concrete parameters when only the concrete strength is known.

2. STEEL REINFORCEMENT

2.1 Introduction of steel reinforcement

Steel reinforcement consists of deformed bars, plain bars, welded wire fabric, or wire. Deformed bars are mainly used for longitudinal reinforcement, wires are mainly used for stirrup or ties.

This document is prepared by Chu Peng, as a part of a project supervised by Dr. Serhan

Guner.

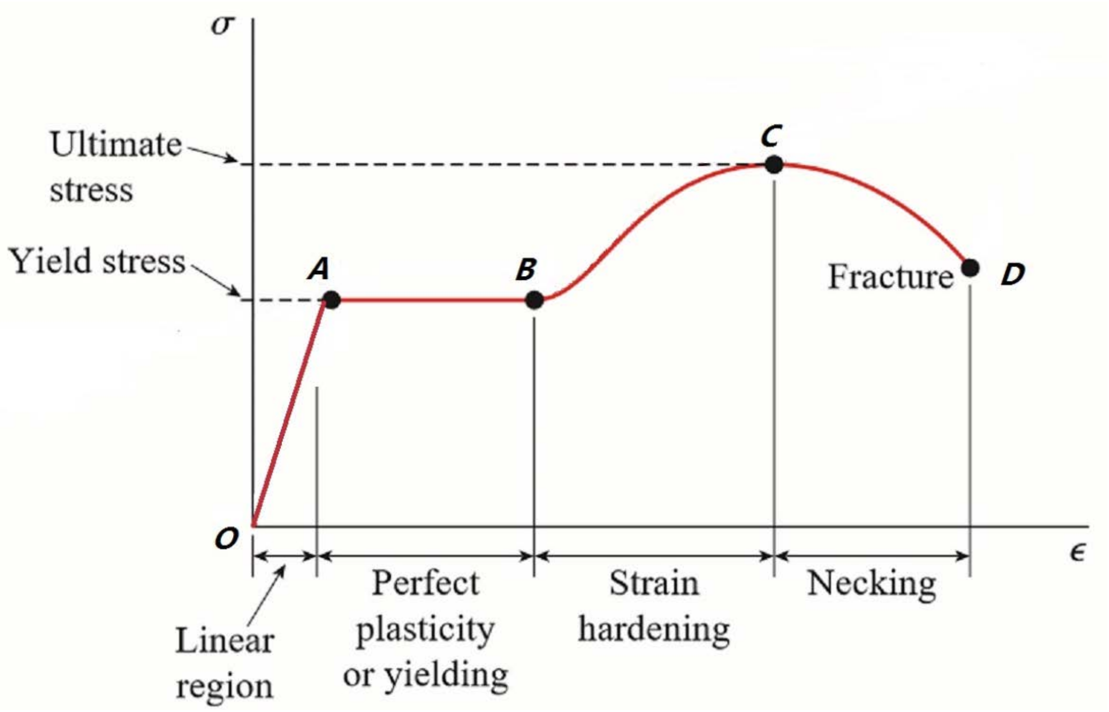


Figure 1 - Stress-strain Diagram for a Typical Deformed Bar in Tension

James and Barry (2009) specifies deformed bar stress-strain response as shown in **Figure 1**. Strains are plotted on the horizontal axis and stresses on the vertical axis. In order to display all of the important features of this material, the strain axis in **Figure 1** is not drawn to scale. The diagram begins with a straight line from the origin O to point A, which means that the relationship between stress and strain in this initial region is not only linear but also proportional. The slope of the straight line from O to A is called *the modulus of elasticity* E_s. Because the slope has units of stress divided by strain, modulus of elasticity has the same units as stress. After point A, the curve becomes horizontal. Beginning at this point, considerable elongation of the steel occurs with no noticeable increase in the tensile force (from A to B). This phenomenon is known as yielding of the material, and point A is called the yield point. The corresponding stress is known as *the yield stress* f_y of the steel. In the region from A to B, the material becomes perfectly plastic, which means that it deforms without an increase in the applied load. After undergoing the large strains that occur during yielding in the region AB, the steel begins to strain harden. During strain hardening, the material undergoes changes in its crystalline structure, resulting in increased resistance of the material to further deformation. Elongation of the test specimen in this region requires an increase in the tensile load, and therefore the stress-strain diagram has a positive slope from B to C. The load eventually reaches its maximum value, and the corresponding stress (at point C) is called the *ultimate stress* F_u. Further stretching of the bar is actually accompanied by a reduction in the load, and fracture finally occurs at a point such as D.

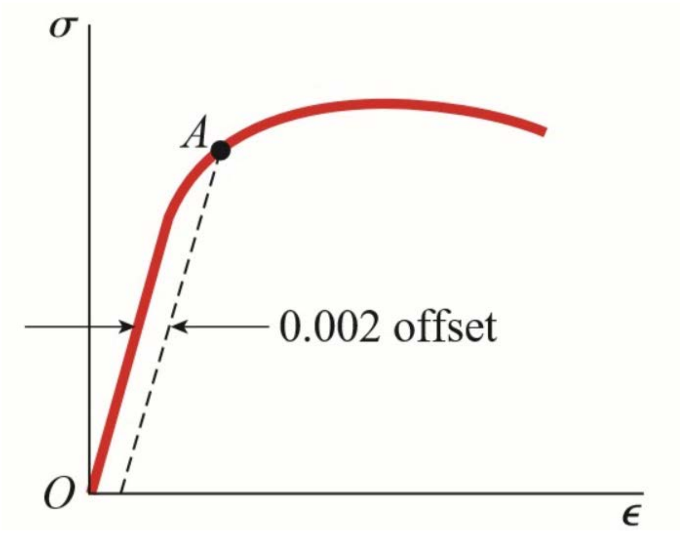
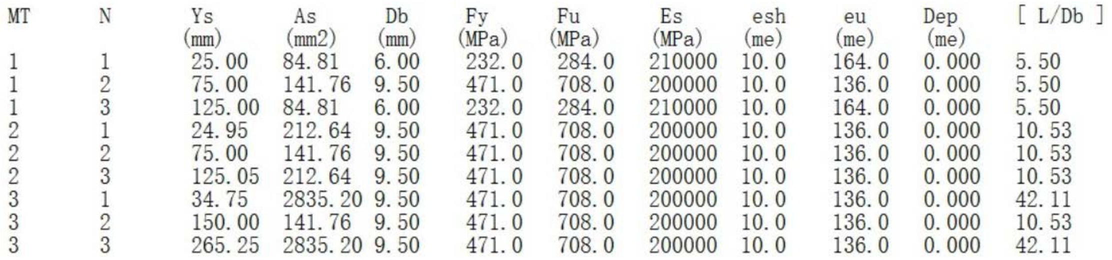


Figure 2 - Offset Method

James and Barry (2009) also illustrates how to get yield strength when a material such as aluminum does not have an obvious yield point and yet undergoes large strains after elastic stage (linear region), yield stress can be determined by the offset method. A straight line is drawn on the stress-strain diagram parallel to the initial linear part of the curve (**Figure 2**) but offset by 0.002 strain. The intersection of the offset line and the stress-strain curve (point A in **Figure 2**) defines the yield stress.



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MT   N    Ys      As       Db    Fy     Fu     Es      esh    eu     Dep    [ L/Db ]
          (mm)    (mm2)    (mm)  (MPa)  (MPa)  (MPa)   (me)   (me)   (me)
1    1    25.00   84.81    6.00  232.0  284.0  210000  10.0   164.0  0.000  5.50
1    2    75.00   141.76   9.50  471.0  708.0  200000  10.0   136.0  0.000  5.50
1    3    125.00  84.81    6.00  232.0  284.0  210000  10.0   164.0  0.000  5.50
2    1    24.95   212.64   9.50  471.0  708.0  200000  10.0   136.0  0.000  10.53
2    2    75.00   141.76   9.50  471.0  708.0  200000  10.0   136.0  0.000  10.53
2    3    125.05  212.64   9.50  471.0  708.0  200000  10.0   136.0  0.000  10.53
3    1    34.75   2835.20  9.50  471.0  708.0  200000  10.0   136.0  0.000  42.11
3    2    150.00  141.76   9.50  471.0  708.0  200000  10.0   136.0  0.000  10.53
3    3    265.25  2835.20  9.50  471.0  708.0  200000  10.0   136.0  0.000  42.11
```

Figure 3 - Rebar Parameters Needed to be Input in VecTor5

Figure 3 shows steel parameters needed to be input in a VecTor5 structure file. As illustrated in Guner and Vecchio (2008), ***MT*** is the member type, ***N*** is the longitudinal reinforcement (i.e., reinforcing or prestressing steel layer) component number starting from 1 and increasing in number by 1, Y_s is the location of the longitudinal reinforcement layer from the top of the cross section, A_s is the total area of the longitudinal reinforcement layer, D_b is the diameter of one bar, F_y and F_u are the yield and ultimate stresses of the longitudinal reinforcement layer, respectively. E_s is the modulus of elasticity of the longitudinal reinforcement, ***esh*** is the strain where the strain hardening of the longitudinal reinforcement begins, ***eu*** is the ultimate strain, and ***DEP*** is the locked-in strain differential if the layer is a prestressed steel layer. L/D_b is the unsupported length ratio, the bracket [ ] means this value can be input as zero indicating that the default value is to be calculated by VecTor5 and assumed for the input. Detailed information about unsupported length ratio can be found in Salgado and Guner (2014).

Normally we can know **D_b**, **F_y**, **F_u** and **E_s** when modelling structures, they are listed in the paper which describes experimental model.

2.2 Rebar size and yield strength f_y is known

Sometimes we only know rebar size (e.g., #3, #4, or #5) and **f_y**, logical assumptions needed to be made towards other parameters.

Table 1 - Specifications of Rebar Diameters

U.S.				Canada		Europe		China		Japan		
Imperial bar size	Metric size	Diameter (in)	Diameter (mm)	Metric size	Diameter (mm)	Metric size	Diameter (mm)	Metric size	Diameter (mm)	Rebar name	Nominal diameter (mm)	Outermost diameter (mm)
#2	#6	0.25	6.35	10M	11.3	6,0	6	6	6	D6	6.4	7
#3	#10	0.375	9.525	15M	16	8,0	8	8	8	D8	8	9
#4	#13	0.5	12.7	20M	19.5	10,0	10	10	10	D10	9.53	11
#5	#16	0.625	15.875	25M	25.2	12,0	12	12	12	D13	12.7	14
#6	#19	0.75	19.05	30M	29.9	14,0	14	14	14	D16	15.9	18
#7	#22	0.875	22.225	35M	35.7	16,0	16	16	16	D19	19.1	21
#8	#25	1	25.4	45M	43.7	20,0	20	18	18	D22	22.2	25
#9	#29	1.128	28.65	55M		25,0	25	20	20	D25	25.4	28
#10	#32	1.27	32.26			28,0	28	22	22	D29	28.6	33
#11	#36	1.41	35.81			32,0	32	25	25	D32	31.8	36
#14	#43	1.693	43			40,0	40	28	28	D35	34.9	40
#18	#57	2.257	57.3			50,0	50	32	32	D38	38.1	43

Table 1 lists diameter for different bar sizes in different countries. When modelling structures using VecTor5, users can decide at which country the structure was located, and find diameter of the given bar size corresponding to this country.

Note:

1. For the U.S. bars, imperial bar size divided by 8 gives the diameter in inches. For example, for #2, we can get a diameter of 0.25 in.
2. For Canadian bars, “M” followed by the size number indicates metric diameter in mm.
3. Europe metric bar sizes are specified in EN 1992, bars have the form “K” followed by the mass in kilograms of a 1-meter length of the bar. For example, “K3” rebar weighs 3 kilograms per meter.
4. China uses different symbols in front of bar sizes to describe the rebar grade. A means yield strength is 300MPa; B means yield strength is 335MPa; C means yield strength is 400MPa; and D means yield strength is 500MPa.
5. Japan rebar properties are specified in JIS G 3112: 2010 (E).

Table 2 - Minimum ***f***

Type	Grade	Bar Sizes	Minimum fy		Minimum fu	
			ksi	MPa	ksi	MPa
U.S. (billet steel)	40	#3 - #6	40		70	
	60	#3 - #18	60		90	
	75	#3 - #18	75		100	
Canada (regular steel)	300	10-20		300		405
	400	10-55		400		540
	500	10-55		500		675
Canada (weldable low-alloy steel)	400	10-55		400		540
	500	10-55		500		625

Table 2 lists the minimum yield strength and the ultimate strength for different bar sizes of different grades according to ACI-318-14 and CSA G30.18. Grade 40, Grade 60 and Grade 75 are used for unit ***"ksi"***, Grade 300, Grade 400 and Grade 500 are used for unit ***"MPa"***. When we know f_y, we can roughly estimate f_u based on ***linear interpolation method***. For example, Grade 40, #3 longitudinal reinforcement has a yield strength of 50 ksi, using the ***linear interpolation method*** and get f_u.

$$fu = \frac{50}{40} * 70 = 87.5 \quad ksi.$$

Note that this is just an approximation. A rebar with a yield strength of 50 ksi might still has an ultimate stress of 70 ksi. For cases where being conservative is important, use the lower-bound minimum f_u. In some cases, we may not know the rebar grade from papers, but we can estimate it by looking at the f_y value. For example, if a bar has a yield strength of 450MPa, then it should belong to Grade 400.

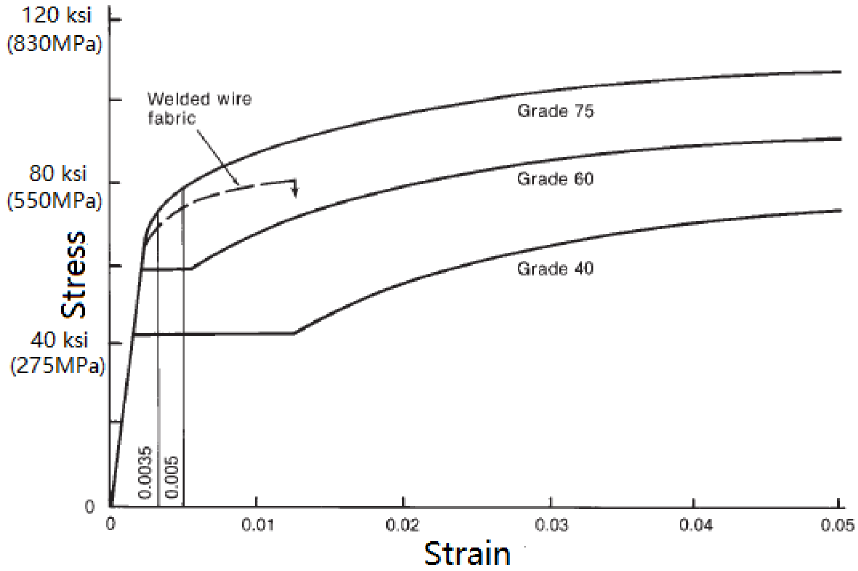


Figure 4 - Typical Rebar Stress-strain Relationship of Grade 40, 60 and 75

Figure 4 shows the typical stress-strain relationship of Grade 40, Grade 60 and Grade 75 reinforcement. We can see that Grade 40 and Grade 60 reinforcements have similar stress-strain relationships to **Figure 1**, and we can directly get the yield strength f_y and ***esh*** (strain at strain hardening). But Grade 75 has no yield plateau, and the yield strength must be obtained using the offset method shown in **Figure 2**; the ***esh*** value will be equal to yield strain value. We can conclude from **Figure 4** that the stiffer the rebar, the more brittle it is. Therefore, the ***esh*** value for high grade rebar is smaller than low grade rebar. As an approximation, the ***esh*** value for Grade 40 can be taken as 13 me, while for Grade 60 as 7 me. According to ACI-318-14, modulus of elasticity for non-prestressed steel can be taken as 200,000 MPa.

Figure 4 also shows stress-strain relationship of welded wire fabric. Wires are mainly used as stirrup or ties. Wires may be smooth (ASTM A82 [1.72]) or deformed (ASTM A496 [1.73]), the wire is specified by the *symbol* ***W*** (for smooth wires) or ***D*** (for deformed wires) followed by a number representing the cross-sectional area in hundredths of a square inch, varying from 1.5 to 31.

Table 3 - Minimum ***fy*** and ***fu*** of Wires

ASTM Designation	Wire Size Designation	Minimum *fy*		Minimum *fu*	
		MPa	ksi	MPa	ksi
A82 (cold-drawn wire)	W1.2 and lager	450	65	515	75
	Smaller than W1.2	385	56	485	70
A496 (deformed steel wire)	D-1 through D-31	485	70	550	80

Table 3 lists the minimum f_y and the minimum f_u requirements for smooth and deformed wires. The ***linear interpolation method*** can be used for deformed wires to estimate the f_u value when only the f_y value is known. Wires are typically brittle with no yield plateau, and therefore ***esh*** should be taken equal to the yield strain value of f_y divided by E_c.

Table 4 - Specification of ***esh*** and ***eu*** according to CSA G30.18-09

	Regular-Steel Bars			Weldable Low-Alloy Bars		
	300R	400R	500R	400W	500W	Cold-Drawn
Fy, min (MPa)	300	400	500	400	500	450
Fu, min (MPa)	405	540	675	540	625	520
E (MPa)	200,000					
estimated esh (me)	15	8	2.5	8	2.5	2.25
eu, min (me)						
10M	110	100	90	130	120	15
15M, 20M	120	100	90	130	120	
25M		90	80	130	120	
30M, 35M		80	70	120	100	
45M, 55M		70	60	120	100	

The minimum ***eu*** values for the deformed bars and the cold-drawn wires can be obtained from **Table 4**.

Note: There are two types of deformed steel bars according to Canadian code CSA G30.18-09. One is the regular type (R), the other one is the weldable type (W). R grades are intended for general application, W grades are appropriate for applications when enhanced ductility and weldability are desired to be obtained.

2.3 Yield strength fy is not known

This rarely happen when we are modelling structures. It might also happen when we are modeling some real structures and cannot obtain the actual material properties. In these cases, some conservative assumptions must be made. Modelling real structures are usually used for evaluating and retrofitting, therefore, conservative assumptions about the material properties are required. According to the Engineering Data Report, it may be reasonable to assume that a reinforced concrete structure built in the period 1910 through 1927 was reinforced with low grade (Grade 33 or 228 MPa yield strength) deformed reinforcing bars, and from 1928 through 1963 with intermediate grade (Grade 40 or 276 MPa yield strength) deformed reinforcing bars. From the year 1963 to present, this report does not give information on what kind of reinforcements may be used. But during this period, higher strength steel reinforcing bars were available; therefore, higher grade (Grade 50, or 345 MPa) may be assumed. After determining the yield strength, the same analyzing methods can be used for estimating the f_u, ***esh*** and ***eu*** values using methods described in Section 2.2.

3. CONCRETE

Plain concrete is made by mixing cement, fine aggregate, coarse aggregate, water, and frequently admixtures. The strength of concrete depends on many factors - notably the proportion of the ingredients and the conditions of temperature and moisture under which it is placed and cured. The ratio of water to cement is the main factor dictating the concrete strength. **Figure 5** shows typical stress-strain curves for concrete in compression under short-term loading. Concrete strength refers to the peak stress values on uniaxial stress-strain curves shown.

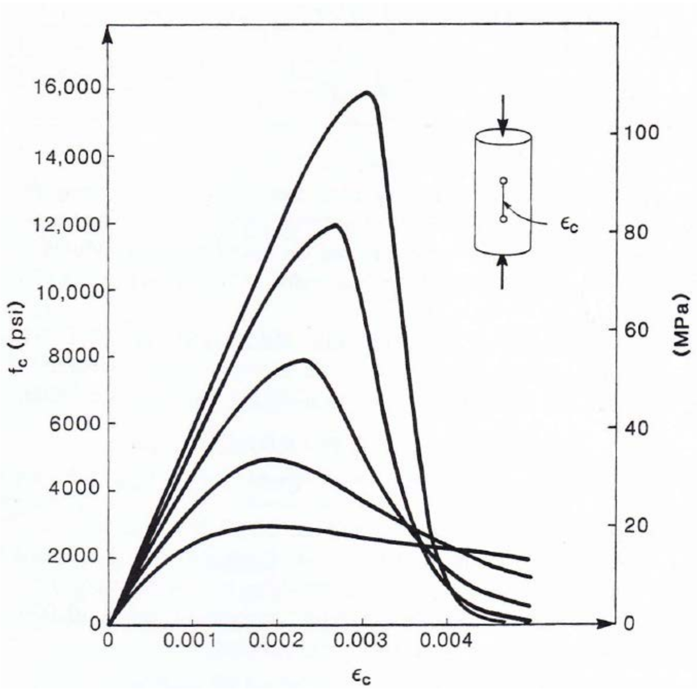
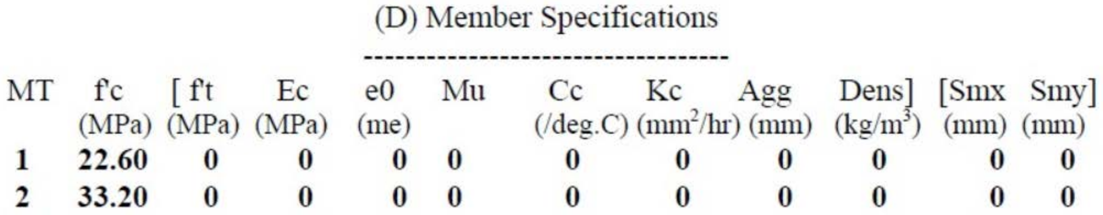


Figure 5 - Typical Stress-strain Curves for Concrete in Compression


(D) Member Specifications

MT	f'c (MPa)	[f't (MPa)	Ec (MPa)	e0 (me)	Mu	Cc (/deg.C)	Kc (mm^2/hr)	Agg (mm)	Dens] (kg/m^3)	[Smx (mm)	Smy] (mm)
1	**22.60**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2	**33.20**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Figure 6 - Concrete Parameters Needed to be Input in VT5

Figure 6 shows values needed to be input in VecTor5. As illustrated in Guner and Vecchio (2008), f'_c is the concrete compressive strength, f'_t is the concrete tensile strength, E_c is the modulus of elasticity of concrete, ***e0*** is the strain corresponding to the peak stress of concrete, M_u is Poisson's ratio. f'_c must be known as a minimum, other values can be automatically calculated by VecTor5. $\boldsymbol{E_c}$ and ***e0*** should be input if the user wants to more accurately define the stress-strain curve.

Table 5 - Specification of Concrete Parameters

f'c (MPa)	20	25	30	35	40	45	50	55	60
f'c (psi)	2901	3625.94	4351.132	5076	5801.51	6526.7	7252	7977	8702.264
Ec (MPa)	21747	23500	25084	26541	27898	29171	30376	31522	32617
Ec (ksi)	3154	3408	3638	3849	4046	4231	4406	4572	4731
eo (me)	1.861	1.9011	1.960331	2.028	2.099765	2.173	2.247	2.32	2.392041
n	1.976	2.27059	2.564706	2.859	3.152941	3.4471	3.741	4.035	4.329412
k	1	1.07288	1.153459	1.234	1.314612	1.3952	1.476	1.556	1.636918

Table 5 shows $\boldsymbol{E_c}$ and ***e0*** correspond to each $\boldsymbol{f'_c}$. They are calculated using equations in Collins and Mitchell (1997), as listed below.

$$Ec = \left(40{,}000\sqrt{f'c}\right) + 1{,}000{,}000 \qquad psi$$

$$Ec = \left(3{,}320\sqrt{f'c}\right) + 6{,}900 \qquad MPa$$

$$n = 0.8 + \frac{f'c}{2{,}500} \qquad \text{psi}$$

$$n = 0.8 + \frac{f'c}{17} \qquad \text{MPa}$$

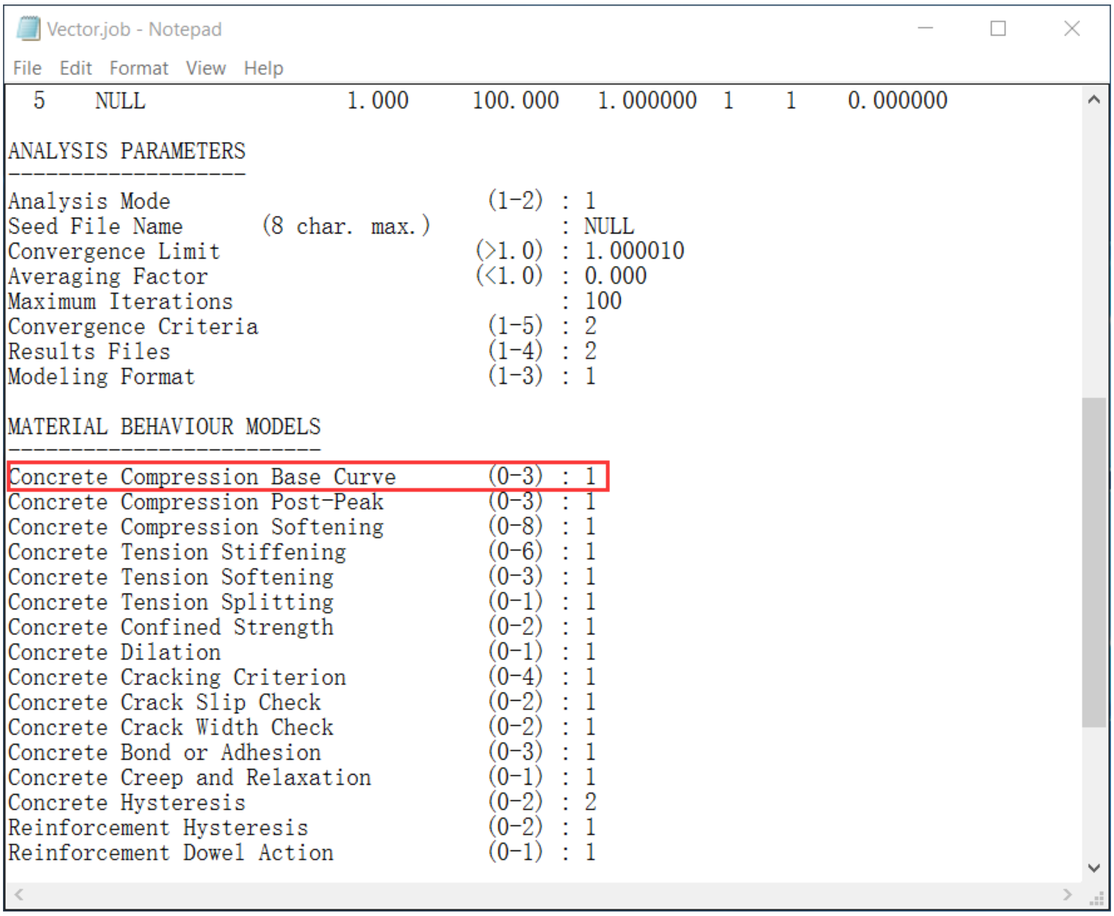
$$e0 = \frac{f'c}{Ec} * \frac{n}{n-1}$$

$$k = 0.67 + \frac{f'c}{9{,}000} \qquad \text{psi (k should be greater or equal to 1)}$$

$$k = 0.67 + \frac{f'c}{62} \qquad \text{MPa (k should be greater or equal to 1)}$$

The users can obtain the $\boldsymbol{E_c}$ and ***e0*** values from **Table 5**. For $\boldsymbol{f'_c}$ values not specified in the table, linear interpolation may be made. Alternatively, $\boldsymbol{E_c}$ and ***e0*** values can be calculated manually using the above equations.

There are four types of concrete models used in VecTor5. They are Hognestad (parabola) model as Option 1, Popovics - NSC (1973) model as Option 2, Popovics - HSC model as Option 3 and Hoshikuma - HSC model as Option 4. The user can select a concrete model type in the job file under the name “Concrete Compression Base Curve”, as shown in **Figure 7**.



```
  5    NULL                1.000     100.000   1.000000  1    1    0.000000

ANALYSIS PARAMETERS
-------------------
Analysis Mode                         (1-2) : 1
Seed File Name      (8 char. max.)          : NULL
Convergence Limit                    (>1.0) : 1.000010
Averaging Factor                     (<1.0) : 0.000
Maximum Iterations                          : 100
Convergence Criteria                  (1-5) : 2
Results Files                         (1-4) : 2
Modeling Format                       (1-3) : 1

MATERIAL BEHAVIOUR MODELS
-------------------------
Concrete Compression Base Curve       (0-3) : 1
Concrete Compression Post-Peak        (0-3) : 1
Concrete Compression Softening        (0-8) : 1
Concrete Tension Stiffening           (0-6) : 1
Concrete Tension Softening            (0-3) : 1
Concrete Tension Splitting            (0-1) : 1
Concrete Confined Strength            (0-2) : 1
Concrete Dilation                     (0-1) : 1
Concrete Cracking Criterion           (0-4) : 1
Concrete Crack Slip Check             (0-2) : 1
Concrete Crack Width Check            (0-2) : 1
Concrete Bond or Adhesion             (0-3) : 1
Concrete Creep and Relaxation         (0-1) : 1
Concrete Hysteresis                   (0-2) : 2
Reinforcement Hysteresis              (0-2) : 1
Reinforcement Dowel Action            (0-1) : 1
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Figure 7 - Location for Changing Concrete Model Types

The first two models are used for normal strength concrete (strength is up to 50 MPa), last two models are used for high strength concrete (strength is greater than 50 MPa). If users use above equations to calculate and input the E_c and $e0$ values, Popovics-NSC (1973) model and Hoshikuma - HSC model are desired to be selected. Note that if other options are selected, VecTor5 will overwrite the input values. Please check the expanded data file after performing an analysis and inspect what material properties are actually used in the analysis. Refer to pages 10 to 13 of Guner and Vecchio (2008).

For the tensile strength of concrete, f'_t, it is recommended to use the lower-bound default value as follows, even if the tensile splitting stress is known. This can be achieved by inputting zero for f'_t.

$$f't = 0.33\sqrt{f'c} \qquad MPa$$

4. REFERENCES

ACI Committee 318. Building Code Requirements for Structural Concrete: (ACI 318-14); Farmington Hills, MI: American Concrete Institute, 2014. Print. Web Link

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This document is prepared by Chu Peng, as a part of a project supervised by Dr. Serhan Guner.