FEM computational models of shear walls with openings

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Abstract. This study is devoted to the comparison of shear wall computational models and the juxtaposition of displacement and stress fields. Two types of numerical models are compared. The first type concerns discretization of the geometry by using the beam finite elements model, and the second type – with plane finite elements. The displacements and the internal forces are used as the key indicators for the comparison of the mechanical behaviour. Some conclusions have been drawn, as well as recommendations have been made on the application of the juxtaposed type computational models and their practical application in real life.

1. Introduction
When designing buildings subjected to seismic actions, vertical bearing elements (earthquake washers) are widely utilized to absorb the seismic forces in the coordinate directions – more information in [6], [7], [10], [11]. Such cases determine the need to know their real mechanical behaviour in order to more adequately model them. In the studied models, it is accepted that the wall is fixed into the foundation, but in the next stage of the research, the soil – structure interaction will be taken into account more precisely-more information in [8], [9].

2. Computational models
Two types of computational models of vertical load-bearing elements are considered as objects for study:
-type I – one-storey earthquake washer, discretized by beam finite elements approach. Conditionally viewed, the computational models are denoted throughout M1-M4 accordingly, as shown in Figure 1a. The following characteristics have been adopted and confirmed for the different types of models:
-model M1 - elements s1 and s2 are modeled upon using real elastic modulus (E=3e⁷ kN/m²), without taking into account the shear stress. Element b is accepted as a non-finite rigid beam (E=3e²⁰ kN/m²);
-model M2 - elements s1 and s2 are modeled upon using real elastic modulus (E=3e⁷ kN/m²) and taking into account the shear stress. Element b is accepted as a non-finite rigid beam (E=3e²⁰ kN/m²);
-model M3 - elements s1 and s2 are modeled upon using real elastic modulus (E=3e⁷ kN/m²), without taking into account the shear stress. Element b is accepted with its real rigidity (E=3e⁷ kN/m²);
-model M4 - elements s1 and s2 are modeled upon using real elastic modulus (E=3e⁷ kN/m²) and taking into account the shear stress. Element b is accepted with its real rigidity (E=3e⁷ kN/m²);
- type II – one-storey and three-storey earthquake washer, discretized by plane-finite-elements method. Conditionally viewed, the computational models are denoted throughout M5–M17 and M18–M28 respectively, as shown in Figure 1a.

\[ F = 1000 \text{kN} \]

Cross sections

\[ E = 3 \times 10^7 \text{kN/m}^2 \]

Figure 1. Computational models

The following fixed parameters have been adopted for the selected models:
- cross sections of the elements \( s_1 \) and \( s_2 \) shown in Figure 1;
- floor elevation 3m;
- horizontal force \( F=1000 \) kN.

Boundary conditions, as follows:
- rigid connection (for firm-fixing) of the ground level;
- rigid connection of the vertical elements \( s_1 \) and \( s_2 \) with the horizontal beam (b);

The study is parametrically based on alteration in the geometric (height) and modification of the material characteristics (elastic modulus) of the horizontal beam (b).

Frame type beam finite elements of 6 degrees of freedom, as well as shell type planar finite elements with 12 degrees of freedom [4] were used to build and simulate the computational models. More
information about FEM modelling can be found in [3], [4], [5]. Based on the parameters accepted and upon a subsequent discretization, discretized models have been obtained, shown in Figure 2.

**Figure 2. Discretized models**

In generating computational models accepted were the following:
- Boundary support conditions: supporting ring on radially movable supports;
- Rigid connection of the elements with the support ring;
- Rigid connection between the elements of the ribs and the inner rings of the lattice.
  Tubular cross-sections and standard hot-rolled profiles were adopted for the structural elements.

3. Results
As main indicators for the comparison of the selected computational models of a vertical bearing element, displacements at nodes 3 and 4, as well as shear forces at nodes 1 and 2 have been used, Figure 1.

In tables 1-3 the numerical results (displacements and shear forces) are presented for the considered computational models.
### Table 1. Numerical results for models from M1 to M4

| Model | $u_{x,3}$ [e$^{-3}$m] | $u_{x,4}$ [e$^{-3}$m] | $Q_1$ [kN] | $Q_2$ [kN] | $M_1$ [kN.m] | $M_2$ [kN.m] |
|-------|-----------------------|-----------------------|------------|------------|-------------|-------------|
| M1    | 0.40                  | 0.40                  | 111.23     | 888.93     | 173.33      | 1385.33     |
| M2    | 0.90                  | 0.90                  | 181.94     | 818.13     | 274.40      | 1283.51     |
| M3    | 2.68                  | 1.22                  | 220.92     | 779.08     | 616.51      | 2225.36     |
| M4    | 3.06                  | 1.60                  | 231.62     | 768.38     | 646.60      | 2194.32     |

### Table 2. Numerical results for M5 to M17 models

| Model | $u_{x,3}$ [e$^{-3}$m] | $u_{x,4}$ [e$^{-3}$m] | $Q_1$ [kN] | $Q_2$ [kN] |
|-------|-----------------------|-----------------------|------------|------------|
| M5    | 2.20                  | 1.78                  | 169.93     | 830.09     |
| M8    | 1.65                  | 1.47                  | 203.10     | 796.92     |
| M9    | 1.25                  | 1.19                  | 239.00     | 761.02     |
| M10   | 1.00                  | 1.00                  | 264.18     | 735.84     |
| M11   | 0.80                  | 0.82                  | 281.91     | 718.11     |
| M12   | 0.70                  | 0.70                  | 296.92     | 703.10     |
| M13   | 0.58                  | 0.61                  | 312.40     | 685.62     |
| M14   | 0.52                  | 0.53                  | 329.86     | 670.16     |
| M15   | 0.47                  | 0.47                  | 349.50     | 650.52     |
| M16   | 0.43                  | 0.43                  | 370.38     | 629.64     |
| M17   | 0.41                  | 0.40                  | 390.95     | 609.07     |

### Table 3. Numerical results for M18 to M28 models

| Model | $u_{x,3}$ [e$^{-3}$m] | $u_{x,4}$ [e$^{-3}$m] | $Q_1$ [kN] | $Q_2$ [kN] |
|-------|-----------------------|-----------------------|------------|------------|
| M18   | 33.07                 | 32.82                 | 169.25     | 830.77     |
| M19   | 17.19                 | 17.19                 | 228.67     | 771.35     |
| M20   | 11.08                 | 11.08                 | 267.50     | 732.52     |
| M21   | 8.43                  | 8.43                  | 295.01     | 705.01     |
| M22   | 7.03                  | 7.03                  | 317.78     | 682.24     |
| M23   | 6.16                  | 6.16                  | 339.57     | 660.45     |
| M24   | 5.48                  | 5.57                  | 362.73     | 637.28     |
| M25   | 5.08                  | 5.14                  | 388.31     | 611.71     |
| M26   | 4.77                  | 4.81                  | 416.22     | 583.80     |
| M27   | 4.52                  | 4.55                  | 445.35     | 554.67     |
| M28   | 4.32                  | 4.33                  | 474.08     | 525.94     |

In the following figures, from Figure 3 to Figure 5, the $Q_2/Q_1$ ratio for the various types of models is correspondingly presented.
Figure 3. The $Q_2/Q_1$ ratio for M1-M4 models

Figure 4. The $Q_2/Q_1$ ratio for M5-M17 models
4. Conclusions

Upon the results presented in the previous section, the following more significant conclusions could be made:

1. A manual calculation based on the displacement method gives an approximate solution, which is known to be based on the well-known work-hypotheses of Construction Statics, Part II. Therefore, the results for the M1 model approximate the manual calculations mentioned, herein afore;

2. The axial deformability of the beam section exercises a strong influence on the distribution of forces in-between the two vertical sections. This is clearly seen via the comparison of models M1 through M4 when developing the modelling by using beam elements, as it is clearly represented by M5-M17 when modelling with KE planar elements;

3. As the height of the beam increases (leading to an increase in its axial stiffness), the displacements at nodes 3 and 4 draw nearer in value, whereas in the simulation of the boundary case of a finite rigid beam (M1) they are the same, just like the behaviour of the M12 - M17 models;

4. As for the ratio \(\frac{Q_2}{Q_1}\), there is a decreasing trend in value ranging from 8.00 to 3.32 for models from M1 to M4 (type I), and ranging from 4.88 to 1.56 for models from M5 to M17 (type II), Table 1 and Table 2.; The same is observed with regard to the bending moments at p. 1 and p. 2, table 1;

5. The higher beam corresponds to an increased value of an equivalent rotation stiffness at node 3 and p.4, which can be expected to lead to an increment in the bending moments at node 3 and p.2. / for all types of computational models /;

6. The higher beam, corresponding to the expansion of the overall geometry of the computational model, leads to a redistribution of the energy of deformation, which in turn reduces the displacements and the ratios (in) between the shear forces.

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