

Development of a free app to learn the design of reinforced concrete walls subject to in-plane bending and axial load

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— Abstract—

The paper shows a support-free tool for the learning-teaching process of reinforced concrete wall design. These structural elements are used in Mexico for buildings and dwelling houses construction. Then, their structural design is an important topic for the students. The algorithm was implemented in a spreadsheet, which shows the operations and decision-making required to compute the bending-axial load strength curve (M_R - P_R). In addition, for a pair of factored mechanical elements (M_U , P_U), it calculates the action/strength ratio. Basic knowledge of arithmetic, analytical geometry, matrix algebra, and the Mexican standard were applied in the development. According to the user's preference, the data vector can be modified. Although a simplified envelope strength curve formed by seven points (M_R - P_R) was obtained, its accuracy is adequate compared to a commercial application result, 98% and 87%, for the nominal and strength curve, respectively. The application shows to the students an introduction to the abstract thinking required in the automation of calculation processes and it can guide them in the implementation of their applications for strengthening of specific competencies.

Keywords:

Reinforced concrete; design; bending and axial load; free software; open source

The training processes in Higher Education Institutions are focused on the learning of interdisciplinary knowledge and oriented towards its application to guarantee the professional training of the student. In this order, the current situation requires the construction of new learning environments with didactic-pedagogical methods and techniques, which allow the development of generic and specific skills of the graduate, highlighting capacity for abstraction, analysis, and synthesis, application of knowledge of basic sciences and engineering. The identification, evaluation, and implementation of technologies appropriate to the context is also required. In the specific case of the state of Guerrero, the graduate must contribute to the solution of the regional problem generated by high seismicity through the conception, analysis, design, construction, and supervision of reliable structures (UAGro, 2011).

One way to achieve this is to use free and open-source computer apps in the learning-teaching process. Among the advantages are (Culebro, *et al.*, 2006; Díaz, *et al.*, 2005; Free Software Foundation, 2020):

1. They are not black boxes because they show the code
2. They develop the calculations quickly and repetitively
3. Serve as a guide for students for developing their own tools
4. They help in the acquisition of competencies
5. They use local regulations
6. Avoid copyright infringement
7. They promote the technological development of the country

In the Civil Engineering field, the analysis-design process has different levels of complexity, where the used tool changes according the objective. Such activity includes performing arithmetic operations and making decisions that can be repetitive. Table 1 shows a classification of the computer applications and their main characteristics, the complexity increases from left to right. In this way, an Excel spreadsheet (Microsoft 2020) was developed, which does not require advanced programming knowledge.

Table 1
Classification of apps for design-review structures

Level 1. Low complexity	Level 2. Medium complexity (ESI Group, 2020; MatWorks, 2020; PTC, 2020)	Level 3. High complexity (Corona, 2020; Computer and Structures, 2018)
Manual calculation Tool: calculator.	Semi-manual or automated calculation Tool: spreadsheet, Scilab, Matlab, Mathcad.	Automated calculation Tools for commercial use.
Advantages: The calculation processes defined by the technical standards are applied.	Advantages: Visualization of calculations, use of national standards, open-source.	Advantages: Specialization and speed.
Disadvantages: Simple structures are studied by the number of calculations.	Disadvantages: In the case of Scilab, Octave, Matlab, and Mathcad basic programming knowledge is required. The last two are proprietary software, meaning they have a price	Disadvantages: Black boxes, copyright payment, use of international standards, closed source.

Source: Own elaboration

II. OBJECTIVE

The use of reinforced concrete walls in the construction of buildings and homes combined with the high seismic risk in large areas of the national territory (Alcocer, *et al*, 2020; Carrillo & Alcocer, 2011) requires special care in the design of these structural elements when they are subjected to in-plane bending and axial load. For this reason, an open-source tool was developed to help in the learning-teaching process in Civil Engineering schools. Due to its characteristics, calculations, decision-making, and repetition of processes are shown, it can also be improved by users (teachers, students, or professionals).

III. METHODOLOGY

Background

Reinforced concrete is the most widely used material worldwide in the building construction (McCormac & Brown, 2014). In the case of reinforced concrete walls, they are subjected to three types of mechanical stress: shear (V_u), bending moment in its plane (M_u), and axial load (P_u), Figure 1. Combination of lateral and gravitational forces are the origin of these mechanical elements.

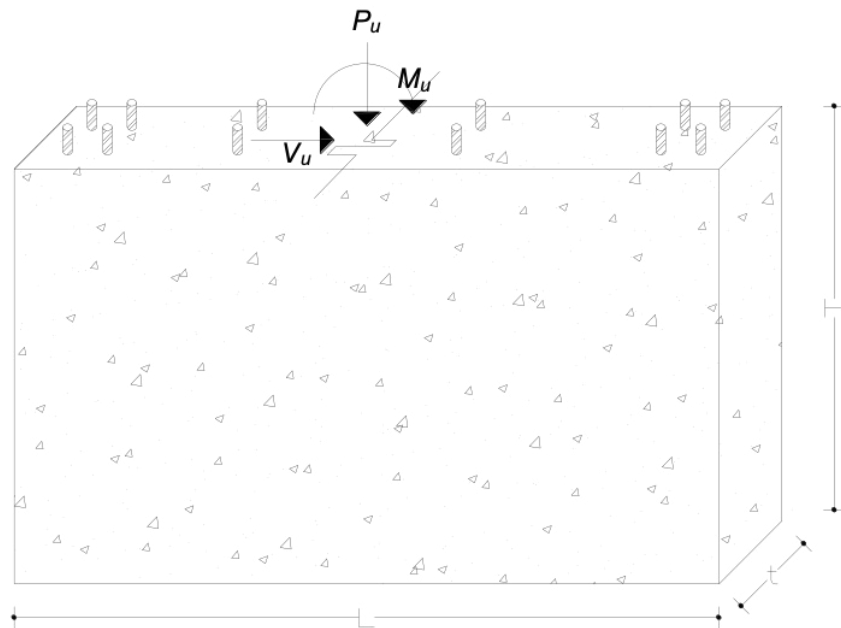


Figure 1. Mechanical elements acting in a reinforced concrete wall. Source: Own elaboration

The concrete structures design here presented is based on the NTCC-2017. Figure 2 shows the flow chart for developing of the spreadsheet. In the first step, the input vector must have the wall geometry, mechanical characteristics of the concrete, and distribution/properties of steel bars. In the second step, the strength interaction curve ($M-P$) is obtained. In the third step, the strength moment and axial load (M_R, P_R) for the design eccentricity (M_U/P_U) are calculated. Finally, it is evaluated if the reinforced concrete element resists the combination of the factored load (P_U) and factored moment (M_U).

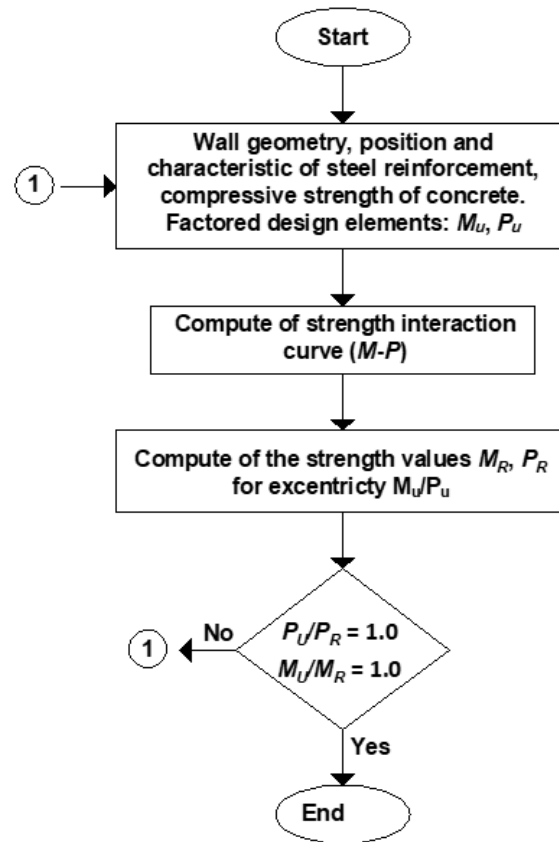


Figure 2. Flow chart used for the app development. Source: Own elaboration

Calculation of the strength interaction curve

For instructional purposes, the concrete wall has only four layers of steel, two at each end, which are subjected to tension or compression effects. The section experiences the strains and stresses shown in Figure 3, sections b and c. To calculate the strength axial load and moment, extreme values of concrete and steel strains are needed. The maximum strain of concrete (ϵ_c) is 0.003 and in the case of steel values from 0.003 in compression to 0.010 in tension are proposed, (ϵ_{s4}). The bending moment causes tension in the lower part and compression in the upper part. The variables in Figure 3 are defined in Table 2.

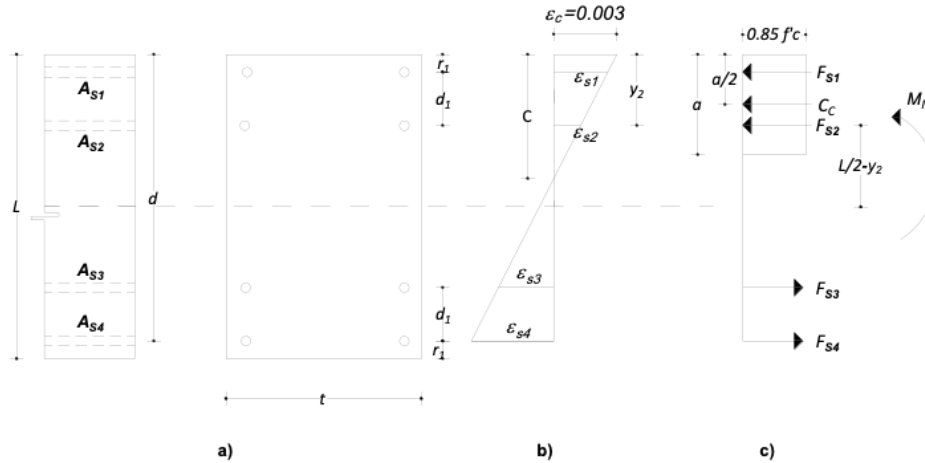


Figure 3. a) Geometry of the section, b) Strain diagram, c) Stress diagram. Source: Own elaboration

The depth of the neutral axis (c) and the strain of the steel layer i (ε_{si}) are a function of the extreme strains of concrete and steel and are obtained with equations 1 and 2. According to Hooke's law, the acting stress is proportional to the strain without exceeding the yield stress, f_y , equation 3. The acting force of layer i is obtained by multiplying the area of rebar by the acting stress, equation 4. Finally, the moment generated by the steel layer i is the multiplication of the force by the lever arm concerning the plastic axis of the section, equation 5.

Table 2
Definition of variables from Figure 3

Variable	Description	Variable	Description
L	Wall's length	ε_{si}	Strain of the steel in layer i
t	Wall's thickness	y_i	Distance from of steel layer i to compression face
A_{si}	Steel area of the layer i	d	Distance from extreme compression fiber to centroid of longitudinal tension reinforcement
r_1	Clear cover of reinforcement	c	Distance from extreme compression fiber to neutral axis
d_1	Distance between steel layers 1-2 and 3-4	a	Depth of equivalent rectangular stress block
f'_c	Compressive strength of concrete less than or equal to 28 MPa	F_{si}	Stress in the steel layer i
C_c	Compression force in the concrete compression block	M_N	Nominal flexural strength at section
ε_c	Concrete strain equal to 0.003		

Source: Own elaboration

$$c = d \varepsilon_c / (\varepsilon_c + \varepsilon_{s4}) \quad (1)$$

$$\varepsilon_{si} = \varepsilon_c (c - y_i) / c \quad (2)$$

$$f_{si} = \varepsilon_{si} f_y / 0.002 \quad (3)$$

$$F_{si} = A_{si} f_{si} \quad (4)$$

$$M_{si} = F_{si} (L/2 - y_i) \quad (5)$$

Due to its position, the steel located at the ends of the wall provides the greatest amount of resistance moment, for this reason, the steel of intermediate layers is not considered, which is calculated to absorb the temperature's effects.

As can be seen in Figure 3c, the maximum concrete stress is $0.85 f'_c$, then, it is possible to evaluate the volume of the stress block with equation 6, where $a = 0.85 c$ when the compressive strength is less than or equal to 28 MPa, the moment is obtained using equation 7. The nominal load (P_N) and nominal moment (M_N) associated with $\varepsilon_c = 0.003$ and a specific value of ε_{s4} are the sum of the forces and moments of the steel and concrete, respectively, equations 8 and 9.

$$C_c = 0.85 f'_c a t \quad (6)$$

$$M_c = C_c (L - a/2) \quad (7)$$

$$P_N = \sum_{i=1}^{i=4} F_{si} + C_c \quad (8)$$

$$M_N = \sum_{i=1}^{i=4} M_{si} + M_c \quad (9)$$

The M_N and P_N define a point on the nominal moment-load interaction curve, Figure 4. In this case, for didactic purposes, only five intermediate points (points P_2 , P_3 , P_4 , P_5 and P_6) associated with different values of the deformation of the extreme layer (ε_{s4}) were calculated. Points P_2 and P_7 with moments equal to zero are the nominal strength to compression and tension, the second one represents the second term of equation 10 and both define the compressive strength, where A_g is the gross area of concrete section. At point P_7 the contribution of concrete is zero.

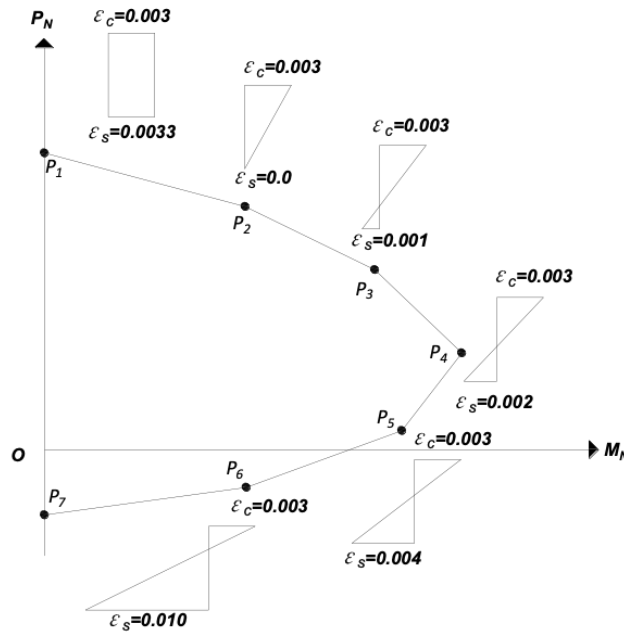


Figure 4. Points analyzed in the nominal interaction curve and associated strains. Source: Own elaboration

$$P_{O,T} = 0.85 f'_c A_g + A_s f_y \quad (10)$$

By multiplying the values of the nominal interaction curve (Figure 4) by the strength reduction factor (F_R) the strength curve is obtained, equation 11 and Figure 5a. The F_R values are defined in section 3.7 of the NTCC-2017, equation 12.

$$\begin{bmatrix} M_R \\ F_R \end{bmatrix} = F_R \begin{bmatrix} M_N \\ P_N \end{bmatrix} \quad (11)$$

$$F_R = \begin{cases} 0.65 & \text{falla en compresión} \\ 0.75 & \text{falla en tensión} \end{cases} \quad (12)$$

Calculation of strength elements (M_R, P_R) to factored moment and load (M_U, P_U)

The third step of the process shown in Figure 2 is to calculate the strength moment (M_R) and strength load (P_R) corresponding to the factored moment (M_U) and load (P_U). According to Figure 5a, the line OA starts at the origin and ends at the coordinates (M_U, P_U) forming an angle θ measured in the clockwise direction for the line OP_1 , its intersection with the strength curve defines the point $B (M_R, P_R)$, between points P_2 and P_3 . The position is obtained by comparing the angle θ with the angles θ_2 and θ_3 , Figure 5b. Next, the slopes of the lines P_2P_3 and OA , m_1 and m_2 , respectively, are calculated.

In segment P_2P_3 , equation 13 is established, which passes through the point of known coordinates (M_{R3}, P_{R3}) , while the definition of the slope m_2 of the line OA allows establishing equation 14 (Lehman, 2006).

$$P_R - m_1 M_R = P_{R3} - m_1 M_{R3} \quad (13)$$

$$P_R - m_2 M_R = 0 \quad (14)$$

The solution of the system of both equations represents the coordinates of point B (Griffiths & Smith, 2006), which are the strength moment (M_R) and strength load (P_R) related to the factored elements (M_U, P_U).

Finally, the relation M_U/M_R and P_U/P_R is compared, if the quotient is less than one, the wall resists the actuating mechanical elements, otherwise the user must modify the input data and repeat the calculation.

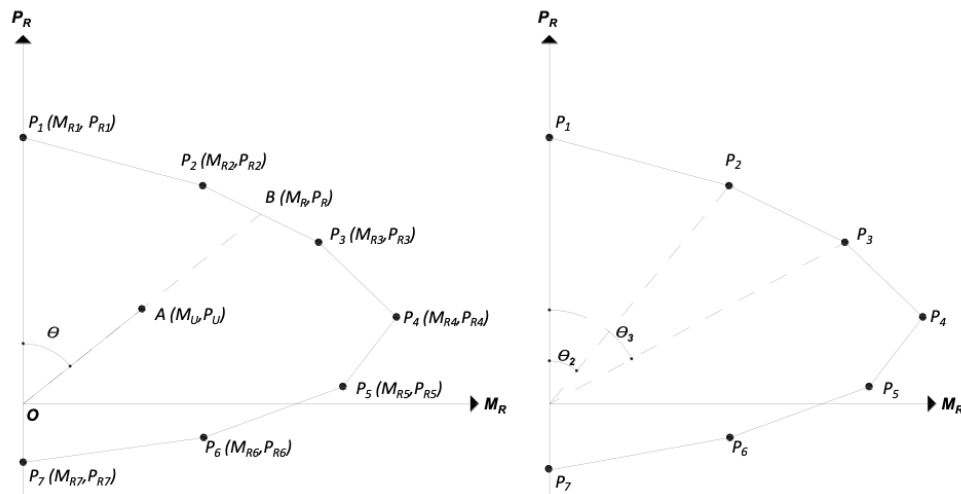


Figure 5. Strength interaction curve ($M_R - P_R$): a) eccentricity angle (θ) and point of intersection in the strength curve, b) definition of angles θ_2 y θ_3 . Source: Own elaboration

Application to a specific case

The application has two spreadsheets, in the first the data is entered and the nominal curve ($M_N - P_N$) is calculated, in the second the strength curve and the pair of values ($M_R - P_R$) associated to the factored elements ($M_U - P_U$) are calculated. Table 3 shows the data vector and Table 4 presents the calculation of the nominal moment (M_N) and nominal load (P_N) of point P_4 . The application has a choice of four different steel diameters ($3/8''$, $1/2''$, $5/8''$, and $3/4''$), which can be modified with simple user manipulation. On the other hand, the length/thickness ratio of the wall must not exceed 40 or

70, depending on the axial load and the thickness will not be less than 100 mm, subsection 7.4.2.1 of the NTCC-2017.

Table 3
Data vector

Geometry, characteristics of steel and concrete (m, MPa)		Factored moment and axial load (KN, m)			
$t =$	0.15	$f_c =$	19.62	M_U	P_U
$r_1 =$	0.04	$f_y =$	412.02	150.0	1000.0
$r_2 =$	0.04	ϕ_1	3/8	Note: 1) Si $M_U=0$ and/or	
$d_1 =$	0.12	# of bars:	8	$P_U=0$, a value equal to 0.001	
$L =$	1.00			is recommended	

Source: Own elaboration

Table 4
Calculation of nominal moment (M_N) and nominal load (P_N) at point 4, balanced strain condition. Units: KN, m

$\epsilon_c = 0.003$	$c = 0.58$	$D = 0.26$					
$\epsilon_{s4} = 0.002$	$\alpha = 0.49$	$M_c = 313$					
	$C_c = 1225$						
# As	As (cm ²)	y_i	ϵ_s	f_s	Fs	Dist	Ms
1	1.42	0.04	0.0028	412	59	0.46	27
2	1.42	0.16	0.0022	412	59	0.34	20
3	1.42	0.84	-0.0014	-283	-40	-0.34	14
4	1.42	0.96	-0.0020	-412	-59	-0.46	27
					18		87
	$\Sigma F = 1243$			$\Sigma M = 400$			

Source: Own elaboration

The system of equations is formed by the equations of intersecting lines (OA and P_2P_3), the solution and the M_U/M_R and P_U/P_R relationships are shown in Figure 6. Figure 7 shows the calculated curves and the OA line and the intersection with the resistant curve whose coordinates are the resistant moment (M_R) and the resistant load (P_R) are presented.

Equation system			System solution (KN m)		Ratio
$[A]$	$[x]$	$= [b]$	$[x] = [A]^{-1} [b]$		$M_U/M_R = 0.80$
1	4.30	2056	$P_R = 1249.4$		$P_U/P_R = 0.80$
1	-6.67	0	$M_R = 187.41$		The wall resists

Figure 6. System of equations, solution, and final result. Source: Own elaboration

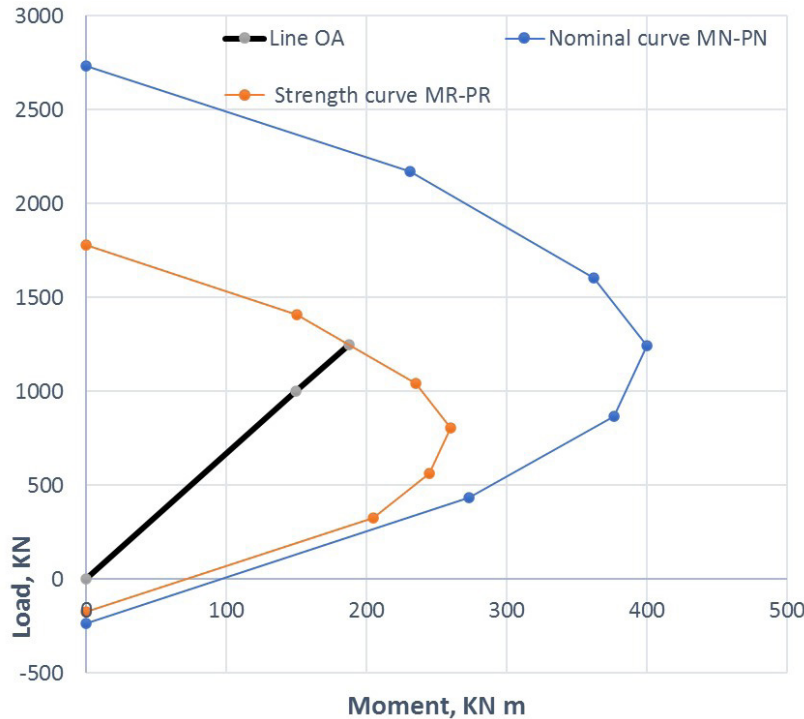


Figure 7. Calculated curves and intersection of the line **OA** with the strength curve. Source: Own elaboration

App access

The application can be downloaded from the site <https://github.com/SULPICIO67/Muros-de-concreto/blob/main/Flexocompression.xlsx> by anyone interested: student, teacher, and professional to use, modify or implement it in a more complex app.

III. RESULTS

The nominal interaction curve calculated with seven points by the app was compared with those obtained using two proprietary software (Corona, 2020; CSI, 2018) to determine its accuracy. The first commercial app (Corona: 2020) evaluates 38 points, as seen in Figure 8a, both nominal curves agree, there is only a negligible error near the point of maximum

moment. The difference between both curves for a fixed value of eccentricity (M_u/P_u) is evaluated by equation 15, where R_C is the modulus of the intersecting line of the curve obtained from the commercial application and R_A is the respective associated with the developed app, the error is $E = 1.8\%$.

Figure 8b shows the curve of the application and that obtained in the Sap2000 program (CSI, 2018), the latter has ten points and the error was $E = 1.7\%$. In this case, it should be noted that the comparison between nominal curves was possible because the Sap2000 program uses the ACI 318-14 version, whose analysis hypotheses are identical to those used in the NTCC-2017.

$$E = 100 (R_C - R_A)/R_C \quad (15)$$

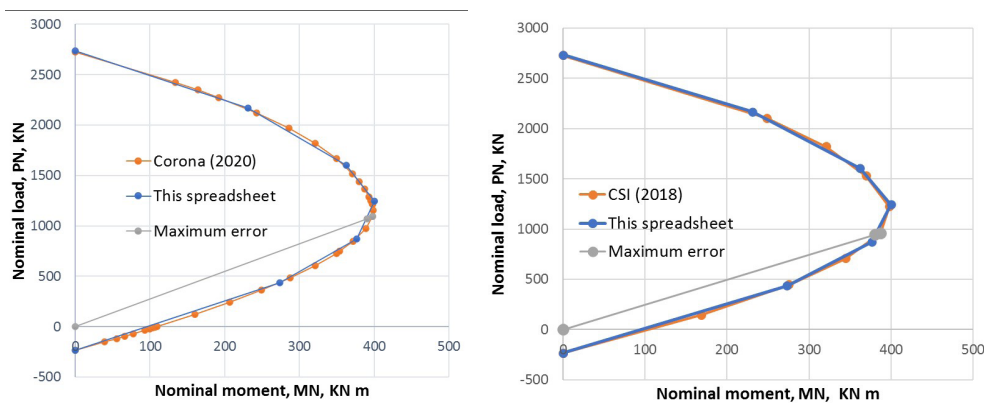


Figure 8. Nominal curves comparison. Source: Own elaboration

The error between strength curves, the first calculated with the application and the second with a commercial application (Corona, 2020), was evaluated with equation 15. Thus, two lines associated with two pairs of M_U-P_U values were proposed. The line $M_{R1}-P_{R1}$ with eccentricity equal to 0.40 had an error, $E_1 = 4.6\%$ while the line $M_{R2}-P_{R2}$ with eccentricity equal to 0.60 registered $E_2 = 13.0\%$, figure 9. As can be seen, the professional software calculates 38 points of the curve, while the developed application computes only seven points. Even so, the approximation, from 87% to 95.4%, is adequate.

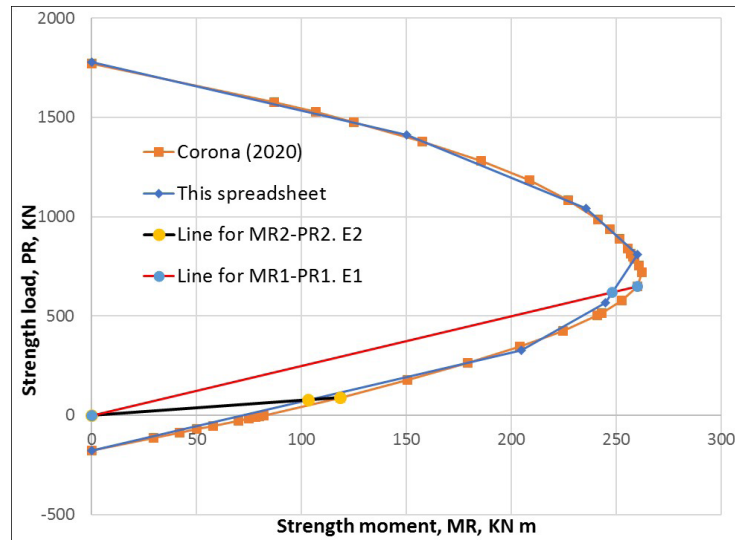


Figure 9. Strength curves comparison. Source: Own elaboration

Considering the didactic characteristics of the developed application, the limitations are:

- The maximum error of 13% is associated to the number of points used in the curve compute.
- Because the contribution of intermediate steel rebars are not evaluated, the section capacity is underestimated.

IV. CONCLUSIONS

The app meets the objective for supporting teaching-learning process of reinforced concrete walls design/revision, through the implementation of a simple algorithm with a reduced number of decisions. The strength curve defined by seven points has an approximation at least of 87% of that obtained by professional software, which evaluates 38 points of the graph. For the nominal curves, the error is less than 2%. This tool is already used by graduate students at the Faculty of Engineering (UAGro) in the courses of concrete structures/masonry structures design.

In another order, the algorithm is a guide for students, teachers, or Higher Education Institutions that intend to develop their own apps. In this sense, unlike internationally recognized universities, many Mexican universities do not have their own or free software to support teaching, so they must pay for the use of commercial licenses. This development shows an alternative to this situation.

The basic knowledge used was analytical geometry, arithmetic, and matrix algebra, all accessible in the Excel tool. In addition, it is possible to modify the input data if the result is not satisfactory.

Finally, an introduction to the abstract thinking required in the automation of calculation processes that students could face in their future professional development was shown, strengthening the acquisition of knowledge, skills, and competencies defined in the students' graduation profile.

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