

Reinforced Concrete Nominal Moment Calculator – A Computer tool for Civil Engineering Students

Abstract

One of the primary objectives of an undergraduate reinforced concrete design course is to learn how to calculate the nominal moment capacity of reinforced concrete beams. This is traditionally accomplished by using basic mechanics, ultimate strength design principles and the Whitney stress block concept. Often this is overwhelming to students due to the plethora of variables in the ACI² code, the composite nature of reinforced concrete and the time it takes for new complex concepts to sink in. For this reason, in addition to classroom examples and homework, it is helpful to have a computer tool to assist in the learning process. Toward this end a computer program (Nominal Moment Calculator) with graphical user interface has been created. The Nominal Moment Calculator allows for up to 100 separate layers of steel (tensile or compressive), both rectangular and T-beams, user defined material properties, a graphical representation of the depth to neutral axis, c , and a descriptive output of calculations. Theory, program capabilities, sample classroom assignments, benefits toward ABET¹ objectives and results in the classroom due to use of the Nominal Moment Calculator are discussed.

1 Introduction

Reinforced concrete design is perhaps one of the most challenging design courses undergraduate Civil engineering students must take. This is probably due to the composite nature of reinforced concrete and the seemingly endless barrage of ACI² variables used. More specifically, students often get overwhelmed with the mechanics of the Whitney stress block concept and strain compatibility for calculating the nominal moment capacity of reinforced concrete beams. The problem is further exacerbated when compression reinforcement, T-beams and multiple layers of steel are considered. Any strategies that foster student interest and comprehension are useful. The usual lectures, homework assignments and computation labs are appropriate, but it seems worthwhile to supplement these traditional methods with a computer program which can quickly provide results and verification. Students can also gain more experience by being able to modify computer input and quickly see the resulting effects on the output. With the above in mind, a computer program, called Nominal Moment Calculator, which is consistent with ACI 318-08², has been created.

In the following sections theory behind the computer program, design of the graphical user interface, sample output, sample assignments, student benefits, ABET¹ objectives addressed and conclusions are provided.

2 Theory behind Nominal Moment Calculator

2.1 General nominal moment strength by strain compatibility

For brevity, only the development of the theory for rectangular beams is presented herein. The case of T-beams follows from similar arguments and little modification.

Consider a rectangular beam with n -layers of steel as shown in Figure 1. In the Force Profile of the figure the steel force, T_{si} , at layer i is calculated based on an algorithm given below. According to the Whitney stress block concept (see Nilson et al⁴ for more) the concrete compressive force, C_c , is calculated as the Whitney stress, $0.85 f'_c$, times the area, $ab = \beta_1 cb$, over which it acts. Note that if a steel bar is in the compression zone, the concrete not present due to the presence of the steel bar is accounted for below in the algorithm for T_{si} .

In Figure 1 an arbitrary distance to the neutral axis, c , is shown. The ensuing formulas are written in terms of this unknown distance c . Horizontal force equilibrium is satisfied when the correct value of c is used. Summing forces in the horizontal direction and choosing positive forces to the *left* as shown in the Force Profile of Figure 1 yields the following:

$$\sum_{i=1}^n T_{si} + C_c = \sum_{i=1}^n T_{si} + 0.85 f'_c \beta_1 cb = 0, \quad (2.1)$$

where force in a steel bar at layer i is T_{si} (negative in tension and positive in compression due to the formula for strain given below). The T_{si} values are found by using the following algorithm:

- (i) Determine the strain in bar i

$$\varepsilon_{si} = \left[\frac{c - d_i}{c} \right] \varepsilon_u,$$

where $\varepsilon_u = 0.003$ is the ultimate concrete strain specified by code.

(2.2)

- (ii) Determine the stress in the steel bar at layer i

$$f_{si} = E_s \varepsilon_{si}$$

(2.3)

where the following restrictions apply to f_{si} in the following *order* given.

- (a) Check if steel stress exceeds yield. If $|f_{si}| > f_y$ then $f_{si} = (f_{si} / |f_{si}|) f_y$.
 (b) Check if steel is in compression, if so; adjust for concrete not present at the steel layer. If $f_{si} > 0$ then $f_{si} = f_{si} - 0.85 f'_c$.

- (iii) Finally, the value of T_{si} is calculated based on the above results.

$$T_{si} = f_{si} A_{si}$$

(2.4)

The correct value of c will be between 0 and h . For example, it is straightforward to test 10 evenly spaced values of c in the interval 0 to h . The increment that bounds the best value of c can

be further subdivided into 10 evenly spaced values of c to test for equilibrium. This process is repeated several times until the equilibrium equation is satisfied within a suitable tolerance. One might argue that a Newton-Raphson algorithm would yield straightforward results. However, it has been found that this method gives unreliable results and can often diverge toward solutions for c that are outside of the sensible interval 0 to h even when a sensible starting value for c is provided. Hence, the successively smaller interval search method described above is used.

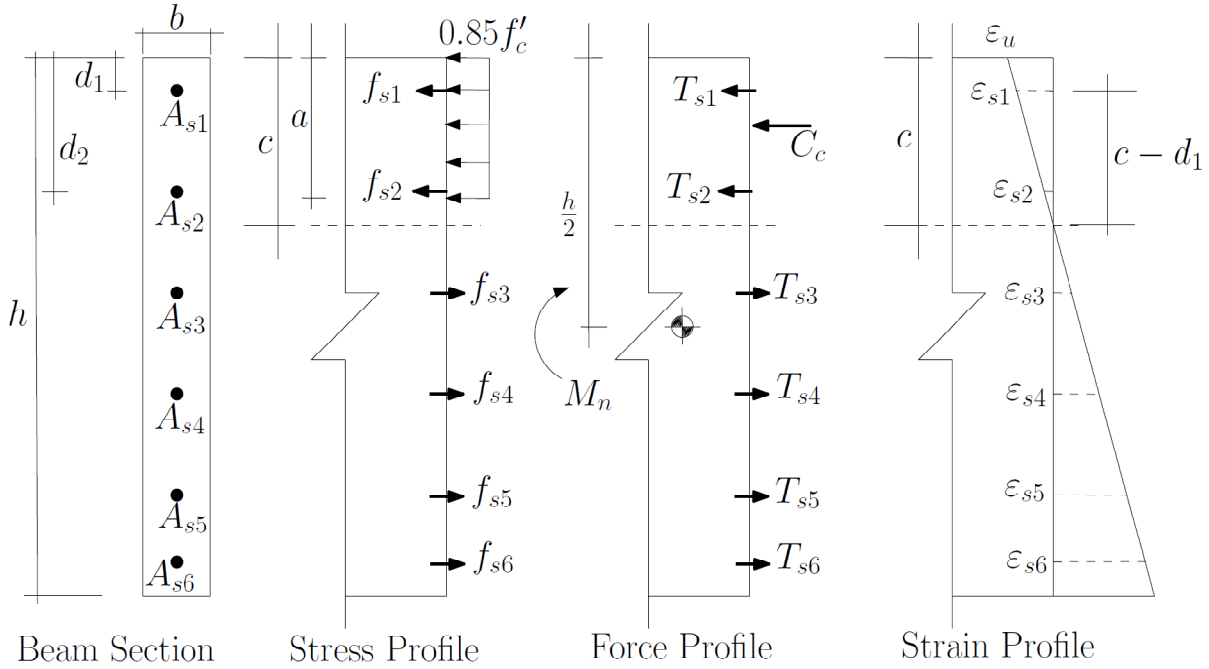


Figure 1: Concrete Beam Section and Profiles - Strain Compatibility.

Once the correct value of c is found such that horizontal equilibrium is satisfied (equation 2.1), then summation of moments about the beam's gross cross-section centroid (at depth $h/2$) gives the nominal moment.

$$M_n = \sum_{i=1}^n \left[T_{si} \left(\frac{h}{2} - d_i \right) \right] + 0.85f'_c \beta_1 c b \left(\frac{h}{2} - \frac{\beta_1 c}{2} \right) = 0. \quad (2.5)$$

2.2 Calculating β_1

The factor β_1 is calculated by using f'_c in units of ksi:

$$\beta_1 = 0.85 - 0.05(f'_c - 4) \quad (2.6)$$

with the restriction that the value used must be within the following limits, $0.65 \leq \beta_1 \leq 0.85$.

2.3 Calculating ϵ_t

The maximum tensile strain in the steel is calculated as

$$\varepsilon_t = \frac{d_{max} - c}{c} \varepsilon_u \quad (2.7)$$

2.4 Calculating ϕ

The nominal resistance factor for beam bending is calculated as

$$\phi = 0.483 + 83.3\varepsilon_t \quad (2.8)$$

with the restriction that the value used must be within the following limits, $0.65 \leq \phi \leq 0.9$. For $\varepsilon_t \geq 0.005$ the value of ϕ is 0.9. With the ϕ factor in hand one can then calculate the nominal factored moment, ϕM_n , required by code and compare it to the factored moment caused by the applied loads.

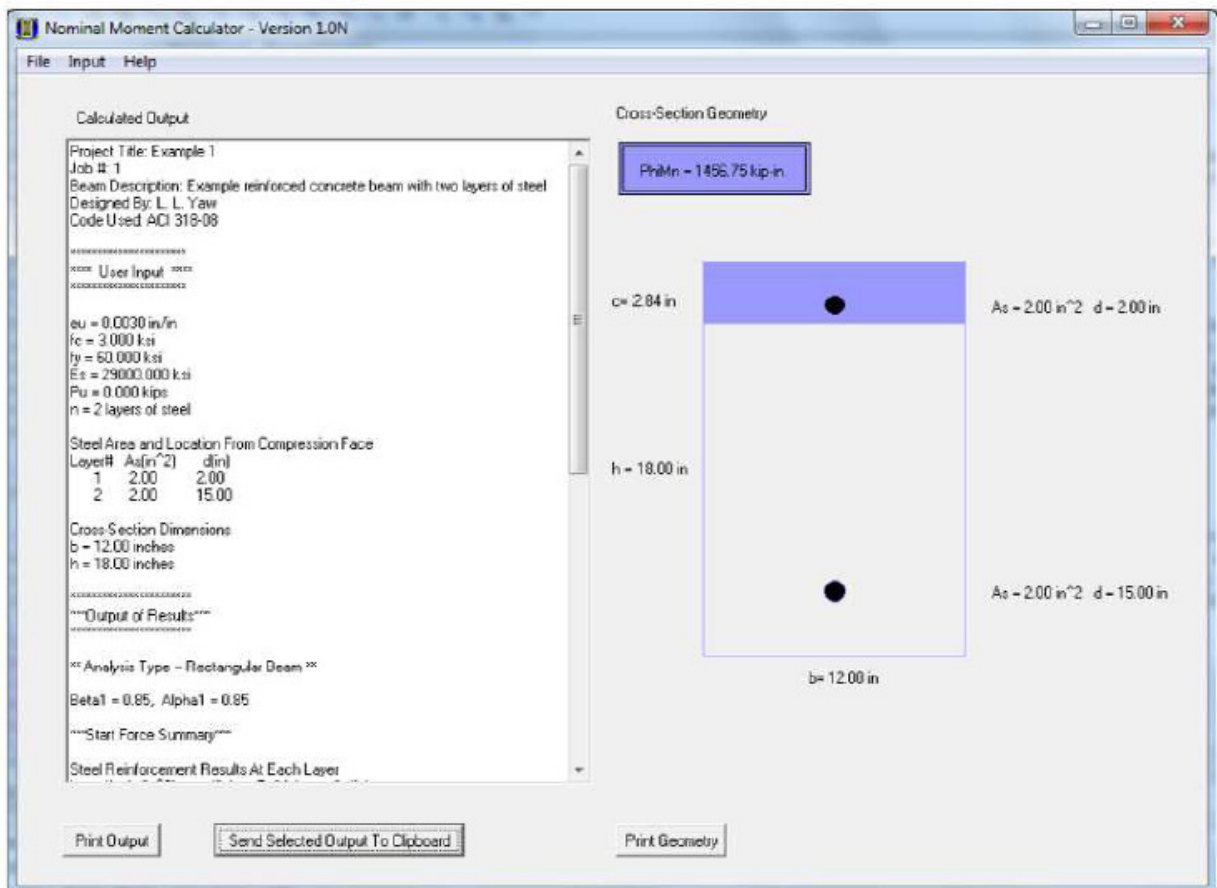


Figure 2: Main screen of Nominal Moment Calculator application.

3 Input and design of the graphical user interface

The graphical user interface (GUI) has been designed as simply as possible to be self explanatory. The GUI has a typical menu bar but with only three menu items, File, Input and Help (see Figure 2).

3.1 File

The File menu contains the typical options of Open, Save, Save As and Exit. The output and input files are in a simple editable text file format. This is deliberate so that an input file with *many* layers of steel could be computer generated and loaded into the Nominal Moment Calculator without having to type in all the data.

3.2 Input

The Input menu has four options, Project Information, Geometry, Material Properties and Applied Axial Load.

Geometry Input

Steel Geometry

Steel Layers (1 - 100)

2

Layer	As(in ²)	d(in)
1	2.00	2.00
2	2.00	15.00
3	0.00	0.00
4	0.00	0.00
5	0.00	0.00
6	0.00	0.00

As = area of steel at the given layer, in²
d = distance from compression face, in

Cross-Section Dimensions:

h = 18.00 in

b = 12.00 in

T-Beam Option

hf = 0.00 in

belf = 1.00 in

Enable

Disable

h

d

b

DONE

CANCEL

Figure 3: Geometry input screen of Nominal Moment Calculator application.

3.2.1 Project Information

In the Project Information option the user may input the following fields: project title, job number, beam description and designed by.

3.2.2 Geometry

For Geometry the user can select number of layers of steel, the total steel area for each layer i and the depth d_i from the compression face to layer i . For rectangular beams the user can input the beam width b and beam height h . When the T-beam option is enabled the user can also input the T-beam flange thickness h_f and the effective width b_{eff} . The Geometry input screen is shown in Figure 3.

3.2.3 Material Properties

The user may enter the steel properties of modulus of elasticity, E_s , and yield stress, f_y . The default values are 29,000 ksi and 60 ksi respectively. The user may also enter the concrete properties of ultimate compressive stress, f'_c and ultimate compressive strain, ϵ_u . The default values are 3 ksi and 0.003.

3.2.4 Applied Axial Load

For rectangular beams only, the program does allow the user to input an axial load applied at the beam's gross cross section centroid. This option is not available for T-beams. The axial load option is beneficial for a nominal moment calculation of a shear wall with axial and moment loads applied to the cross-section. The default axial load is 0.0 kips.

3.3 Help

The help menu item contains the three options of Help, Disclaimer and About. The Help option is a brief scroll bar with help text describing the program input. A Disclaimer is provided to avoid liability for improper use of the program. Version information is provided in the About option.

3.4 Calculations and Graphical Output To Screen

Two forms of output are provided on the main screen of the application (see Figure 2). First, a text field is provided which shows detailed information about the calculations and final results for ϕM_n . The text field is automatically updated when any input item is changed. Output calculations can be selected (highlighted) and saved to clipboard or sent to a printer. Second, a graphical representation of the beam cross-section is drawn on the screen. The steel bars and their location are shown. The concrete of the cross-section in compression is depicted by shading on the cross-section down to the neutral axis c . This graphical representation can be sent to printer also.

4 Sample output

To demonstrate use of the program and the resulting output, several examples are provided. A rectangular beam with two layers of steel and a T-beam are given as examples.

4.1 Example 1 - Rectangular Beam

A rectangular beam is given with the following information, $h=18$ inches, $b=12$ inches, $n=2$ layers of steel, $A_{s1} = 2 \text{ in}^2$, $d_1 = 2$ inches, $A_{s2} = 2 \text{ in}^2$, $d_2 = 15$ inches, $f'_c = 3 \text{ ksi}$, $f_y = 60 \text{ ksi}$. The main screen and the geometry input pages for this case are shown in Figures 2 and 3. The results indicate that the top layer of steel is in the compression zone and has not yet yielded. This problem, if done by hand, would likely require several tedious iterations to find the correct value of c . The output of calculations is given below.

Project Title: Example 1

Job #: 1

Beam Description: Example reinforced concrete beam with two layers of steel

Designed By: L. L. Yaw

Code Used: ACI 318-08

**** User Input ****

eu = 0.0030 in/in

fc = 3.000 ksi

fy = 60.000 ksi

Es = 29000.000 ksi

Pu = 0.000 kips

n = 2 layers of steel

Steel Area and Location From Compression Face

Layer#	As(in ²)	d(in)
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1	2.00	2.00
---	------	------

2	2.00	15.00
---	------	-------

Cross-Section Dimensions

b = 12.00 inches

h = 18.00 inches

Output of Results

** Analysis Type = Rectangular Beam **

Beta1 = 0.85, Alpha1 = 0.85

Start Force Summary

Steel Reinforcement Results At Each Layer

Layer#	As(in ²)	d(in)	Ts(kip)	es(in/in)
--------	----------------------	-------	---------	-----------

1	2.00	2.000	-51.32	-0.00088
---	------	-------	--------	----------

2	2.00	15.000	120.00	0.01286
---	------	--------	--------	---------

Maximum Steel Tensile Strain
 $\epsilon_t = 0.01286$ in/in
 The Concrete Compressive Force (reduced for any compression steel)
 $C_f = 68.68$ kips
 The Applied Axial Force
 $P_u = 0.00$ kips
 End Force Summary
 Distance From Compression Face to Neutral Axis
 $c = 2.837$ in
 Nominal Moment Strength
 $M_n = 1618.61$ kip-in
 $M_n = 134.88$ kip-ft

 ** Phi Mn **

 $\Phi = 0.900$
 $\Phi M_n = 1456.75$ kip-in
 $\Phi M_n = 121.40$ kip-ft

 *****End of Output*****

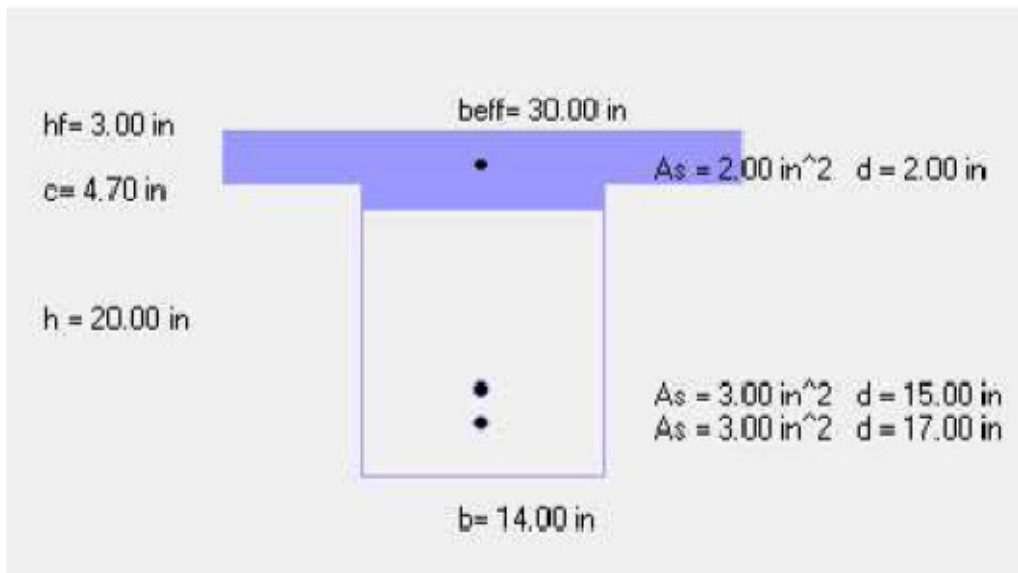


Figure 4: Example 2 - graphical results.

4.2 Example 2 - T-Beam

The T-beam has a flange thickness, $h_f = 3$ inches and effective flange width of $b_{eff} = 30$ inches. The beam depth is $h = 20$ inches and a beam web width of $b_w = 14$ inches. Three layers of steel are provided such that $A_{s1} = 2$ in², $d_1 = 2$ inches, $A_{s2} = 3$ in², $d_2 = 15$ inches, $A_{s3} = 3$ in², $d_3 = 17$

inches. The material properties are $f'_c = 3$ ksi and $\epsilon_u = 0.003$ for concrete and $f_y = 60$ ksi for steel. The calculated output is given below. The graphical output for this case is shown in Figure 4

Project Title: Example 1

Job #: 1

Beam Description: Example reinforced concrete beam with two layers of steel

Designed By: L. L. Yaw

Code Used: ACI 318-08

**** User Input ****

eu = 0.0030 in/in

fc = 3.000 ksi

fy = 60.000 ksi

Es = 29000.000 ksi

Pu = 0.000 kips

n = 3 layers of steel

Steel Area and Location From Compression Face

Layer# As(in²) d(in)

1 2.00 2.00

2 3.00 15.00

3 3.00 17.00

Cross-Section Dimensions

b = 14.00 inches

h = 20.00 inches

hf = 3.00 inches

beff = 30.00 inches

Output of Results

** Analysis Type = T-Beam **

Beta1 = 0.85, Alpha1 = 0.85

Start Force Summary

Steel Reinforcement Results At Each Layer

Layer# As(in²) d(in) Ts(kip) es(in/in)

1 2.00 2.000 -100.00 -0.00172

2 3.00 15.000 180.00 0.00657

3 3.00 17.000 180.00 0.00785

Maximum Steel Tensile Strain

et = 0.00785 in/in

The Overhanging Beam Flanges Concrete Compressive Force

Ff = 122.40 kips

The Beam Web Concrete Compressive Force (reduced for any compression steel)

Cf = 137.60 kips

The Applied Axial Force

Pu = 0.00 kips

End Force Summary

Distance From Compression Face to Neutral Axis

$c = 4.703$ in

Nominal Moment Strength

$M_n = 5101.40$ kip-in

$M_n = 425.12$ kip-ft

** Phi Mn **

$\Phi = 0.900$

$\Phi M_n = 4591.26$ kip-in

$\Phi M_n = 382.60$ kip-ft

*****End of Output*****

5 Sample assignments

Several example assignments are provided that make use of the Nominal Moment Calculator. These assignments are easily integrated into a typical course in reinforced concrete design.

5.1 Assignment # 1

- Students are assigned regular reinforced concrete beam problems in which they are required to find ϕM_n by hand.
- Students are required to use the Nominal Moment Calculator to verify their results of part (a). If they find differences in results they need to verify that they have entered all of the correct information and/or they need to go back to their hand calculations and find what they did incorrectly.

5.2 Assignment # 2

- Consider the following given beam. The beam has a depth $h = 18$ inches and a beam width of $b = 9$ inches. One layer of steel is provided such that $A_{s1} = 2$ in², $d_1 = 15$ inches. The material properties are $f'_c = 3$ ksi and $\epsilon_u = 0.003$ for concrete and $f_y = 60$ ksi for steel. Input the information for the given beam into the Nominal Moment Calculator. What are the results for ϕM_n , c , ϵ_t and ϕ ?
- Change the concrete strength for the beam of part (a) to $f'_c = 5$ ksi. How does c change? Why?
- Change area of steel for the beam of part (a) to $A_{s1} = 4$ in². How does c change? Why?
- Change area of steel for the beam of part (a) to $A_{s1} = 12$ in². What happens to ϵ_t ? Why? What happens to ϕ ? Why?

5.3 Assignment # 3

- (a) Consider the following given beam. The beam has a depth $h = 24$ inches and a beam width of $b = 12$ inches. Three layers of steel are provided such that $A_{s1} = 2 \text{ in}^2$, $d_1 = 3$ inches, $A_{s2} = 3 \text{ in}^2$, $d_2 = 18$ inches, $A_{s3} = 3 \text{ in}^2$, $d_3 = 21$ inches. The material properties are $f'_c = 4$ ksi and $\epsilon_u = 0.003$ for concrete and $f_y = 60$ ksi for steel. Guess a value of $c = 6$ inches for the following beam. Show work to determine if horizontal equilibrium is achieved with the guessed value for c . If equilibrium is not achieved, should your next guess for c be bigger or smaller? Why?
- (b) Use the Nominal Moment Calculator to determine c and ϕM_n for the beam of part (a).
- (c) Use the correct value of c determined in part (b) and demonstrate by hand calculations that horizontal equilibrium is achieved.
- (d) Use the correct value of c and demonstrate by hand calculations that ϕM_n determined in part (b) is correct.

6 Observed Student benefits and feedback

A variety of benefits to students arise by use of the Nominal Moment Calculator. An attempt at a comprehensive (though certainly not exhaustive) list is provided. Feedback from students is also given.

6.1 List of Benefits to students

1. Students can compare the calculated results with their hand solutions. This helps students check their own work and find errors so they may learn from their mistakes.
2. Students can try many cases and begin to develop intuition about the behavior of concrete beams when material and/or geometric parameters are changed. This provides a ‘What if?’ scenario in which students may explore.
3. Students using the program can home in on efficient designs by easily trying a variety of cases. Structures problems are often (if not always) iterative. This helps students appreciate computer tools that can help them reach an acceptable design in a timely fashion.
4. Students can receive better feedback on exams from teachers. There is no single answer for structural design problems. When starting an exam problem each student might make different but perfectly valid assumptions. This can make grading exams and finding mistakes laborious. Student assumptions can be easily input into the Nominal Moment Calculator and their results can be verified or found to be in error quickly. This can greatly assist the grading process and provide the teacher with accurate feedback to write on the exams.
5. Many students are visual learners. The graphical display of the beam cross-section with the depth to neutral axis shown helps students visualize what is physically happening when the beam is loaded to its ultimate condition. This is particularly helpful when considering beams with steel above the neutral axis or when working on T-beams with the neutral axis above or below the bottom of the T-beam flange.
6. Learning about the algorithms for the program and how to make it work provides an excellent example of the use of computing in engineering.
7. Later on in many introductory courses, short column design and interaction diagrams are covered. The algorithms for the program are easily extended with little modification to

allow computation of points on a column interaction diagram. Hence, the information learned by using the nominal moment calculator is a precursor to future topics. Students can with adequate guidance write their own algorithms to construct concrete column interaction diagrams.

8. Using computers for learning exercises appeals to many students.
9. Computers are often used in professional practice. The Nominal Moment Calculator provides an input page as mentioned previously where students may enter *project title*, *job number*, *beam description* and *designed by*. These items are a small but simple introduction of how real world professionals document their work. Every form of professionalism that can be instilled in students during the course of their education will be beneficial to them.
10. Shear walls in flexure require the calculation of their nominal moment. Rectangular walls can be easily treated as rectangular beams with multiple layers of steel. When shear walls have a thicker boundary element than the rest of the wall, the T-beam option may be used with multiple layers of steel.
11. The nominal moment capacity of masonry beams or shear walls can be calculated. The Nominal Moment Calculator allows the user to alter the ultimate compressive strain specified for the materials being used. Per MSJC³ section 3.3.2(c) the maximum usable strain ε_{mu} is assumed to be 0.0035 for clay masonry and 0.0025 for concrete masonry. Hence, the Nominal Moment Calculator prepares the way to introduce design of masonry flexural elements and how they are designed differently than concrete.
12. Undergraduate students are better prepared for graduate school. The extension of the Whitney stress block concept and strain compatibility for a singly reinforced concrete beam to the general case of n layers of steel is beneficial to a student's development. Many concepts in graduate school are general extensions of simpler cases covered in undergraduate courses. Developing this kind of thinking in students early on helps them think toward the 'next' step. It leads to thinking that allows them to confront more difficult problems.

6.2 Student Feedback

Student feedback has been very positive since the program was included in the reinforced concrete course. Students really appreciate the ability to verify their own work and, if they find a mistake, discover on their own what they did incorrectly. The user interface is consistently described as 'very easy to use'. The graphical display is based on input and students have realized dimensional input mistakes by looking at the graphical results. Many students specifically note that the graphical display helps them better visualize and internalize the concepts involved in nominal moment calculations. This is very appealing to them instead of just looking at equations. Students enjoy being able to change variables and immediately see the results. This helps them develop better understanding and intuition about how reinforced concrete beams function. Students recognize the benefits from using the application.

6.3 Observed Results in the Classroom

The Nominal Moment Calculator is a beneficial supplement for students. Clearly, the traditional class room lectures and hand calculation exercises are still needed in the course. However, using

the Nominal Moment Calculator reinforces what students learn. As mentioned previously students can more easily find mistakes and correct their work. This reduces some of their frustration and often helps them to learn and work more efficiently, rather than searching by hand for elusive errors. Students are better prepared to do calculations for a beam involving multiple layers of steel. They are able to follow the algorithm for verifying horizontal equilibrium or calculating the nominal moment capacity of a reinforced concrete beam with multiple layers of steel.

One common thread in engineering education is the issue of contact time. Complex concepts take time to sink in. Students require a certain amount of contact time in order to grasp some topics. Anything that fosters student comfort and confidence with new material is beneficial. Student comfort and comprehension takes place faster by including the Nominal Moment Calculator in the reinforced concrete course.

7 ABET objectives achieved

ABET¹ lists the following desired outcomes for engineering programs.

Criterion 3. Program Outcomes

Engineering programs must demonstrate that their students attain the following outcomes:

- (a) an ability to apply knowledge of mathematics, science, and engineering
- (b) an ability to design and conduct experiments, as well as to analyze and interpret data
- (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- (d) an ability to function on multidisciplinary teams
- (e) an ability to identify, formulate, and solve engineering problems
- (f) an understanding of professional and ethical responsibility
- (g) an ability to communicate effectively
- (h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
- (i) a recognition of the need for, and an ability to engage in life-long learning
- (j) a knowledge of contemporary issues
- (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

It seems reasonable that meeting ABET criteria (a) through (k) can be accomplished by using a diversified approach. Due to student personalities and various learning styles a multi prong approach is helpful. Students like variety. The Nominal Moment Calculator is not the whole solution but it does help students make progress toward the ABET objectives. Specifically, the Nominal Moment Calculator is a tool that assists in the achievement of outcomes (a), (c), (e), (f), (g) and (k).

8 Conclusion

A computer program for the calculation of the nominal moment capacity of reinforced concrete beams is included in a standard undergraduate reinforced concrete design course. The intent is to help students learn the concepts of reinforced concrete beam design better for the various cases of rectangular beams, T-beams, compression reinforcement and multiple layers of steel. The feedback from students, regarding the computer application, has been very positive. Students really appreciate being able to check their hand calculations with the Nominal Moment Calculator. The computer program, which supplements traditional lectures and homework problems, also helps students make progress toward achieving ABET outcomes (a), (c), (e), (f), (g) and (k). Many other benefits have also been identified. Learning is a multifaceted endeavor. A diversified use of learning tools is helpful and appreciated by students when learning complex concepts in the engineering curriculum.

The Nominal Moment Calculator (mnN.exe) can be downloaded from the following location:
<http://people.wallawalla.edu/~louie.yaw/otherfiles/>

References

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