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Structural Analysis of a RC Shear Wall by Use of a Truss Model

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Abstract

Purpose of present work is to develop a reliable and simple method for structural analysis of RC Shear Walls. The shear wall is simulated by a truss model as the bar of a truss is the simplest finite element. An iterative method is used. Initially, there are only concrete bars. Repeated structural analyses are performed. After each structural analysis, every concrete bar exceeding tensile strength is replaced by a steel bar. For every concrete bar exceeding compressive strength, first its section area is increased. If this is not enough, a steel bar is placed at the side of it. For every steel bar exceeding tensile or compressive strength, its section area is increased. After the end of every structural analysis, if all concrete and steel bars fall within tensile and compressive strengths, the output data are written and the analysis is terminated. Otherwise, the structural analysis is repeated. As all the necessary conditions (static, elastic, linearized geometric) are satisfied and the stresses of ALL concrete and steel bars fall within the tensile and compressive strengths, the results are acceptable. Usually, the proposed method exhibits a fast convergence in 4 - 5 repeats of structural analysis of the RC Shear Wall.

Keywords

Reinforced Concrete Shear Wall, Structural Analysis, Truss Model, Iterative Method, Computer Program, Boundary Columns and Beam, Grid of Horizontal and Diagonal Reinforcing Steel Bars

1. Introduction

The study of behavior of structural shear walls is recently of great interest for Civil Engineers [1] [2]. The structural analysis of a RC shear wall can be performed by the FEM (Finite Element Method).

The FEM, appeared in about 1965 [3] [4] [5], was a revolution in structural analysis, because it allowed the analysis of structures of any shape, any support conditions and any loading. However, in the case of nonlinear structural analysis, physical (of stress-strain law) or geometrical one, the FEM exhibits some problems [6] [7]. Even in the linear case, the local stiffness matrices of FEM are complicated.

The bar of a truss is the simplest possible finite element [8]. Its local stiffness matrix reduces to its axial stiffness $k = EA/l_0$, where E Young (Elasticity) modulus, A section area and l_0 initial undeformed length of the bar. And any nonlinear stress-strain law can be easily described by its uniaxial σ-ε law [9].

Even geometric nonlinearity can be easily taken into account by a truss model, by simply considering the equilibrium conditions with respect to the deformed truss [10], within an incremental loading procedure.

Here, a computer program, developed for the 2D structural analysis of overdetermined trusses, will be applied to the truss model of a typical RC (reinforced concrete) shear wall. And the computer program will be documented, step-by-step, by applying it to this specific example.

Initially, it will be assumed that the shear wall consists only of concrete, obeying a linear elastic stress-strain law. After every structural analysis, four steps are performed, for strengthening of the shear wall:

1) Every concrete bar exceeding tensile strength is replaced by a steel bar. 2) For every concrete bar exceeding compressive strength, its section area is increased by local increase of width of shear wall. 3) If this is not enough, the compressed concrete bar remains by receiving a part of the compressive axial force and a steel bar is added, to the side of it, by receiving the excess of compressive force. 4) For every steel bar exceeding tensile or compressive strength, its section area is increased.

At the compressed side of shear wall, due to overturning moments from horizontal seismic loading, the concrete section is enlarged near the base, in order to avoid stress concentrations.

Usually, in about 4 - 5 runs of the computer program, the stresses, of ALL concrete and steel bars, fall within the permissible limits of corresponding tensile and compressive strengths. So, the proposed method exhibits a rapid convergence. And, as all the necessary conditions (static, elastic, linearized geometric) are satisfied, as will be shown in the following, the results of the proposed iterative method are acceptable.

2. Application

2.1. Input Data

A typical ground floor shear wall of a building is considered, as shown in **Figure 1**, fixed at the base, with length l = 3.0 m, height h = 4.0 m, width w = 30 cm, subjected to vertical loading, from weights of storeys above it, with resultant R = 12,000 kN, thus loading intensity q = 12,000 kN/(300 cm × 30 cm) = 1.333 kN/cm^2, by assuming uniform distribution of loading. And a horizontal seismic load $H = 6000$ kN is considered, at the top left corner of shear wall, directed to right.

It is assumed that the shear wall initially consists only of concrete obeying the stress-strain σ-ε law of Figure 2.

2.2. Discretization

The shear wall is discretized to a grid of 8 × 6 = 48 equal square elements with dimensions 50 cm × 50 cm × 30 cm, as shown in Figure 3(a). One of these square elements is shown enlarged in Figure 3(b).

2.3. Truss Model

Every continuum square element is simulated by an elementary square plane truss, as shown in Figure 4.

By combining the stress-strain equations of the continuum square element of Figure 4(a), with the force-displacement equations of the elementary square plane truss model of Figure 4(b), by taking into account the relations between

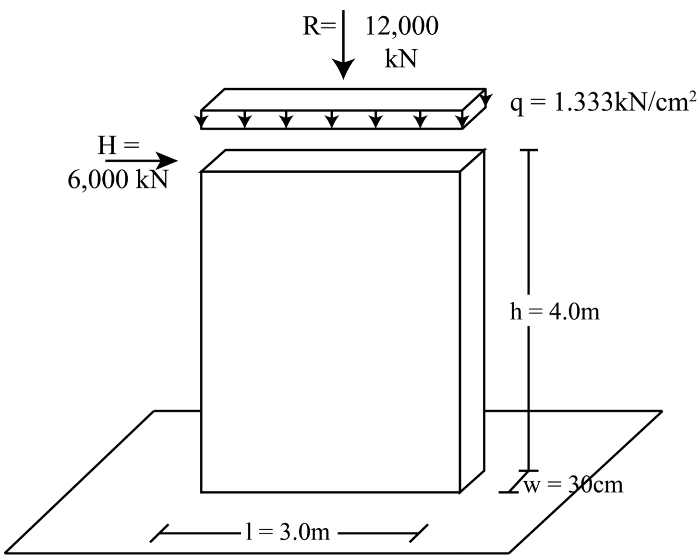


Figure 1. The typical shear wall under consideration.

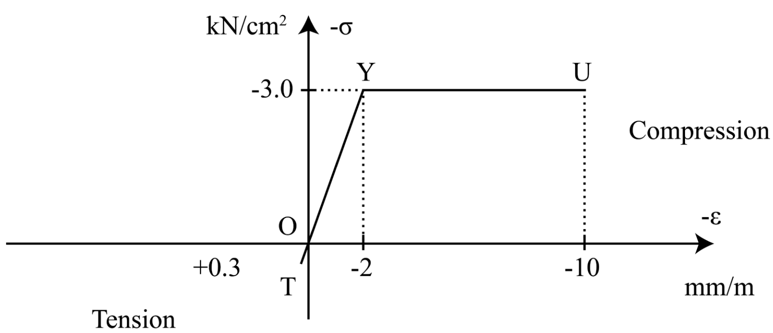


Figure 2. Concrete stress-strain σ-ε law of present application. Initial Young (Elasticity) modulus $E_0 = \sigma_y/\varepsilon_y = 3.0\ \text{kN/cm}^2/0.002 = 1500\ \text{kN/cm}^2$.

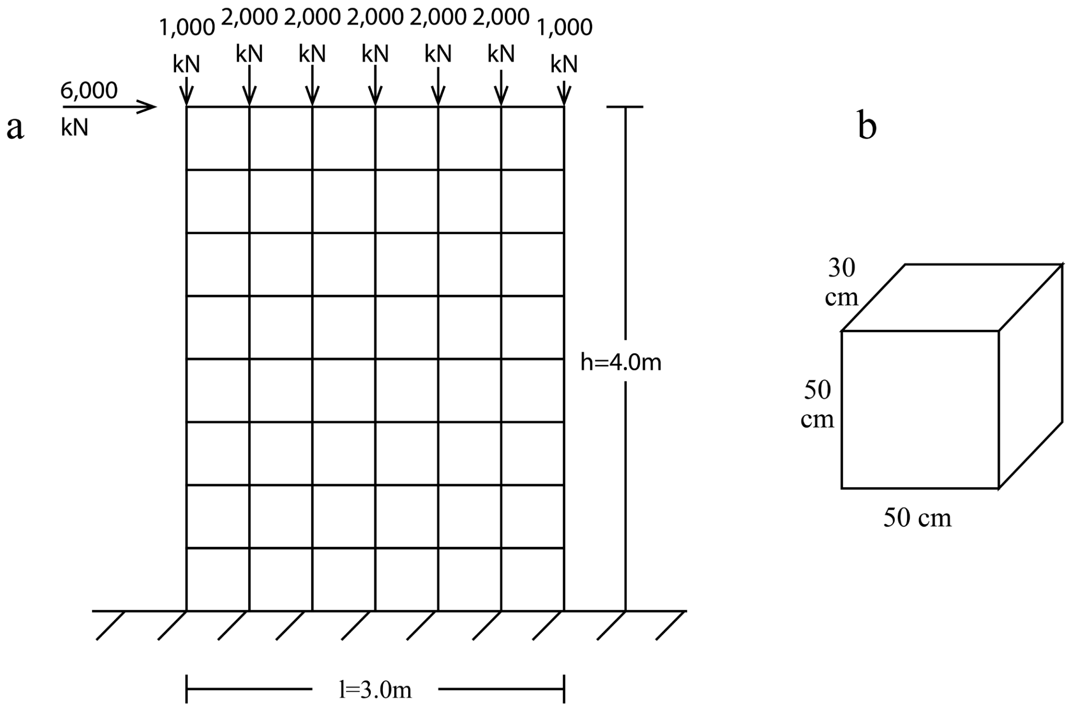


Figure 3. (a) Discretization of the shear wall. (b) One of the square elements enlarged.

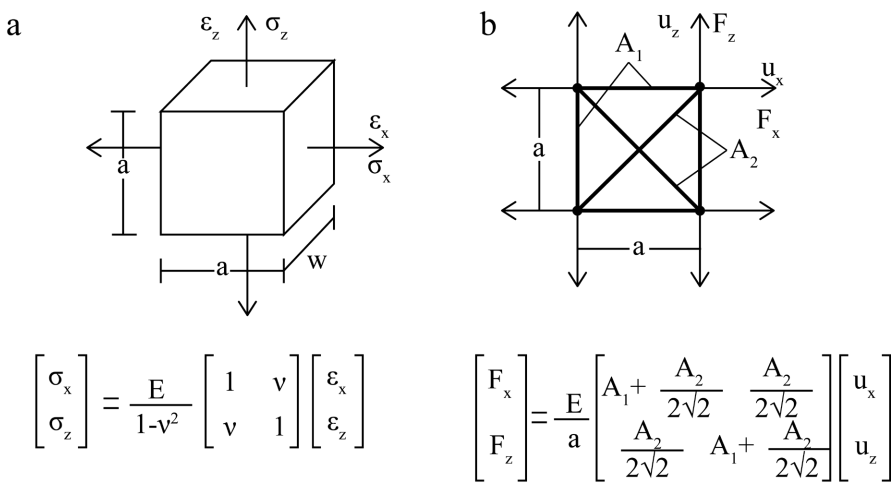


Figure 4. (a) Stress-Strain relations of the continuum square element. (b) Force-deformation relations of the elementary square truss model.

strains and displacements $\{\varepsilon_x,\varepsilon_z\}=\frac{2}{a}\{u_x,u_z\}$, the relations between stresses and forces $\{\sigma_x\sigma_z\}=\frac{2}{aw}\{F_xF_z\}$ and by assuming a Poisson ratio $v=1/3$, the bars section areas of the elementary square truss model are obtained with respect to the dimensions of the continuum square element: $A_1=\frac{3}{8}aw$, $A_2=\sqrt{2}A_1=\frac{3\sqrt{2}}{8}aw$.

2.4. Numbering of Nodes and Bars

For the structural analysis of the truss model of the shear wall, the 9 × 7 = 63 nodes and 8 (7 + 6 + 2 × 6) = 200 bars, of the whole truss model of the shear wall, are systematically numbered, as shown in Appendix A. In the same figure, are also shown the external loads P_x, P_z at the top nodes of the wall, as well as the reference axes system Oxz.

2.5. Computer Program

The computer program, developed here for the 2D structural analysis of the truss model of a RC (reinforced concrete) shear wall, will be documented, in the following, step-by-step, by applying it on the specific example under consideration.

First, the main program MAIN reads the input data, as shown in the flow-chart of Figure 5.

The numbers of nodes $\nu_n = 63$ and bars $\nu_b = 200$ are read. For every node are read: its support codes K_x, K_z, which have the value 0 if the corresponding displacement u_x or u_z is free or 1 if it is restricted. So, K_x, K_z are equal to 1 only for the support nodes 1 up to 7. Then, the initial co-ordinates *x*, *z* in m of the node, with respect to global reference axes system *Oxz*, are read, and the external loads P_x, P_z in kN, acting on the node, which are here nonzero only for top nodes 57 up to 63.

For every bar, the numbers l, r of nodes it connects, left and right, are read, its section area *A* in cm^2 and its initial undeformed length l_0 in m, which is 0.5 m for all vertical and horizontal bars and $l_0 = \sqrt{2} \times 0.5\ \text{m} = 0.7071\ \text{m}$ for all diagonal bars.

Then, subroutine STIF is called to form the global stiffness matrix $\boldsymbol{K}$ (126 ×126) of the truss model. To the diagonal elements (2*k* − 1) (2*k* − 1) and (2*k*) (2*k*) of matrix $\boldsymbol{K}$ corresponding to restricted displacements u_x, u_z of a support node *k*,

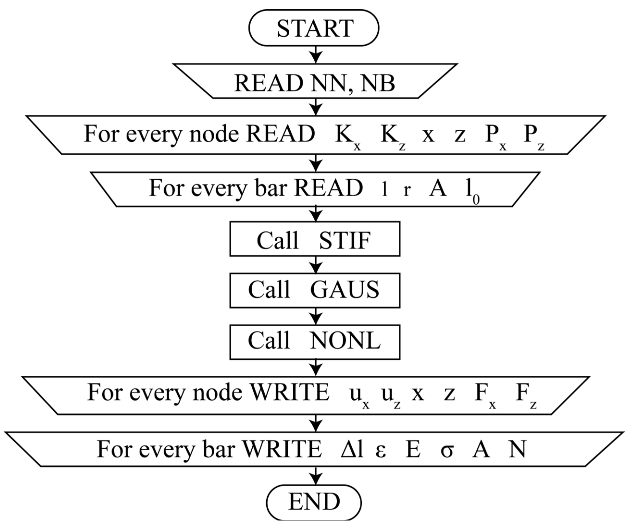


Figure 5. Flow-chart of the main program MAIN, which performs the 2D structural analysis of an over-determined truss model of a RC shear wall.

very large values 10^{13} kN/m (practically infinite) are given, in order, for the corresponding support displacements u_x, u_z to tend to zero, $u_{kx} \to \varnothing, u_{kz} \to \varnothing$, as shown in **Figure 6**.

Within subroutine STIF, for every concrete bar, its axial elastic stiffness is determined $k = E_0 A/l_0$, where $E_0 = 1500\ \text{kN/cm}^2$ initial Young (Elasticity) modulus of concrete (later, when steel bars will be considered, $E_0 = 7000\ \text{kN/cm}^2$ will be used, too, as initial Young (Elasticity) modulus of steel). A is section area in cm^2 of the bar and l_0 initial undeformed length in m of the bar. The initial projections $l_x = x_r - x_l$, $l_z = z_r - z_l$ of bar axis are found and its initial direction cosines $c_x = l_x/l_0$, $c_z = l_z/l_0$. The quantities $K_x = kc_x^2$, $K_z = kc_z^2$, $K_{xz} = kc_x c_z$ are determined and the 2 × 2 stiffness matrix of the bar is formed $\boldsymbol{k} = \begin{pmatrix} K_x & K_{xz} \\ K_{xz} & K_z \end{pmatrix}$, which, with positive or negative sign, is summed to appropriate submatrices 2 × 2 of the global stiffness matrix $\boldsymbol{K}$, as shown in **Figure 7**, where l, r numbers of nodes that the bar connects, left and right. When this procedure is completed for

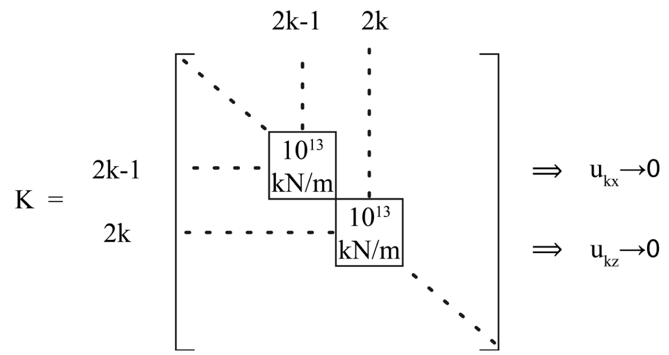


Figure 6. Giving very large (practically infinite) values 10^{13} kN/m to the diagonal elements $(2k-1)$ $(2k-1)$ and $(2k)$ $(2k)$ of global stiffness matrix $\boldsymbol{K}$, corresponding to restricted displacements u_x, u_z of a support node k, so that to obtain, for these displacements, values tending to zero, $u_{kx} \to 0, u_{kz} \to 0$.

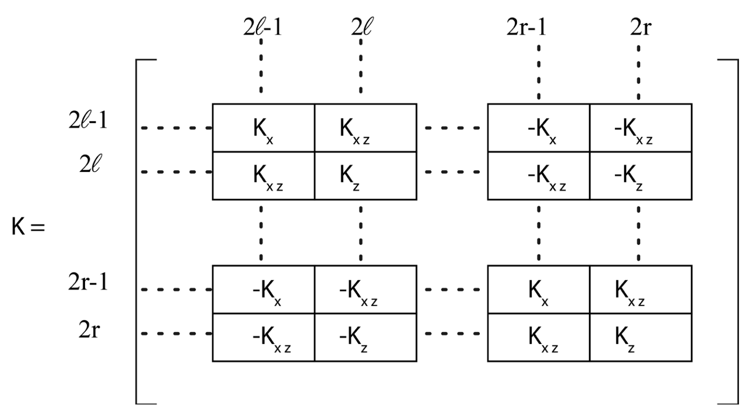


Figure 7. Summing of the 2 × 2 stiffness matrix $\pm\boldsymbol{k} = \pm\begin{pmatrix} K_x & K_{xz} \\ K_{xz} & K_z \end{pmatrix}$ of every bar to appropriate positions of the global stiffness matrix $\boldsymbol{K}$, so that to form $\boldsymbol{K}$, where l, r numbers of nodes that the bar connects, left and right.

all the bars, the global stiffness matrix $\boldsymbol{K}$ of the structure is formed. This formulation is based on the consideration of the linearized equations expressing the nodal forces F_x, F_z with respect to the nodal displacements u_x, u_z.

The global load vector $\boldsymbol{p}$ (126) is formed, containing the external loads P_x, P_z in kN of all nodes, which, in present application, are zero in all nodes, except of the seven top nodes (57 up to 63), where the external loads are applied.

Now, we have to solve the linear algebraic system, $\boldsymbol{Ku} = \boldsymbol{p}$, which will give, as result, the global vector $\boldsymbol{u}$ (126) of nodal displacements u_x, u_z.

Subroutine GAUS is called to solve the linear algebraic system, $\boldsymbol{Ku} = \boldsymbol{p}$. By successive eliminations, this algebraic system is triangularized, so that we can easily solve it by beginning from bottom equation, with only one unknown, and proceeding upwards, one by one equation, by substituting the already known nodal displacements, so by solving, each time, only one equation, with only one unknown nodal displacement u_x or u_z.

So, all the nodal displacements u_x, u_z are, successively, easily determined.

For every node, its displacements u_x, u_z in mm and its new co-ordinates $x + u_x, z + u_z$ in m, are written as output in Appendix B.

Then, the main program MAIN calls subroutine NONL, which applies the geometrically nonlinear equations of the problem.

For every bar, first the present projections of its axis $l_x = x_r - x_l, l_z = z_r - z_l$ are determined, where l, r the numbers of nodes that the bar connects, left and right, then its present length $l = \left(l_x^2 + l_z^2\right)^{1/2}$, and its direction cosines $c_x = l_x/l$, $c_z = l_z/l$, its elongation $\Delta l = l - l_0$, its dimensionless elongation $\varepsilon = \Delta l/l_0$, its stress $\sigma = E_0\varepsilon$, where $E_0 = 1500\ \text{kN/cm}^2$ initial Young (Elasticity) modulus of concrete (or $E_0 = 7000\ \text{kN/cm}^2$, for steel bars later) and $N = \sigma A$ axial force of the bar, where A its section area.

All the above data, $\Delta l, \varepsilon, E_0, \sigma, A, N$, for every bar, are written as output, for first run of computer program, in Appendix C.

Then, the quantities $\pm Nc_x, \pm Nc_z$ are formed for every bar, which are summed to the nodal forces F_{lx}, F_{lz} and F_{rx}, F_{rz} of the nodes l, r, that the bar connects, left and right, as shown in **Figure 8**:

For left node: $F_{lx} \leftarrow F_{lx} + Nc_x, F_{lz} \leftarrow F_{lz} + Nc_z$

For right node: $F_{rx} \leftarrow F_{rx} - Nc_x, F_{rz} \leftarrow F_{rz} - Nc_z$

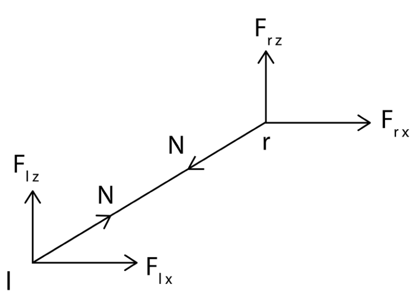
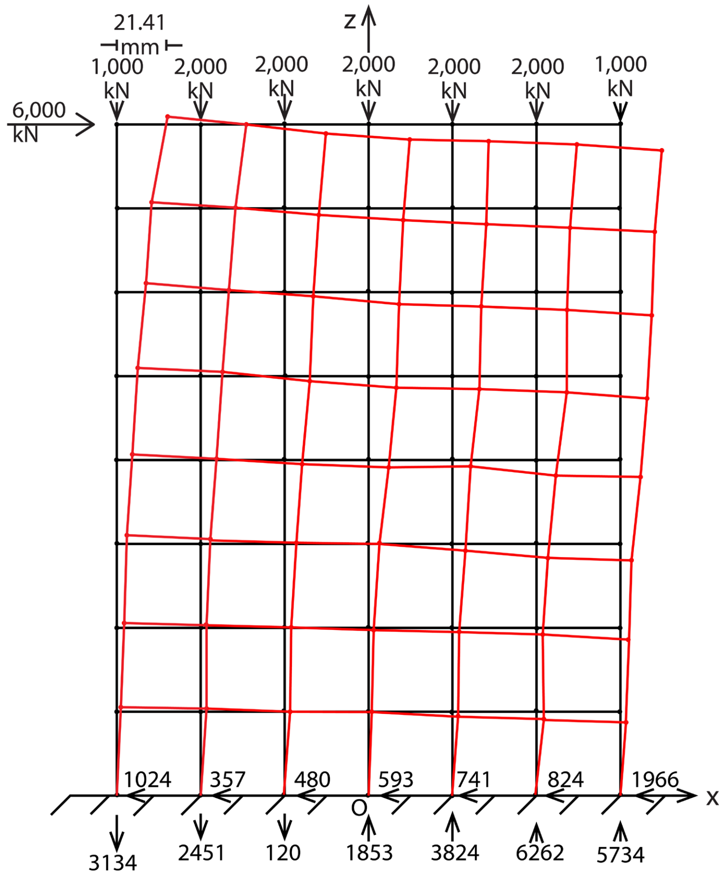


Figure 8. Summation of the quantities $\pm Nc_x, \pm Nc_z$ of a bar to the forces F_x, F_z of the nodes l, r, that the bar connects left, and right.

Initially, the nodal forces are equal to the external loads P_x, P_z. After completion of above procedure for all the bars, the nodal forces F_x, F_z obtain their total values, which are included in the previously mentioned Appendix B of nodal results, for first run of program.

The total nodal forces F_x, F_z have small values in all the nodes, except of the support nodes, 1 up to 7, where they are opposite to the external reactions R_x, R_z. In all the other nodes their small nonzero values are due to ignoring of geometric nonlinearity. Only at the nodes 50, 51, 57, 58, at top left corner of shear wall, where larger deformations occur, the geometric nonlinearity error is somewhat larger, but it does not significantly affects the global equilibrium equations, as will be shown below.

From the nodal displacements u_x, u_z of first run of Appendix B, the deformed configuration of the structure has been drawn in **Figure 9**, by using a



ΣF_x=6,000-1024-357-480-593-741-824-1966=15, 15/6,000 = 2.500‰

ΣF_z= -12,000-3134 -2451-120+1853+3824+6262+5734=-17705+17673
= - 32, 32/12,000 = 2.667‰

ΣM_0= 6,000x4.0-(5734+3134)1.5-(6262+2451)1.0-(3824+120)0.5=
=24,000-13302-8713-1972 = 13, 13/24,000 = 0.542‰

Figure 9. First run. Deformed configuration and equilibrium equations $\sum F_x = 0$, $\sum F_z = 0$, $\sum M_0 = 0$ of the shear wall.

displacements scale (1:1) 25 times larger than lengths scale (1:25). The largest displacement $u_x = 21.41\text{ mm}$ is observed at the top left corner of the wall.

In the same figure, the external reactions R_x, R_z of support nodes, 1 up to 7, are noted, as opposite of corresponding nodal forces F_x, F_z, as well as the external loads P_x, P_z at the top nodes 57 up to 63. By use of external loads P_x, P_z and external reactions R_x, R_z, the global equilibrium equations $\sum F_x = 0$, $\sum F_z = 0$, $\sum M_0 = 0$ are written with respect to global reference axes *Oxz*. And, it is observed that they are verified with high accuracy, with errors only 0.542‰ up to 2.667‰ (per thousand), as demonstrated in **Figure 9**.

From the bars results of subroutine NONL, for first run, in Appendix C, is obtained, in the summarizing **Table 1**, that, in the first run, 66 concrete bars exceed tensile strength, $\sigma > +0.3\text{ kN/cm}^2$ (12 vertical + 25 horizontal + 27 ascending diagonals + 2 descending diagonals), 13 concrete bars exceed compressive strength, $\sigma < -3.0\text{ kN/cm}^2$ (9 vertical + 2 horizontal + 2 descending diagonals). So, remain 121 concrete bars with stresses within tensile and compressive strengths, $-3.0\text{ kN/cm}^2 < \sigma < +0.3\text{ kN/cm}^2$ (35 vertical + 21 horizontal + 21 ascending diagonals + 44 descending diagonals).

Based also on Appendix C, **Figure 10** shows, for the first run, the stresses in kN/cm^2 of the 66 concrete bars exceeding tensile strength, $\sigma > +0.3\text{ kN/cm}^2$, as well as the stresses in kN/cm^2 of the 13 concrete bars exceeding compressive strength, $\sigma < -3.0\text{ kN/cm}^2$.

3. Four Steps for the Strengthening of the Shear Wall

After every run of the program, the following four steps are performed, for the strengthening of the shear wall, as described by the flow-chart of **Figure 11**.

Step 1

Every concrete bar exceeding tensile strength, $\sigma > +0.3\text{ kN/cm}^2$, is replaced by a steel reinforcing bar with section area $A_s = A_c E_c / E_s$, where $E_c = 1500\text{ kN/cm}^2$ and $E_s = 7000\text{ kN/cm}^2$ Young moduli of concrete and steel, respectively, according to stress-strain σ-ε laws of concrete and steel of **Figure 12** and A_c, A_s section areas of concrete and steel bar, respectively. So, A_s results $E_c/E_s = 1500/7000 = 1/4.667$ times smaller than A_c, and the initial axial stiffnesses of the failed concrete bar and the replacing steel bar result equal

Table 1. First run.Numbers of concrete bars exceeding or not exceeding strengths. V: Vertical bars, H: Horizintal bars, AD: Ascenting Diagonal bars, DD: Descenting Diagonal bars.

	V	H	AD	DD	Total
$+0.3\text{ kN/cm}^2 < \sigma$	12	25	27	2	66
$\sigma < -3.0\text{ kN/cm}^2$	9	2	0	2	13
$-3.0\text{ kN/cm}^2 < \sigma < +3.0\text{ kN/cm}^2$	35	21	21	44	121
Total	56	48	48	48	200

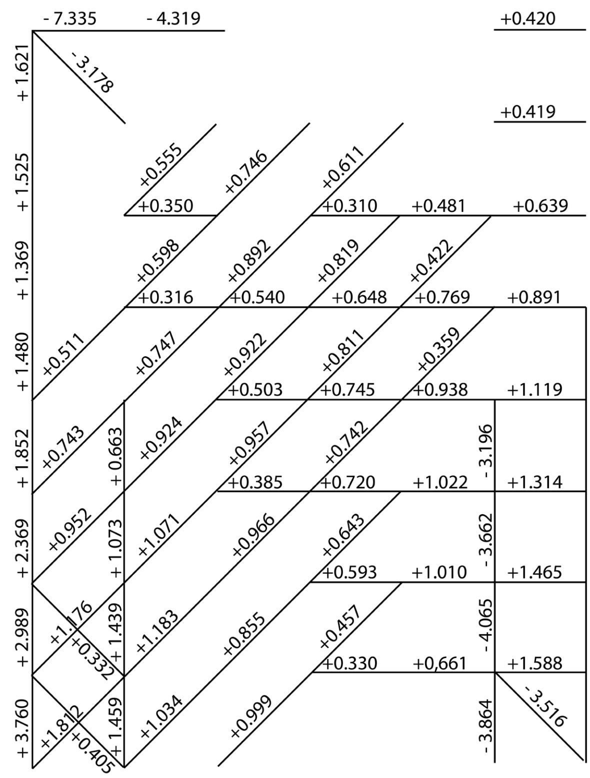


Figure 10. First run of computer program. Based on bars results of Appendix C, drawing of diagram of stresses in kN/cm² of the 66 concrete bars exceeding tensile strength, $\sigma > +0.3\ \text{kN/cm}^2$ as well asstresses in kN/cm² of the 13 concrete bars exceeding compressive strength, $\sigma < -3.0\ \text{kN/cm}^2$.

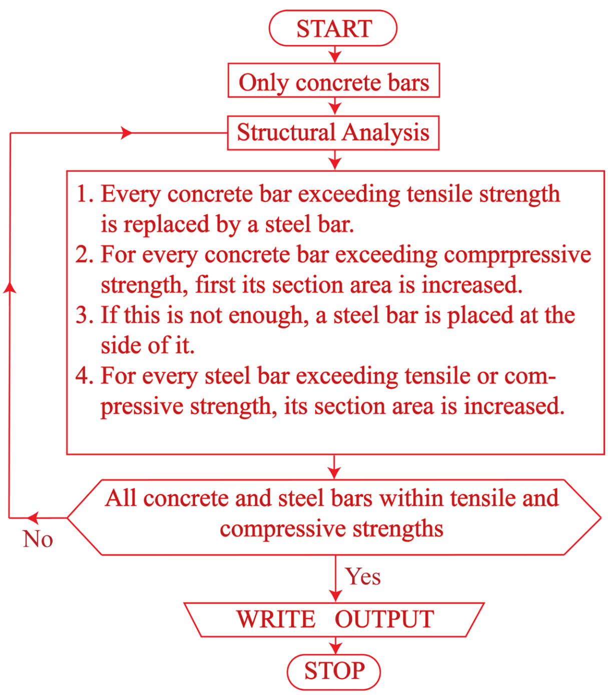


Figure 11. Flow-chart of the proposed iterative method for strengthening of the RC Shear Wall.

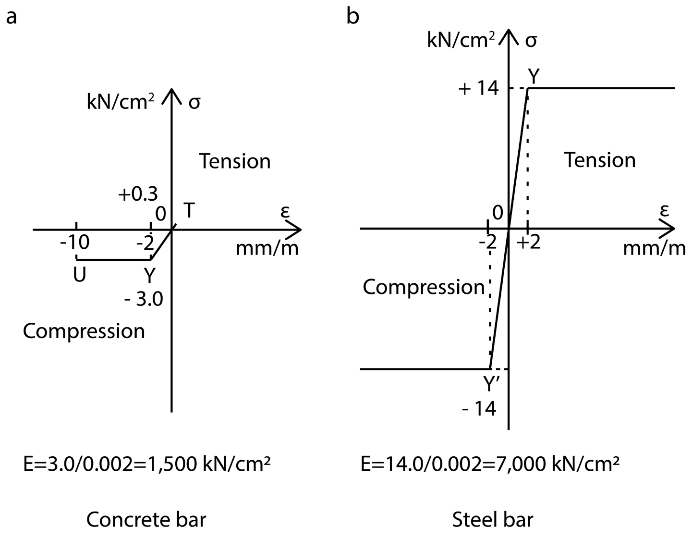


Figure 12. Concrete bar stress-strain σ-ε curve compared with b. Steel bar stress-strain σ-ε curve.

$K_s = E_s A_s / l_0 = E_c A_c / l_0 = K_c$, so the structural behavior is not disturbed.

If the replacing steel bar exceeds its tensile strength, $\sigma > +14\ \text{kN/cm}^2$, its section area A_s is increased.

Step 2

For every concrete bar exceeding compressive strength, $\sigma < -3.0\ \text{kN/cm}^2$, first its section area is increased, by increasing the corresponding local width w of the shear wall, so that to achieve, as far as possible, a reduction of compressive stress σ of concrete bar.

Step 3

If the above step 2 is not enough to allow a sufficient reduction of concrete bar compressive stress, the compressed concrete bar is maintained by receiving a part of the axial compression $N_0 = \sigma_{cc} \times A_c$, where $\sigma_{cc} = 3.0\ \text{kN/cm}^2$ compressive strength of concrete and A_c section area of concrete bar. And a steel bar is added, at the side of the compressed concrete bar, in order to receive the excess of the axial compression $\Delta N = N - N_0$, with section area $A_s = \Delta N / \sigma_{sc}$ where $\sigma_{sc} = 14.0\ \text{kN/cm}^2$ compressive strength of steel. So, for the limit axial compressive deformation $\varepsilon_y = -0.002$, for both compressed bars, the initial concrete bar and the additional steel bar at the side of it, the total axial compressive force of two bars tends to $N_0 + \Delta N = N$, as is required. If any of two bars slightly exceeds the corresponding compressive strength, the steel bar section area is increased.

Step 4

For every steel bar exceeding tensile or compressive strength, its section area is increased.

At the right side of the shear wall, compressed due to overturning moments of horizontal seismic loading, it is here advised that the concrete section is increased, near the base, in order to avoid stress concentrations.

Usually, the performing of above four steps takes only 3 - 4 runs of the computer program, after which, ALL stresses σ, of concrete and steel bars, fall within the permissible limits of corresponding tensile and compressive strengths: $-3.0\ \text{kN/cm}^2 < \sigma < +0.3\ \text{kN/cm}^2$ for concrete bars and $-14\ \text{kN/cm}^2 < \sigma < +14\ \text{kN/cm}^2$ for steel bars.

So, the proposed iterative method, for strengthening of a shear wall, exhibits a rapid convergence, in 4 - 5 runs of the computer program.

And, as all the necessary conditions (static, elastic, linearized geometric) are satisfied, according to what mentioned in previous sections, the results of the proposed here iterative method, for the strengthening of a shear wall, are acceptable.

4. Fourth and Final Run of the Computer Program

In the fourth and final run of the computer program, for the present application, the number of nodes is $\nu_n = 66$, that is 63 initial nodes and 3 additional ones, of the truss model for right base enlargement, as shown in Figure 13.

Whereas, the number of bars is $\nu_b = 212$, that is the 200 initial bars, plus 4 new compressed vertical steel bars at the right lower side of the shear wall and 2 new compressed horizontal steel bars at the top left corner of the shear wall, as well as the 6 new bars of the truss model, for right base enlargement, as shown in Figure 13.

The numbering of 3 additional nodes and 12 additional bars, for the fourth and final run of the computer program, is shown in Figure 13.

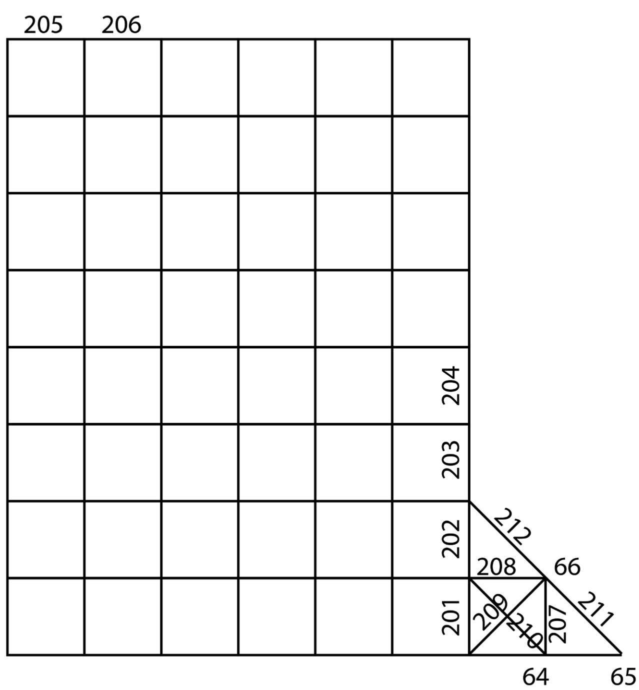


Figure 13. Fourth and final run of computer program. Numbering of additional 3 nodes and additional 12 bars.

As shown in Appendix E, in the results of bars of fourth and final run of computer program, for present application, ALL stresses σ, of concrete and steel bars, fall within the permissible limits of corresponding tensile and compressive strengths: $-3.0\ \text{kN}/\text{cm}^2 < \sigma < +0.3\ \text{kN}/\text{cm}^2$ for concrete bars and $-14\ \text{kN}/\text{cm}^2 < \sigma < +14\ \text{kN}/\text{cm}^2$ for steel bars.

And, as all the necessary conditions (static, elastic, linearized geometric) are satisfied, as mentioned in previous sections, the results of the proposed here iterative method, for strengthening of a shear wall, are acceptable.

By use of nodal displacements u_x, u_z, of the fourth and final run of present application, from Appendix D, the final deformed configuration of the RC (reinforced concrete) shear wall has been drawn in **Figure 14**, with displacements

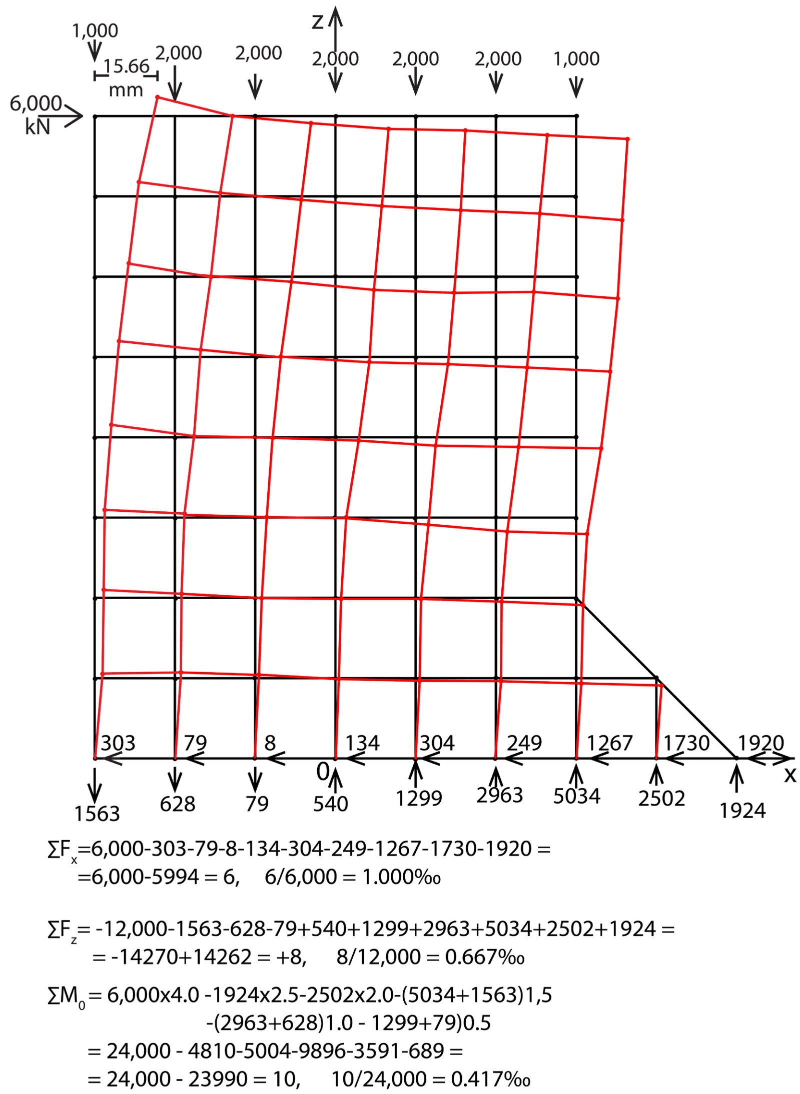


Figure 14. Fourth and final run of computer program. a. Based on nodal displacements u_x, u_z of Appendix D, drawing of deformed configuration of shear wall. b. Based on external reactions $R_x = -F_x, R_z = -F_z$ of Appendix D, writing of global equilibrium equations $\sum F_x = 0$, $\sum F_z = 0$, $\sum M_0 = 0$ of the shear wall.

scale 1:1, 25 times larger than lengths scale 1:25 and maximum displacement $u_x = 15.66$ mm at the top left corner of the shear wall.

In the same **Figure 14**, by using, from Appendix D, of nodal results of final run, the opposites of nodal forces F_x, F_z of supports, as external reactions R_x, R_z, the three final global equilibrium equations $\sum F_x = 0$, $\sum F_z = 0$, $\sum M_0 = 0$ are written, which are verified with further higher accuracy than in the first run, with errors only 0.417‰ up to 1.000‰ (per thousand), as shown in **Figure 14**.

5. Conclusions

An iterative method is proposed for the nonlinear 2D structural analysis of a truss model of a RC shear wall, which is applied on a typical RC shear wall.

A relevant computer program has been developed, which is documented, step-by-step, by applying it on the specific example under consideration.

Initially, the truss model of the shear wall is assumed consisting only of concrete bars obeying a linear elastic axial σ-ε law.

After every structural analysis of truss model, the following four steps are performed:

1) Every concrete bar exceeding tensile strength is replaced by a steel bar.

2) For every concrete bar exceeding compressive strength, its section area is increased.

3) If the above is not enough,the concrete bar is maintained, by receiving part of axial compression and a steel bar is added at the side of it.

4) For every steel bar exceeding tensile or compressive strength, its section area is increased.

At the lower part of side of shear wall, compressed due to overturning moments from horizontal seismic loading, the concrete section is enlarged, in order to avoid stress concentration.

Usually, in 4 - 5 runs of the computer program, ALL stresses of concrete and steel bars fall within tensile and compressive strengths. So, the proposed here iterative method exhibits a rapid convergence.

And, as all necessary conditions (static, elastic, linearized geometric) are satisfied, the results of proposed here iterative method are acceptable.

Because of alternating nature, in direction of the horizontal seismic loading, the results of the application have to be symmetrically extended to both sides of the shear wall.

The results of the application confirm the need for boundary columns, at the two sides of the shear wall, and a boundary horizontal beam at the top, as well as the need for a grid of ascending diagonal and horizontal steel bars, receiving tension and shear, in the main body of the shear wall.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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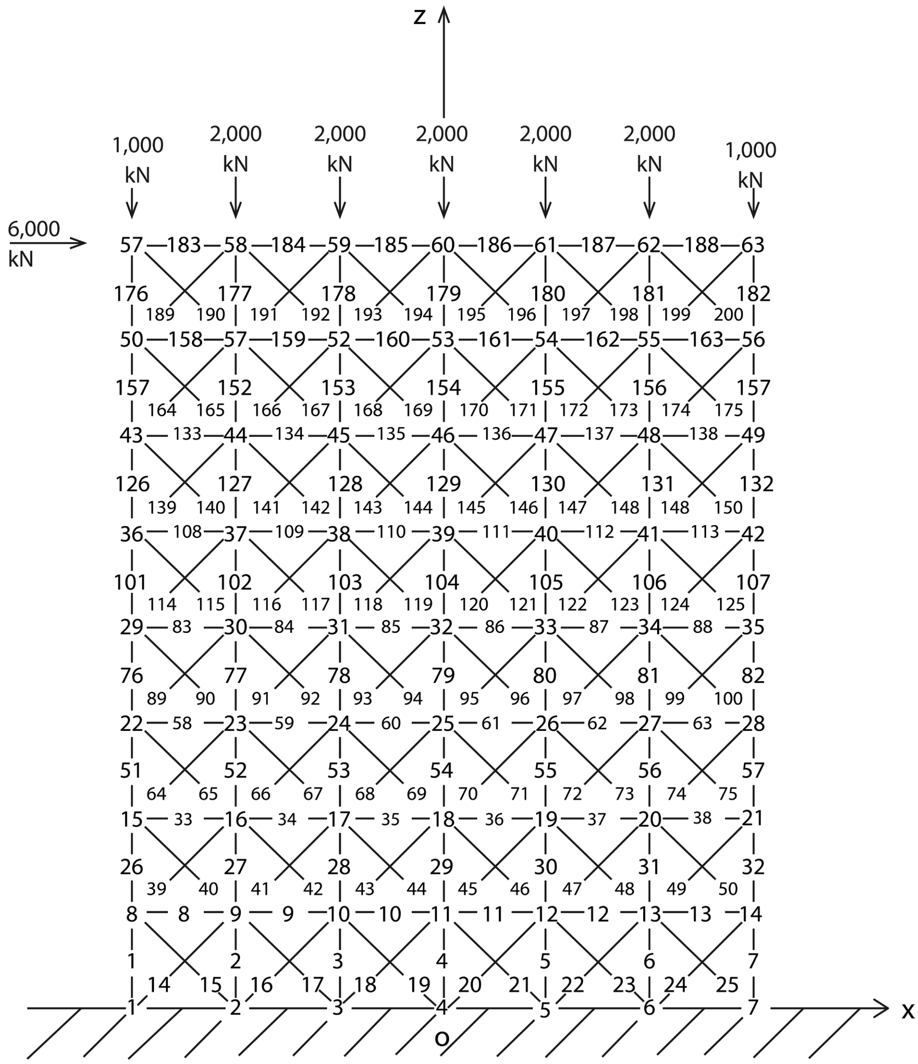
Appendices

Appendix A. Systematic Numbering of the 9 × 7 = 63 Nodes and 8 (7 + 6 + 2 × 6) = 200 Bars of the Whole Truss Model of the Shear Wall



Appendix B

FIRST RUN, RESULTS OF NODES							
	DISPLACEMENTS		NEW CO-ORDINATES		NODAL FORCES		
Node number	U_x mm	U_z mm	X m	Z m	F_x kN	F_z kN	layer
1	0.0000	0.0000	−1.5000000	0.0000000	1023.8	3133.9	0
2	0.0000	0.0000	−1.0000000	0.0000000	356.8	2451.0	
3	0.0000	0.0000	−0.5000000	0.0000000	479.5	119.7	
4	0.0000	0.0000	0.0000000	0.0000000	593.4	−1852.8	
5	0.0000	0.0000	0.5000000	0.0000000	741.5	−3823.7	
6	0.0000	0.0000	1.0000000	0.0000000	824.0	−6261.9	
7	0.0000	0.0000	1.5000000	0.0000000	1966.0	−5734.1	
8	0.9848	1.2520	−1.4990152	0.5012520	5.5	−0.1	1
9	0.7222	0.4859	−0.9992778	0.5004859	0.0	8.0	
10	0.6779	0.0109	−0.4993221	0.5000109	−0.4	7.1	
11	0.7245	−0.3925	0.0007245	0.4996075	−0.7	7.0	
12	0.8343	−0.7965	0.5008343	0.4992035	−1.3	8.5	
13	1.0540	−1.2890	1.0010540	0.4987110	−0.4	10.6	
14	1.5810	−2.2290	1.5015810	0.4977710	−5.3	−5.7	
15	2.2680	2.2470	−1.4977320	1.0022470	13.5	0.1	2
16	2.0560	0.9639	−0.9979440	1.0009639	−2.0	10.4	
17	2.0040	−0.0082	−0.4979960	0.9999918	−1.1	9.7	
18	2.0890	−0.8327	0.0020890	0.9991673	−0.6	9.5	
19	2.2850	−1.6530	0.5022850	0.9983470	0.5	9.5	
20	2.6210	−2.6470	1.0026210	0.9973530	3.7	10.1	
21	3.1070	−4.0530	1.5031070	0.9959470	−16.8	−6.6	
22	3.9850	3.0340	−1.4960150	1.5030340	22.9	0.9	3
23	3.8270	1.3180	−0.9961730	1.5013180	−3.6	12.6	
24	3.8190	−0.0897	−0.4961810	1.4999103	−2.2	12.0	
25	3.9460	−1.3120	0.0039460	1.4986880	−0.5	10.6	
26	4.1850	−2.5070	0.5041850	1.4974930	0.7	9.8	
27	4.5240	−3.8710	1.0045240	1.4961290	3.9	10.0	
28	4.9590	−5.6150	1.5049590	1.4943850	−24.0	−7.6	
29	6.0760	3.6470	−1.4939240	2.0036470	33.1	1.6	4
30	5.9730	1.5350	−0.9940270	2.0015350	−5.1	13.0	
31	6.0200	−0.2658	−0.4939800	1.9997342	−3.4	11.3	

Continued

32	6.1850	−1.8260	0.0061850	1.9981740	−2.2	9.1	
33	6.4310	−3.3130	0.5064310	1.9966870	1.1	8.7	
34	6.7410	−4.9410	1.0067410	1.9950590	4.5	8.6	
35	7.1110	−6.9380	1.5071110	1.9930620	−30.3	−7.1	
36	8.5040	4.1340	−1.4914960	2.5041340	46.1	4.9	5
37	8.4510	1.6020	−0.9915490	2.5016020	−8.1	17.8	
38	8.5510	−0.5565	−0.4914490	2.4994435	−8.0	11.9	
39	8.7280	−2.3710	0.0087280	2.4976290	−4.2	6.8	
40	8.9410	−4.0530	0.5089410	2.4959470	0.8	5.2	
41	9.1940	−5.8510	1.0091940	2.4941490	4.5	4.5	
42	9.4870	−8.0030	1.5094870	2.4919970	−34.7	−8.4	
43	11.3300	4.5820	−1.4886700	3.0045820	68.3	13.0	6
44	11.3000	1.4890	−0.9887000	3.0014890	−22.3	27.7	
45	11.4100	−0.9700	−0.4885900	2.9990300	−16.3	8.6	
46	11.4900	−2.9170	0.0114900	2.9970830	−7.2	2.8	
47	11.5900	−4.7020	0.5115900	2.9952980	−0.9	1.0	
48	11.7500	−6.5940	1.0117500	2.9934060	4.5	−0.2	
49	11.9600	−8.8000	1.5119600	2.9912000	−35.9	−7.3	
50	14.8200	5.0780	−1.4851800	3.5050780	108.5	57.9	7
51	14.7900	1.1330	−0.9852100	3.5011330	−86.6	39.8	
52	14.5400	−1.4080	−0.4854600	3.4985920	−29.7	−3.1	
53	14.3000	−3.3840	0.0143000	3.4966160	−8.8	−7.5	
54	14.1900	−5.2240	0.5141900	3.4947760	−0.2	−6.8	
55	14.2300	−7.1750	1.0142300	3.4928250	3.9	−4.5	
56	14.3600	−9.3680	1.5143600	3.4906320	−33.9	−6.8	
57	21.4100	5.5760	−1.4785900	4.0055760	57.0	95.0	8
58	18.9400	1.0180	−0.9810600	4.0010180	58.0	−18.5	
59	17.5000	−1.6290	−0.4825000	3.9983710	3.4	−54.9	
60	16.7400	−3.6980	0.0167400	3.9963020	6.3	−36.0	
61	16.4600	−5.6250	0.5164600	3.9943750	7.2	−31.4	
62	16.4700	−7.6390	1.0164700	3.9923610	6.6	−32.5	
63	16.6100	−9.8250	1.5166100	3.9901750	−14.2	−19.7	

Appendix C

FIRST RUN, RESULTS OF BARS									
Bar number	$\Delta l = l - l_0$ mm	$\varepsilon = \Delta l / l_0$ -	E kN/cm²	$\sigma = E\varepsilon$ kN/cm²	A cm²	$N = \sigma A$ kN	Mater. code	Bars failed	layer
1	1.2530	0.0025060	1500	3.7600	562.5	2115.0	1	+	1
2	0.4864	0.0009729	1500	1.4590	1125.0	1642.0	1	+	
3	0.0114	0.0000228	1500	0.0342	1125.0	38.4	1		
4	−0.3920	−0.0007839	1500	−1.1760	1125.0	−1323.0	1		
5	−0.7958	−0.0015920	1500	−2.3870	1125.0	−2686.0	1		
6	−1.2880	−0.0025760	1500	−3.8640	1125.0	−4347.0	1	−	
7	−2.2260	−0.0044530	1500	−6.6790	562.5	−3757.0	1	−	
8	−0.2620	−0.0005239	1500	−0.7859	1125.0	−884.1	1		
9	−0.0441	−0.0000882	1500	−0.1323	1125.0	−148.9	1		
10	0.0467	0.0000935	1500	0.1402	1125.0	157.7	1		
11	0.1100	0.0002201	1500	0.3301	1125.0	371.4	1	+	
12	0.2205	0.0004410	1500	0.6614	1125.0	744.1	1	+	
13	0.5273	0.0010550	1500	1.5820	1125.0	1780.0	1	+	
14	0.8543	0.0012080	1500	1.8120	795.5	1442.0	1	+	
15	0.1909	0.0002700	1500	0.4050	795.5	322.2	1	+	
16	0.4872	0.0006890	1500	1.0340	795.5	822.2	1	+	
17	−0.1666	−0.0002356	1500	−0.3534	795.5	−281.1	1		
18	0.2351	0.0003325	1500	0.4988	795.5	396.8	1	+	
19	−0.4715	−0.0006668	1500	−1.0000	795.5	−795.6	1		
20	0.0277	0.0000392	1500	0.0588	795.5	46.8	1		
21	−0.7898	−0.0011170	1500	−1.6750	795.5	−1333.0	1		
22	−0.1640	−0.0002319	1500	−0.3478	795.5	−276.7	1		
23	−1.1530	−0.0016310	1500	−2.4460	795.5	−1946.0	1		
24	−0.4531	−0.0006407	1500	−0.9611	795.5	−764.5	1		
25	−1.6570	−0.0023440	1500	−3.5160	795.5	−2797.0	1	−	
26	0.9963	0.0019930	1500	2.9890	562.5	1681.0	1	+	2
27	0.4798	0.0009596	1500	1.4390	1125.0	1619.0	1	+	
28	−0.0174	−0.0000348	1500	−0.0521	1125.0	−58.6	1		
29	−0.4383	−0.0008767	1500	−1.3150	1125.0	−1479.0	1		
30	−0.8541	−0.0017080	1500	−2.5620	1125.0	−2883.0	1		
31	−1.3550	−0.0027100	1500	−4.0650	1125.0	−4573.0	1	−	
32	−1.8220	−0.0036430	1500	−5.4650	562.5	−3074.0	1	−	

Continued

33	−0.2101	−0.0004203	1500	−0.6304	1125.0	−709.2	1		
34	−0.0511	−0.0001022	1500	−0.1532	1125.0	−172.4	1		
35	0.0855	0.0001709	1500	0.2564	1125.0	288.5	1		
36	0.1975	0.0003951	1500	0.5926	1125.0	666.7	1	+	
37	0.3367	0.0006734	1500	1.0100	1125.0	1136.0	1	+	
38	0.4882	0.0009764	1500	1.4650	1125.0	1648.0	1	+	
39	0.5541	0.0007837	1500	1.1760	795.5	935.1	1	+	
40	0.1563	0.0002211	1500	0.3317	795.5	263.8	1	+	
41	0.5579	0.0007890	1500	1.1830	795.5	941.5	1	+	
42	−0.2986	−0.0004222	1500	−0.6333	795.5	−503.8	1		
43	0.4028	0.0005697	1500	0.8545	795.5	679.7	1	+	
44	−0.6319	−0.0008937	1500	−1.3410	795.5	−1066.0	1		
45	0.2156	0.0003049	1500	0.4573	795.5	363.8	1	+	
46	−0.9120	−0.0012900	1500	−1.9350	795.5	−1539.0	1		
47	−0.0401	−0.0000567	1500	−0.0851	795.5	−67.7	1		
48	−1.1270	−0.0015940	1500	−2.3910	795.5	−1902.0	1		
49	−0.4944	−0.0006991	1500	−1.0490	795.5	−834.2	1		
50	−1.0310	−0.0014580	1500	−2.1870	795.5	−1739.0	1		
51	0.7898	0.0015800	1500	2.3690	562.5	1333.0	1	+	3
52	0.3577	0.0007154	1500	1.0730	1126.0	1208.0	1	+	
53	−0.0782	−0.0001565	1500	−0.2347	1125.0	−264.0	1		
54	−0.4760	−0.0009520	1500	−1.4280	1125.0	−1607.0	1		
55	−0.8509	−0.0017020	1500	−2.5530	1125.0	−2872.0	1		
56	−1.2210	−0.0024410	1500	−3.6620	1125.0	−4119.0	1	−	
57	−1.5590	−0.0031170	1500	−4.6760	562.5	−2630.0	1	−	
58	−0.1545	−0.0003091	1500	−0.4636	1125.0	−521.5	1		
59	−0.0059	−0.0000117	1500	−0.0176	1125.0	−19.8	1		
60	0.1283	0.0002565	1500	0.3848	1125.0	432.9	1	+	
61	0.2398	0.0004797	1500	0.7195	1125.0	809.5	1	+	
62	0.3408	0.0006816	1500	1.0220	1125.0	1150.0	1	+	
63	0.4380	0.0008761	1500	1.3140	1125.0	1478.0	1	+	
64	0.4485	0.0006343	1500	0.9515	795.5	756.9	1	+	
65	0.1053	0.0001489	1500	0.2234	795.5	177.7	1		
66	0.5047	0.0007138	1500	1.0710	795.5	851.7	1	+	
67	−0.3477	−0.0004918	1500	−0.7377	795.5	−586.8	1		

Continued

68	0.4551	0.0006437	1500	0.9655	795.5	768.1	1	+	
69	−0.6964	−0.0009848	1500	−1.4770	795.5	−1175.0	1		
70	0.3030	0.0004285	1500	0.6428	795.5	511.4	1	+	
71	−0.9320	−0.0013180	1500	−1.9770	795.5	−1573.0	1		
72	0.0210	0.0000297	1500	0.0445	795.5	35.4	1		
73	−1.0060	−0.0014220	1500	−2.1340	795.5	−1697.0	1		
74	−0.4361	−0.0006168	1500	−0.9252	795.5	−736.0	1		
75	−0.8718	−0.0012330	1500	−1.8490	795.5	−1471.0	1		
76	0.6172	0.0012340	1500	1.8520	562.5	1042.0	1	+	4
77	0.2208	0.0004417	1500	0.6625	1125.0	745.3	1	+	
78	−0.1711	−0.0003422	1500	−0.5133	1125.0	−577.4	1		
79	−0.5089	−0.0010180	1500	−1.5270	1125.0	−1718.0	1		
80	−0.8009	−0.0016020	1500	−2.4030	1125.0	−2703.0	1		
81	−1.0650	−0.0021310	1500	−3.1960	1125.0	−3596.0	1	−	
82	−1.3190	−0.0026370	1500	−3.9560	562.5	−2225.0	1	−	
83	−0.0981	−0.0001961	1500	−0.2941	1125.0	−330.9	1		
84	0.0504	0.0001009	1500	0.1513	1125.0	170.2	1		
85	0.1675	0.0003350	1500	0.5025	1125.0	565.3	1	+	
86	0.2483	0.0004965	1500	0.7448	1125.0	837.9	1	+	
87	0.3126	0.0006251	1500	0.9377	1125.0	1055.0	1	+	
88	0.3731	0.0007461	1500	1.1190	1125.0	1259.0	1	+	
89	0.3504	0.0004955	1500	0.7432	795.5	591.2	1	+	
90	0.0638	0.0000903	1500	0.1354	795.5	107.7	1		
91	0.4357	0.0006161	1500	0.9242	795.5	735.2	1	+	
92	−0.3692	−0.0005221	1500	−0.7832	795.5	−623.0	1		
93	0.4513	0.0006382	1500	0.9573	795.5	761.5	1	+	
94	−0.7233	−0.0010230	1500	−1.5340	795.5	−1221.0	1		
95	0.3496	0.0004944	1500	0.7416	795.5	589.9	1	+	
96	−0.9306	−0.0013160	1500	−1.9740	795.5	−1570.0	1		
97	0.0957	0.0001353	1500	0.2029	795.5	161.4	1		
98	−0.9525	−0.0013470	1500	−2.0210	795.5	−1607.0	1		
99	−0.3283	−0.0004643	1500	−0.6964	795.5	−554.0	1		
100	−0.7821	−0.0011060	1500	−1.6590	795.5	−1320.0	1		
101	0.4932	0.0009865	1500	1.4800	562.5	832.3	1	+	5
102	0.0734	0.0001467	1500	0.2201	1125.0	247.6	1	+	

Continued

103	−0.2843	−0.0005687	1500	−0.8530	1125.0	−959.7	1		
104	−0.5381	−0.0010760	1500	−1.6140	1125.0	−1816.0	1		
105	−0.7339	−0.0014680	1500	−2.2020	1125.0	−2477.0	1		
106	−0.9035	−0.0018070	1500	−2.7110	1125.0	−3049.0	1		
107	−1.0590	−0.0021190	1500	−3.1780	562.5	−1788.0	1	−	
108	−0.0471	−0.0000941	1500	−0.1412	1125.0	−158.8	1		
109	0.1052	0.0002104	1500	0.3156	1125.0	355.1	1	+	
110	0.1798	0.0003597	1500	0.5395	1125.0	606.9	1	+	
111	0.2160	0.0004320	1500	0.6480	1125.0	729.0	1	+	
112	0.2562	0.0005125	1500	0.7687	1125.0	864.8	1	+	
113	0.2971	0.0005941	1500	0.8912	1125.0	1003.0	1	+	
114	0.2407	0.0003404	1500	0.5106	795.5	406.2	1	+	
115	0.0573	0.0000811	1500	0.1216	795.5	96.8	1		
116	0.3522	0.0004981	1500	0.7471	795.5	594.3	1	+	
117	−0.3915	−0.0005536	1500	−0.8305	795.5	−660.6	1		
118	0.4345	0.0006144	1500	0.9216	795.5	733.2	1	+	
119	−0.7707	−0.0010900	1500	−1.6350	795.5	−1301.0	1		
120	0.3825	0.0005409	1500	0.8114	795.5	645.4	1	+	
121	−0.9537	−0.0013490	1500	−2.0230	795.5	−1609.0	1		
122	0.1692	0.0002392	1500	0.3588	795.5	285.5	1	+	
123	−0.9243	−0.0013070	1500	−1.9610	795.5	−1560.0	1		
124	−0.2120	−0.0002998	1500	−0.4497	795.5	−357.8	1		
125	−0.7010	−0.0009913	1500	−1.4870	795.5	−1183.0	1		
126	0.4564	0.0009128	1500	1.3690	562.5	770.2	1	+	6
127	−0.1051	−0.0002103	1500	−0.3154	1125.0	−354.9	1		
128	−0.4053	−0.0008105	1500	−1.2160	1125.0	−1368.0	1		
129	−0.5386	−0.0010770	1500	−1.6160	1125.0	−1818.0	1		
130	−0.6422	−0.0012840	1500	−1.9270	1125.0	−2167.0	1		
131	−0.7366	−0.0014730	1500	−2.2100	1125.0	−2486.0	1		
132	−0.7912	−0.0015820	1500	−2.3730	562.5	−1335.0	1		
133	−0.0198	−0.0000396	1500	−0.0595	1125.0	−66.9	1		
134	0.1166	0.0002333	1500	0.3499	1125.0	393.7	1	+	
135	0.0897	0.0001793	1500	0.2689	1125.0	302.6	1		
136	0.1034	0.0002068	1500	0.3102	1125.0	349.0	1	+	
137	0.1603	0.0003206	1500	0.4808	1125.0	540.9	1	+	

Continued

138	0.2130	0.0004261	1500	0.6391	1125.0	719.0	1	+	
139	0.1138	0.0001609	1500	0.2414	795.5	192.0	1		
140	0.0873	0.0001234	1500	0.1851	795.5	147.3	1		
141	0.2820	0.0003989	1500	0.5983	795.5	476.0	1	+	
142	−0.4862	−0.0006876	1500	−1.0310	795.5	−820.5	1		
143	0.4203	0.0005944	1500	0.8917	795.5	709.3	1	+	
144	−0.8975	−0.0012690	1500	−1.9040	795.5	−1515.0	1		
145	0.3861	0.0005460	1500	0.8190	795.5	651.5	1	+	
146	−0.9953	−0.0014080	1500	−2.1110	795.5	−1680.0	1		
147	0.1991	0.0002816	1500	0.4224	795.5	336.0	1	+	
148	−0.8794	−0.0012440	1500	−1.8660	795.5	−1484.0	1		
149	−0.1205	−0.0001704	1500	−0.2555	795.5	−203.3	1		
150	−0.5985	−0.0008464	1500	−1.2700	795.5	−1010.0	1		
151	0.5084	0.0010170	1500	1.5250	562.5	857.9	1	+	7
152	−0.3440	−0.0006880	1500	−1.0320	1125.0	−1161.0	1		
153	−0.4286	−0.0008572	1500	−1.2860	1125.0	−1446.0	1		
154	−0.4594	−0.0009188	1500	−1.3780	1125.0	−1550.0	1		
155	−0.5144	−0.0010290	1500	−1.5430	1125.0	−1736.0	1		
156	−0.5749	−0.0011500	1500	−1.7250	1125.0	−1940.0	1		
157	−0.5617	−0.0011230	1500	−1.6850	562.5	−947.8	1		
158	−0.0170	−0.0000339	1500	−0.0509	1125.0	−57.2	1		
159	−0.2362	−0.0004724	1500	−0.7086	1125.0	−797.2	1		
160	−0.2365	−0.0004729	1500	−0.7094	1125.0	−798.0	1		
161	−0.1064	−0.0002128	1500	−0.3192	1125.0	−359.1	1		
162	0.0389	0.0000777	1500	0.1166	1125.0	131.2	1		
163	0.1397	0.0002793	1500	0.4190	1125.0	471.3	1	+	
164	0.0250	0.0000353	1500	0.0530	795.5	42.1	1		
165	0.0650	0.0000919	1500	0.1378	795.5	109.6	1		
166	0.2616	0.0003700	1500	0.5549	795.5	441.5	1	+	
167	−0.8928	−0.0012630	1500	−1.8940	795.5	−1507.0	1		
168	0.3514	0.0004970	1500	0.7455	795.5	593.0	1	+	
169	−1.0840	−0.0015330	1500	−2.2990	795.5	−1829.0	1		
170	0.2878	0.0004071	1500	0.6106	795.5	485.7	1	+	
171	−0.9789	−0.0013840	1500	−2.0770	795.5	−1652.0	1		
172	0.1251	0.0001769	1500	0.2654	795.5	211.1	1		

Continued

173	−0.7545	−0.0010670	1500	−1.6000	795.5	−1273.0	1		
174	−0.1026	−0.0001451	1500	−0.2176	795.5	−173.1	1		
175	−0.4513	−0.0006383	1500	−0.9574	795.5	−761.6			
176	0.5405	0.0010810	1500	1.6210	562.5	912.1	1	+	8
177	−0.0976	−0.0001953	1500	−0.2929	1125.0	−329.5	1		
178	−0.2116	−0.0004231	1500	−0.6347	1125.0	−714.0	1		
179	−0.3080	−0.0006161	1500	−0.9241	1125.0	−1040.0	1		
180	−0.3961	−0.0007923	1500	−1.1880	1125.0	−1337.0	1		
181	−0.4587	−0.0009174	1500	−1.3760	1125.0	−1548.0	1		
182	−0.4520	−0.0009040	1500	−1.3560	562.5	−762.8	1		
183	−2.4450	−0.0048900	1500	−7.3350	562.5	−4126.0	1	−	
184	−1.4400	−0.0028790	1500	−4.3190	562.5	−2429.0	1	−	
185	−0.7485	−0.0014970	1500	−2.2450	562.5	−1263.0	1		
186	−0.2812	−0.0005623	1500	−0.8435	562.5	−474.4	1		
187	0.0173	0.0000347	1500	0.0520	562.5	29.3	1		
188	0.1401	0.0002801	1500	0.4202	562.5	236.4	1	+	
189	0.0688	0.0000973	1500	0.1459	795.5	116.1	1		
190	−1.4980	−0.0021180	1500	−3.1780	795.5	−2528.0	1	−	
191	−0.0250	−0.0000354	1500	−0.0531	795.5	−42.3	1		
192	−1.3790	−0.0019510	1500	−2.9260	795.5	−2328.0	1		
193	−0.0559	−0.0000791	1500	−0.1186	795.5	−94.4	1		
194	−1.0080	−0.0014260	1500	−2.1390	795.5	−1701.0	1		
195	−0.0531	−0.0000751	1500	−0.1127	795.5	−89.6	1		
196	−0.7190	−0.0010170	1500	−1.5250	795.5	−1213.0	1		
197	−0.0882	−0.0001248	1500	−0.1871	795.5	−148.9	1		
198	−0.4764	−0.0006737	1500	−1.0110	795.5	−803.9	1		
199	−0.1824	−0.0002579	1500	−0.3869	795.5	−307.8	1		
200	−0.2635	−0.0003727	1500	−0.5590	795.5	−444.7	1		

Appendix D

FOURTH AND FINAL RUN RESULTS OF NODES							
	DISPLACEMENTS		NEW CO-ORDINATES		NODAL FORCES		
Node numb.	U_x mm	U_z mm	X m	Z m	F_x kN	F_z kN	layer
1	0.0000	0.0000	−1.5000000	0.0000000	302.8	1562.9	0
2	0.0000	0.0000	−1.0000000	0.0000000	78.6	628.3	
3	0.0000	0.0000	−0.5000000	0.0000000	7.7	78.9	
4	0.0000	0.0000	0.0000000	0.0000000	134.5	−539.8	
5	0.0000	0.0000	0.5000000	0.0000000	303.6	−1298.7	
6	0.0000	0.0000	1.0000000	0.0000000	249.3	−2963.2	
7	0.0000	0.0000	1.5000000	0.0000000	1266.6	−5034.1	
8	0.3606	0.5960	−1.4996394	0.5005960	0.9	0.5	1
9	0.2897	0.3024	−0.9997103	0.5003024	0.5	0.3	
10	0.2565	0.1028	−0.4997435	0.5001028	−0.2	0.7	
11	0.2553	−0.1231	0.0002553	0.4998769	−1.2	1.6	
12	0.3149	−0.2858	0.5003149	0.4997142	−1.2	1.6	
13	0.2281	−0.3952	1.0002281	0.4996048	−0.6	6.3	
14	0.4366	−0.5891	1.5004366	0.4994109	−5.0	−0.3	
15	0.9935	1.2350	−1.4990065	1.0012350	2.2	0.7	2
16	0.9249	0.6745	−0.9990751	1.0006745	−1.4	2.5	
17	0.9192	0.2297	−0.4990808	1.0002297	−0.4	4.3	
18	0.9513	−0.2722	0.0009513	0.9997278	−2.1	4.4	
19	1.1020	−0.5864	0.5011020	0.9994136	−1.7	5.4	
20	1.0990	−0.8180	1.0010990	0.9991820	−3.0	10.1	
21	1.1330	−1.4770	1.5011330	0.9985230	−31.7	21.8	
22	2.0400	1.9000	−1.4979600	1.5019000	5.9	−1.2	3
23	1.9540	1.0600	−0.9980460	1.5010600	−1.9	3.7	
24	1.9470	0.2321	−0.4980530	1.5002321	−3.5	7.4	
25	2.1840	−0.4892	0.0021840	1.4995108	−2.2	6.1	
26	2.5410	−0.9587	0.5025410	1.4990413	−0.6	5.4	
27	2.8470	−1.3540	1.0028470	1.4986460	2.6	4.1	
28	3.6620	−2.4710	1.5036620	1.4975290	1.8	−13.5	
29	3.4900	2.6490	−1.4965100	2.0026490	10.3	−3.1	4
30	3.4350	1.4620	−0.9965650	2.0014620	−1.2	4.4	
31	3.4680	0.1558	−0.4965320	2.0001558	−8.4	10.8	

Continued

32	3.9090	−0.8231	0.0039090	1.9991769	−3.4	6.2	
33	4.3880	−1.4880	0.5043880	1.9985120	−3.3	6.0	
34	4.9910	−2.1300	1.0049910	1.9978700	0.3	3.6	
35	5.8100	−3.3850	1.5058100	1.9966150	−5.0	−5.4	
36	5.4150	3.4690	−1.4945850	2.5034690	18.9	−3.8	5
37	5.3750	1.7470	−0.9946250	2.5017470	−11.8	27.8	
38	5.6090	−0.0430	−0.4943910	2.4999570	−5.4	11.2	
39	6.0410	−1.2670	0.0060410	2.4987330	−6.5	7.3	
40	6.6910	−2.0530	0.5066910	2.4979470	−1.0	1.5	
41	7.3560	−2.8050	1.0073560	2.4971950	14.3	−3.2	
42	7.9660	−4.2680	1.5079660	2.4957320	−3.0	−4.9	
43	7.8790	4.2400	−1.4921210	3.0042400	35.9	−3.6	6
44	7.8610	1.6960	−0.9921390	3.0016960	−31.4	9.6	
45	8.2200	−0.3921	−0.4917800	2.9996079	−11.2	12.2	
46	8.6020	−1.7130	0.0086020	2.9982870	−6.3	−0.6	
47	9.0250	−2.6130	0.5090250	2.9973870	−1.8	−3.1	
48	9.4280	−3.6250	1.0094280	2.9963750	7.7	1.3	
49	9.8170	−5.1370	1.5098170	2.9948630	−12.6	−8.0	
50	11.2400	4.8340	−1.4887600	3.5048340	130.2	32.4	7
51	11.2700	1.4410	−0.9887300	3.5014410	−85.9	122.4	
52	11.2300	−0.7857	−0.4887700	3.4992143	−32.1	16.0	
53	11.1200	−2.0920	0.0111200	3.4979080	−4.1	−6.3	
54	11.0900	−3.1040	0.5110900	3.4968960	4.8	−3.3	
55	11.1500	−4.2630	1.0111500	3.4957370	3.5	3.9	
56	11.4600	−5.7110	1.5114600	3.4942890	−9.9	−5.5	
57	15.6600	5.1340	−1.4843400	4.0051340	135.6	−33.3	8
58	14.6900	1.4040	−0.9853100	4.0014040	−60.8	−156.3	
59	13.7700	−0.9570	−0.4862300	3.9990430	−16.6	−58.7	
60	12.8900	−2.4150	0.0128900	3.9975850	2.8	−19.3	
61	12.5700	−3.5290	0.5125700	3.9964710	3.7	−12.8	
62	12.6100	−4.6960	1.0126100	3.9953040	1.8	−15.3	
63	13.0200	−6.2450	1.5130200	3.9937550	−3.6	−10.4	
64	0.0000	0.0000	2.0000000	0.0000000	1729.7	−2501.9	Right base enlargement
65	0.0000	0.0000	2.5000000	0.0000000	1920.4	−1923.6	
66	0.9861	−0.1533	2.0009861	0.4998467	5.2	−0.3	

Appendix E

FOURTH AND FINAL RUN. RESULTS OF BARS. ALL BARS WITHIN STRENGTHS LIMITS									
Barnumb	$\Delta l = l\text{-}l_0$ mm	$\varepsilon = \Delta l / l_0$ -	E kN/cm²	$\sigma = E\varepsilon$ kN/cm²	A cm²	$N = \sigma A$ kN	Mater. code	Bars failed NONE	layer
1	0.5961	0.0011920	7000	8.3450	151.1	1261.0	2		1
2	0.3025	0.0006050	7000	4.2350	117.2	496.3	2		
3	0.1029	0.0002058	7000	1.4400	34.3	49.4	2		
4	−0.1231	−0.0002461	1500	−0.3692	1125.0	−415.3	1		
5	−0.2857	−0.0005715	1500	−0.8572	1125.0	−964.4	1		
6	−0.3951	−0.0007903	1500	−1.1850	1856.0	−2200.0	1		
7	−0.5889	−0.0011780	1500	−1.7670	1350.0	−2385.0	1		
8	−0.5889	−0.0011780	7000	−8.2450	220.2	−1816.0	2		
9	−0.0708	−0.0001417	1500	−0.2125	1125.0	−239.1	1		
10	−0.0332	−0.0000664	1500	−0.0996	1125.0	−112.0	1		
11	−0.0011	−0.0000021	1500	−0.0032	1125.0	−3.6	1		
12	0.0597	0.0001193	7000	0.8353	26.5	22.1	2		
13	−0.0869	−0.0001738	7000	−1.2170	53.1	−64.6	2		
14	0.2087	0.0004174	7000	2.9210	127.1	371.3	2		
15	0.4187	0.0005922	7000	4.1450	103.0	426.9	2		
16	0.1668	0.0002359	7000	1.6510	23.0	38.0	2		
17	0.2540	0.0003593	7000	2.5150	59.1	148.6	2		
18	0.0092	0.0000130	1500	0.0195	795.5	15.5	1		
19	0.0935	0.0001323	7000	0.9258	28.4	26.3	2		
20	−0.1086	−0.0001536	1500	−0.2304	795.5	−183.3	1		
21	0.0207	0.0000293	7000	0.2053	35.4	7.3	2		
22	−0.2676	−0.0003784	1500	−0.5676	795.5	−451.5	1		
23	−0.1181	−0.0001670	7000	−1.1690	18.2	−21.3	2		
24	−0.4248	−0.0006008	1500	−0.9011	795.5	−716.9	1		
25	−0.1074	−0.0001519	1500	−0.2278	1591.0	−362.5	1		
26	−0.4407	−0.0006232	1500	−0.9348	1591.0	−1487.0	1		
27	0.6398	0.0012800	7000	8.9570	120.1	1076.0	2		2
28	0.3725	0.0007449	7000	5.2150	115.6	602.8	2		
29	0.1273	0.0002546	7000	1.7820	34.6	61.7	2		
30	−0.1486	−0.0002972	1500	−0.4459	1125.0	−501.6	1		
31	−0.3000	−0.0006000	1500	−0.9000	1125.0	−1012.0	1		
32	−0.4221	−0.0008441	1500	−1.2660	1632.0	−2066.0	1		

Continued

33	−0.8871	−0.0017740	1500	−2.6610	1013.0	−2696.0	1	
34	−0.8871	−0.0017740	7000	−12.4200	160.0	−1987.0	2	
35	−0.0683	−0.0001366	1500	−0.2048	1125.0	−230.4	1	
36	−0.0055	−0.0000109	1500	−0.0164	1125.0	−18.4	1	
37	0.0323	0.0000645	1500	0.0967	1125.0	108.8	1	
38	0.1513	0.0003027	7000	2.1190	47.7	101.1	2	
39	−0.0030	−0.0000061	7000	−0.0426	81.2	−3.5	2	
40	0.0339	0.0000678	7000	0.4748	117.7	55.9	2	
41	0.4546	0.0006429	7000	4.5000	66.8	300.6	2	
42	0.1630	0.0002305	7000	1.6130	18.9	30.5	2	
43	0.3939	0.0005571	7000	3.9000	67.2	262.1	2	
44	−0.0679	−0.0000960	1500	−0.1440	795.5	−114.6	1	
45	0.2266	0.0003204	7000	2.2430	28.4	63.7	2	
46	−0.2196	−0.0003105	1500	−0.4658	795.5	−370.5	1	
47	0.2720	0.0003847	7000	2.6930	26.0	70.0	2	
48	−0.4402	−0.0006225	1500	−0.9338	795.5	−742.8	1	
49	0.1790	0.0002531	7000	1.7720	58.7	104.0	2	
50	−0.7533	−0.0010650	1500	−1.5980	795.5	−1271.0	1	
51	−0.1236	−0.0001747	1500	−0.2621	1591.0	−417.0	1	
52	−0.6304	−0.0008915	1500	−1.3370	1591.0	−2128.0	1	
53	0.6660	0.0013320	7000	9.3240	95.2	887.7	2	3
54	0.3866	0.0007732	7000	5.4120	86.2	466.5	2	
55	0.0035	0.0000069	1500	0.0104	1125.0	11.7	1	
56	−0.2155	−0.0004310	1500	−0.6465	1125.0	−727.3	1	
57	−0.3701	−0.0007403	1500	−1.1100	1125.0	−1249.0	1	
58	−0.5324	−0.0010650	1500	−1.5970	1463.0	−2337.0	1	
59	−0.9879	−0.0019760	1500	−2.9640	938.0	−2780.0	1	
60	−0.9879	−0.0019760	7000	−13.8300	174.5	−2413.0	2	
61	−0.0860	−0.0001719	1500	−0.2578	1125.0	−290.1	1	
62	−0.0065	−0.0000129	1500	−0.0194	1125.0	−21.8	1	
63	0.2378	0.0004755	7000	3.3290	30.9	102.9	2	
64	0.3577	0.0007154	7000	5.0080	57.9	289.9	2	
65	0.3060	0.0006120	7000	4.2840	82.1	351.7	2	
66	0.8164	0.0016330	7000	11.4300	105.6	1207.0	2	
67	0.5555	0.0007855	7000	5.4990	54.1	297.5	2	

Continued

68	0.0800	0.0001131	1500	0.1697	795.5	135.0	1	
69	0.4104	0.0005804	7000	4.0630	60.9	247.4	2	
70	−0.1432	−0.0002025	1500	−0.3037	795.5	−241.6	1	
71	0.3872	0.0005476	7000	3.8330	54.9	210.4	2	
72	−0.3464	−0.0004898	1500	−0.7347	795.5	−584.5	1	
73	0.6407	0.0009062	7000	6.3430	36.5	231.5	2	
74	−0.6954	−0.0009835	1500	−1.4750	795.5	−1174.0	1	
75	0.6935	0.0009808	7000	6.8650	46.0	315.8	2	
76	−1.1180	−0.0015820	1500	−2.3730	795.5	−1887.0	1	
77	0.6497	0.0009188	7000	6.4320	40.9	263.1	2	
78	−1.1240	−0.0015890	1500	−2.3840	1326.0	−3161.0	1	
79	0.7508	0.0015020	7000	10.5100	74.4	782.1	2	4
80	0.4039	0.0008079	7000	5.6550	53.3	301.4	2	
81	−0.0739	−0.0001477	1500	−0.2216	1125.0	−249.2	1	
82	−0.3308	−0.0006616	1500	−0.9924	1125.0	−1116.0	1	
83	−0.5259	−0.0010520	1500	−1.5780	1125.0	−1775.0	1	
84	−0.7721	−0.0015440	1500	−2.3160	1350.0	−3127.0	1	
85	−0.9090	−0.0018180	1500	−2.7270	938.0	−2558.0	1	
86	−0.9090	−0.0018180	7000	−12.7300	84.6	−1077.0	2	
87	−0.0536	−0.0001072	1500	−0.1608	1125.0	−180.9	1	
88	0.0356	0.0000712	1500	0.1068	1125.0	120.1	1	
89	0.4412	0.0008824	7000	6.1770	40.4	249.5	2	
90	0.4799	0.0009599	7000	6.7190	59.9	402.5	2	
91	0.6030	0.0012060	7000	8.4420	82.1	693.1	2	
92	0.8204	0.0016410	7000	11.4900	89.9	1033.0	2	
93	0.6769	0.0009573	7000	6.7010	42.2	282.8	2	
94	0.0411	0.0000581	1500	0.0871	795.5	69.3	1	
95	0.4339	0.0006136	7000	4.2950	52.5	225.5	2	
96	−0.1801	−0.0002547	1500	−0.3820	795.5	−303.9	1	
97	0.6446	0.0009116	7000	6.3810	54.4	347.1	2	
98	−0.4508	−0.0006376	1500	−0.9564	795.5	−760.8	1	
99	0.8562	0.0012110	7000	8.4760	42.2	357.7	2	
100	−0.8702	−0.0012310	1500	−1.8460	795.5	−1468.0	1	
101	0.9084	0.0012850	7000	8.9920	62.8	564.7	2	
102	−1.1840	−0.0016750	1500	−2.5120	795.5	−1998.0	1	

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103	0.6675	0.0009440	7000	6.6080	41.9	276.9	2	
104	−0.6974	−0.0009863	1500	−1.4790	1326.0	−1962.0	1	
105	0.8241	0.0016480	7000	11.5400	59.5	686.5	2	5
106	0.2891	0.0005783	7000	4.0480	29.5	119.4	2	
107	−0.1943	−0.0003885	1500	−0.5828	1125.0	−655.6	1	
108	−0.4399	−0.0008797	1500	−1.3200	1125.0	−1485.0	1	
109	−0.5597	−0.0011190	1500	−1.6790	1125.0	−1889.0	1	
110	−0.6692	−0.0013380	1500	−2.0080	1406.0	−2823.0	1	
111	−0.8785	−0.0017570	1500	−2.6350	844.0	−2224.0	1	
112	−0.0374	−0.0000747	1500	−0.1121	1125.0	−126.1	1	
113	0.2373	0.0004747	7000	3.3230	25.4	84.4	2	
114	0.4335	0.0008670	7000	6.0690	43.4	263.4	2	
115	0.6507	0.0013010	7000	9.1100	52.1	474.6	2	
116	0.6661	0.0013320	7000	9.3250	61.8	576.3	2	
117	0.6121	0.0012240	7000	8.5700	71.6	613.6	2	
118	0.6979	0.0009870	7000	6.9090	29.0	200.4	2	
119	0.0250	0.0000353	1500	0.0530	795.5	42.1	1	
120	0.4782	0.0006763	7000	4.7340	42.4	200.7	2	
121	−0.2184	−0.0003089	1500	−0.4633	795.5	−368.5	1	
122	0.8181	0.0011570	7000	8.0990	52.4	424.4	2	
123	−0.6483	−0.0009169	1500	−1.3750	795.5	−1094.0	1	
124	1.1030	0.0015600	7000	10.9200	46.1	503.5	2	
125	−1.0110	−0.0014300	1500	−2.1450	795.5	−1707.0	1	
126	1.1740	0.0016600	7000	11.6200	20.4	237.1	2	
127	−1.1460	−0.0016210	1500	−2.4320	795.5	−1935.0	1	
128	0.6018	0.0008511	7000	5.9580	19.1	113.8	2	
129	−0.6822	−0.0009648	1500	−1.4470	1193.0	−1727.0	1	
130	0.7766	0.0015530	7000	10.8700	55.0	598.0	2	6
131	−0.0451	−0.0000902	1500	−0.1353	1125.0	−152.2	1	
132	−0.3425	−0.0006849	1500	−1.0270	1125.0	−1156.0	1	
133	−0.4393	−0.0008786	1500	−1.3180	1125.0	−1483.0	1	
134	−0.5551	−0.0011100	1500	−1.6650	1125.0	−1873.0	1	
135	−0.8156	−0.0016310	1500	−2.4470	1125.0	−2753.0	1	
136	−0.8656	−0.0017310	1500	−2.5970	562.5	−1461.0	1	
137	−0.0123	−0.0000245	1500	−0.0368	1125.0	−41.3	1	

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138	0.3635	0.0007271	7000	5.0890	28.1	143.0	2	
139	0.3840	0.0007681	7000	5.3760	26.5	142.5	2	
140	0.4235	0.0008470	7000	5.9290	24.9	147.6	2	
141	0.4039	0.0008078	7000	5.6540	38.7	218.8	2	
142	0.3920	0.0007839	7000	5.4870	51.3	281.5	2	
143	0.4815	0.0006810	7000	4.7670	34.0	162.1	2	
144	0.0005	0.0000007	1500	0.0010	795.5	0.8	1	
145	0.5080	0.0007184	7000	5.0280	50.7	254.9	2	
146	−0.3572	−0.0005052	1500	−0.7578	795.5	−602.8	1	
147	0.9432	0.0013340	7000	9.3380	46.5	434.2	2	
148	−0.9186	−0.0012990	1500	−1.9490	795.5	−1550.0	1	
149	1.1650	0.0016470	7000	11.5300	24.0	276.8	2	
150	−1.1090	−0.0015690	1500	−2.3540	795.5	−1872.0	1	
151	0.8303	0.0011740	7000	8.2190	51.3	421.7	2	
152	−1.0430	−0.0014750	1500	−2.2130	795.5	−1760.0	1	
153	0.0995	0.0001407	1500	0.2110	795.5	167.9	1	
154	−0.5772	−0.0008163	1500	−1.2240	795.5	−974.1	1	
155	0.6054	0.0012110	7000	8.4760	61.3	519.6	2	7
156	−0.2430	−0.0004860	1500	−0.7290	562.5	−410.1	1	
157	−0.3843	−0.0007686	1500	−1.1530	1125.0	−1297.0	1	
158	−0.3727	−0.0007455	1500	−1.1180	1125.0	−1258.0	1	
159	−0.4866	−0.0009732	1500	−1.4600	1125.0	−1642.0	1	
160	−0.6355	−0.0012710	1500	−1.9070	1125.0	−2145.0	1	
161	−0.5712	−0.0011420	1500	−1.7130	562.5	−963.8	1	
162	0.0401	0.0000802	1500	0.1203	1969.0	237.0	1	
163	−0.0310	−0.0000621	1500	−0.0931	1406.0	−130.9	1	
164	−0.1107	−0.0002214	1500	−0.3321	1125.0	−373.6	1	
165	−0.0258	−0.0000516	1500	−0.0774	1125.0	−87.1	1	
166	0.0601	0.0001202	1500	0.1802	1125.0	202.8	1	
167	0.3154	0.0006307	7000	4.4150	33.7	148.8	2	
168	0.4306	0.0006090	7000	4.2630	25.1	107.0	2	
169	−0.1550	−0.0002192	1500	−0.3287	795.5	−261.5	1	
170	0.6413	0.0009070	7000	6.3490	31.5	200.0	2	
171	−0.8505	−0.0012030	1500	−1.8040	795.5	−1435.0	1	
172	0.8558	0.0012100	7000	8.4720	42.4	359.2	2	

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173	−1.1990	−0.0016960	1500	−2.5440	795.5	−2024.0	1	
174	0.7828	0.0011070	7000	7.7490	34.7	268.9	2	
175	−1.1100	−0.0015700	1500	−2.3550	795.5	−1874.0	1	
176	0.3422	0.0004840	7000	3.3880	17.7	60.0	2	
177	−0.8077	−0.0011420	1500	−1.7130	795.5	−1363.0	1	
178	−0.0283	−0.0000400	1500	−0.0601	795.5	−47.8	1	
179	−0.3241	−0.0004584	1500	−0.6876	795.5	−547.0	1	
180	0.3189	0.0006379	7000	4.4650	65.1	290.7	2	8
181	−0.0257	−0.0000514	1500	−0.0772	2250.0	−173.6	1	
182	−0.1650	−0.0003300	1500	−0.4950	1688.0	−835.5	1	
183	−0.3195	−0.0006389	1500	−0.9584	1125.0	−1078.0	1	
184	−0.4227	−0.0008454	1500	−1.2680	1125.0	−1427.0	1	
185	−0.4309	−0.0008617	1500	−1.2930	1406.0	−1817.0	1	
186	−0.5324	−0.0010650	1500	−1.5970	562.5	−898.4	1	
187	−0.9543	−0.0019090	1500	−2.8630	1219.0	−3490.0	1	
188	−0.9543	−0.0019090	7000	−13.3600	87.5	−1169.0	2	
189	−0.9129	−0.0018260	1500	−2.7390	938.0	−2569.0	1	
190	−0.9129	−0.0018260	7000	−12.7800	25.5	−325.9	2	
191	−0.8801	−0.0017600	1500	−2.6400	562.5	−1485.0	1	
192	−0.3149	−0.0006298	1500	−0.9448	562.5	−531.4	1	
193	0.0355	0.0000709	1500	0.1064	562.5	59.9	1	
194	0.4146	0.0008292	7000	5.8050	16.9	98.1	2	
195	0.0299	0.0000423	1500	0.0635	1723.0	109.4	1	
196	−0.4693	−0.0006636	1500	−0.9955	1723.0	−1715.0	1	
197	0.0818	0.0001157	1500	0.1735	1325.0	229.9	1	
198	−0.8846	−0.0012510	1500	−1.8770	1325.0	−2486.0	1	
199	0.0225	0.0000318	1500	0.0477	795.5	37.9	1	
200	−1.0660	−0.0015080	1500	−2.2620	795.5	−1799.0	1	
201	0.0135	0.0000191	1500	0.0287	795.5	22.8	1	
202	−0.7794	−0.0011020	1500	−1.6530	795.5	−1315.0	1	
203	−0.0525	−0.0000743	1500	−0.1114	795.5	−88.6	1	
204	−0.4834	−0.0006836	1500	−1.0250	795.5	−815.7	1	
205	−0.0765	−0.0001082	1500	−0.1623	795.5	−129.1	1	
206	−0.0879	−0.0001242	1500	−0.1864	795.5	−148.3	1	

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207	−0.1523	−0.0003046	1500	−0.4569	1688.0	−771.2	1	right base enlarge-ment
208	0.5496	0.0010990	7000	7.6950	44.2	340.1	2	
209	0.5894	0.0008335	7000	5.8340	52.9	308.6	2	
210	−0.7253	−0.0010260	1500	−1.5390	1591.0	−2448.0	1	
211	−0.8054	−0.0011390	1500	−1.7080	1591.0	−2718.0	1	
212	−1.0390	−0.0014690	1500	−2.2040	1591.0	−3507.0	1	