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Virtual and Rapid Prototyping Methods Applied in Civil Engineering. Snow, Wind and Earthquake Simulations on a Five Storey Building

The paper presents a virtual model of a building with five levels, which was subjected to virtual testing. The results are shown in the figures and diagrams.
Also, the finite element method for building simulation for the snow load was used.
Based on the 3D model of the building and the digitalized displacement diagram the kinematics and dynamics simulation of the building was made similar to the earthquake on March 4, 1977 in Vrancea, Romania, felt throughout the Balkans.
Also, the action of the wind in front of building was simulated with Flow simulations analysis module. The results were shown in the maps of pressures, speeds or temperatures.
To obtain real similar calculations, the simulations of the building for the situations were made when we have multiple loads (snow, earthquake, wind). Also, the rapid prototyping method was presented, applied on the scaled building using Prusa Mendel I3 3D printer.

Keywords: *computer graphics; virtual simulation; civil engineering; computer science.*

1. INTRODUCTION

The safety of construction ensured since the design phase is provided by Euro Codes, that are valid for most classical types of buildings. The question is whether they are valid for buildings with a special or spectacular configuration. In this paper, a building with five levels was subjected to virtual testing using primary requirement, starting from the known principles of verification and testing. The results of these tests were compared with the results obtained by classical calculations given by Euro Codes. Also, we know the importance of checking the calculations of the earthquake. The dynamics of construction, analyzed by the finite element method, a solution seems generally valid for any type of construction, even with a futuristic architectural configuration [1].

The finite element method (FEM) is a numerical technique for analyzing continuous structures, develo–ped especially for the two and three dimensions (2D and 3D), mainly engineering applications (for the study of formability, heat transfer, fluid flow, a.s.o.).

FEM is based on the idea that a continuous structure, based on geometry and some complex boundary conditions, the exact solution cannot be found, and if it can be found, the computational effort is unjustified. If we can find an approximate solution, easier to reach and with a reasonable approximation engineering degree, this becomes the solution to the original structure. In other words, the analysis of a FEM structure consists of replacing it with another solution which is easier to find. The results approximate initial structure, but are acceptable from the engineering point of view [1].

Our study tried to demonstrate and find a general computational method, using main mechanical principles and formulation, which can verify any kind of structures used in civil engineering. Euro Codes give us complicated methods available only on classical structures. For complex, futuristic, non-linear or composite structures we do not believe these Codes works very well, or the calculation become too complicate to be applied.

In this paper we want to test various FEM techniques on a classical structure and compare to the results given by Euro Codes. If the results are similar, the FEM method can be extended and used for non-conform and futuristic structures.

2. THE 3D MODEL OF THE FIVE LEVEL OFFICE BUILDING

First, the entire reinforced concrete structure of the building was modelled [2]. The steps of the that operation are common for any type of CAD software (Figure 1) [3, 4].

Using similar CAD operations the first and second floor brickwork structures were defined (Figure 2) [2, 5].

Also, the woodwork elements as doors and windows were defined (Figure 3).

It was also defined, an element that will simulate soil that is placed around the basement concrete structure. This component is shown in Figure 4 [6-8].

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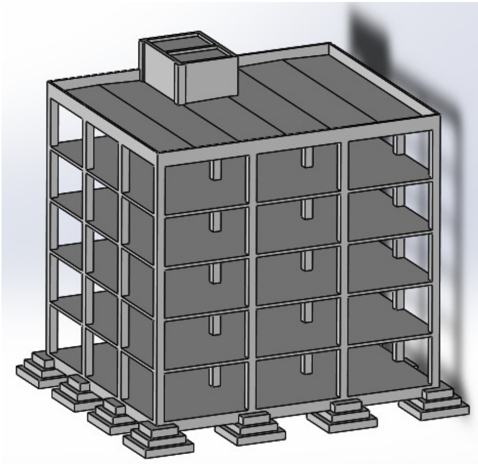

Figure 1. Virtual reinforced concrete building structure

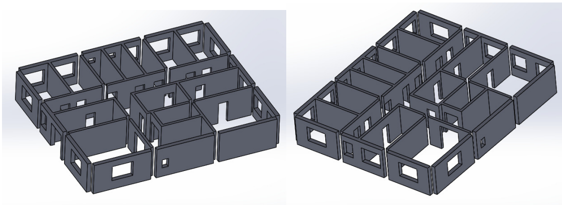

Figure 2. The building brickwork structures: first floor and second floor

Figure 3. The models of woodwork elements

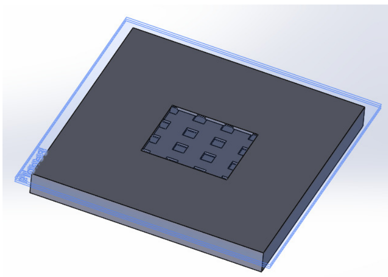

Figure 4. The model of ground (soil) element

These elements, as outlined above, were reunited in the assembly module using specific constraints [2]. Figure 5 shows the final model of the office building.

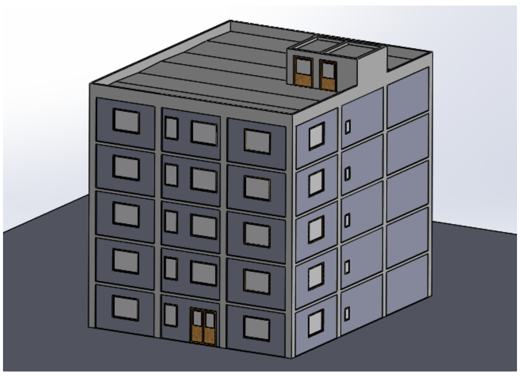

Figure 5. The final model of the building including ground element

3. DETERMINATION OF AN EQUIVALENT ELASTICITY MODULUS FOR THE ENTIRE REINFORCED CONCRETE STRUCTURE

It is known that for determining the modulus of elasticity in a mechanical element, it is subjected to experimental testing, so by measuring the elongation for different strengths, we determine specific normal stress σ and strain ε which are known components in the relationship (1).

$$\sigma = E \cdot \varepsilon \tag{1}$$

Obviously, these two components can be expressed by equation (2)

$$\sigma = \frac{F}{A_0}, \varepsilon = \frac{\Delta l}{l_0} \tag{2}$$

where Δl is the elongation (measurable)
l_0 is the original length (measurable)
F is the force (known)

Initial section A_0 is the element area under virtual test operation (measurable).

The intention is to test different virtual concrete items for different loads, underlying the idea of determining a medium modulus that can be used for the whole structure of the building. Subsequently, we plan to suppose this structure to various loads:

- static load;
- snow load;
- equivalent loads similar to earthquake from Vrancea, Romania on 4 March 1977;
- wind loads;
- different combinations of these primary loads.

3.1. Simulation of the behavior of different reinforced concrete elements at different loads

The model shown in Figure 6 is a composite column made of concrete and metallic bars, columns being placed at the distance specified in the project [1].

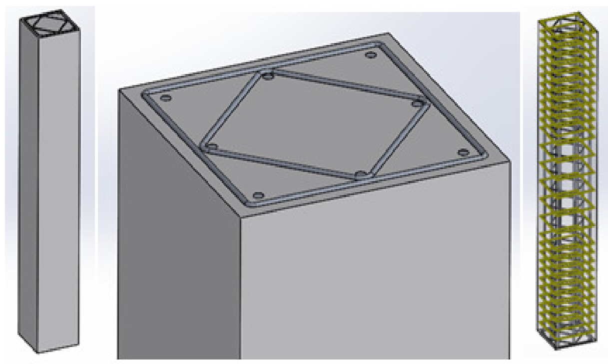

Figure 6. The model of a column made by concrete and metallic elements

This model was the subject of a simple loading scheme. Also, in Figure 7, it is presented the mesh structure of the column used to test to different forces.

This model was successively loaded with traction forces between 100000 and 900000 N. The results for the extreme loadings are shown in displacement maps in Figure 8.

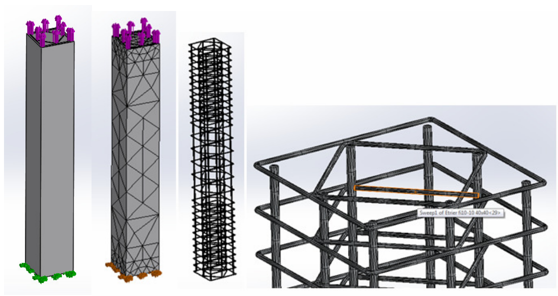

Figure 7. The loading scheme and the mesh structure of the column

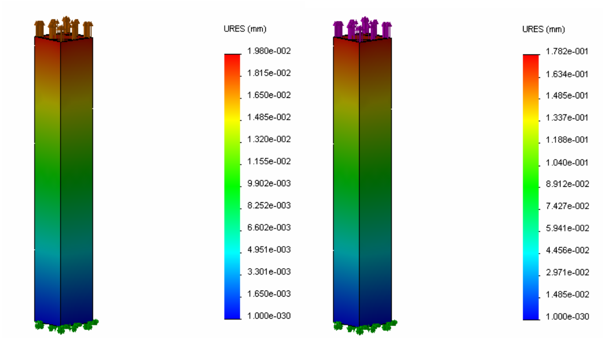

Figure 8. The displacement maps for F=100000 N and F=900000 N

Reinforced concrete elements were all tested using different loading schemes to determine the main characteristic parameters of the material as elastic modulus and Poisson's ratio [1]. For two reinforced concrete elements we obtain the diagrams presented in Fig. 9.

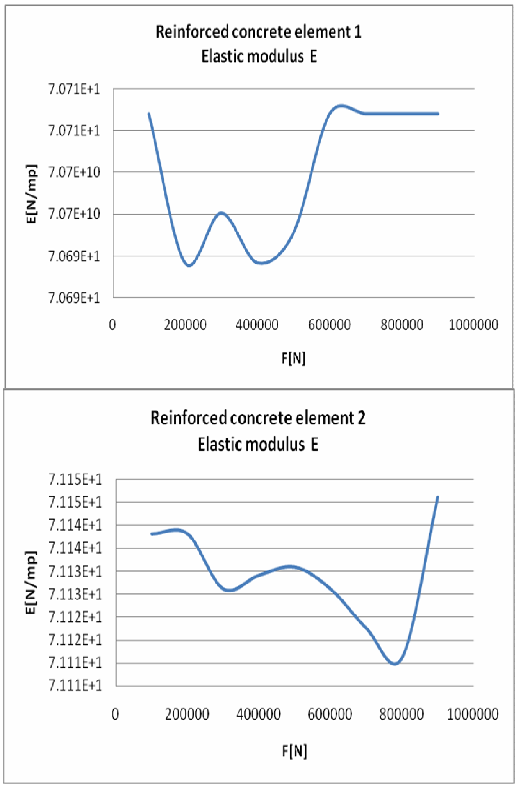

Figure 9. The elastic modulus diagrams for two reinforced concrete elements

Analyzing many elastic modulus diagrams made for different elements and loadings, we obtained an average value $E_{average} = 70913621431.34\ N/m^2 = 7.091 \cdot 10^{10}\ N/m^2$.

That value and other average parameters were used in the following simulations.

4. FEA SIMULATION MADE FOR SNOW LOADING [9]

In Romania, determining of the snow loading for the structure calculus was done using the map with the maximal values as shown in Figure 10.

To achieve the simulation the model presented in Figure 11 was used, where the pressure of snow of 2 kN/m^2 and the weights caused by the action of gravity were taken into account. Also, in that figure the load scheme and the finite elements structure was presented.

The results are composed by three types of maps: stress, strain and displacement maps. In Figure 12 the map results obtained after the snow loading simulation (only stress and displacement maps) are presented. The model is shown in the deformed shape, magnified by 1392 times.

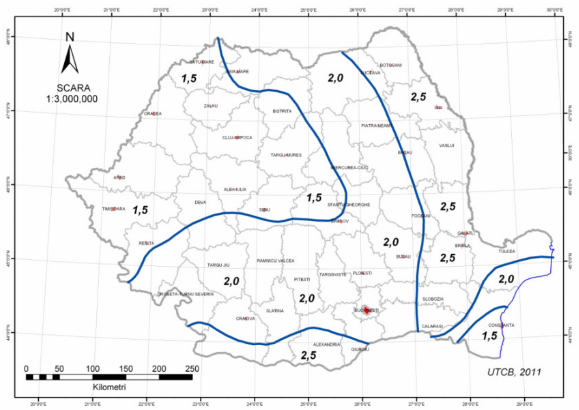

Figure 10. The geographic snow loading area in kN/m^2 for Romania [13]

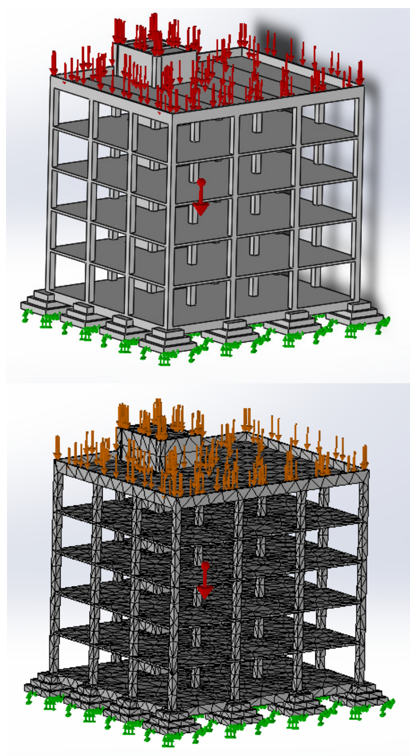

Figure 11. The model supposed to the loading scheme and the finite elements structure

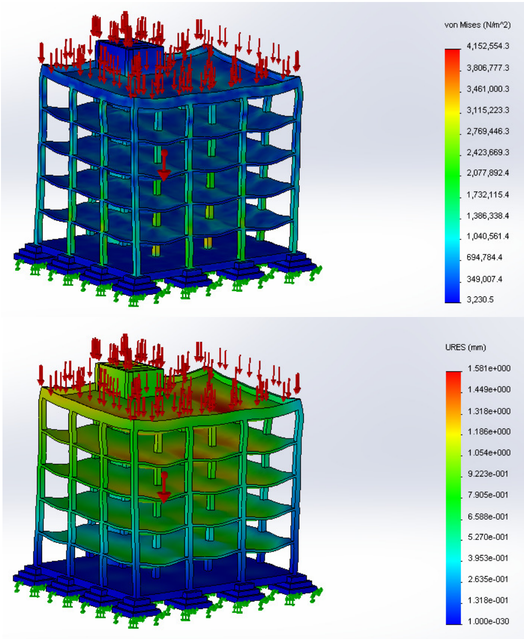

Figure 12. The stress and displacement maps obtained after the snow loading simulation

5. KINEMATIC SIMULATION OF THE BUILDING SUB–JECTED TO A VIRTUAL EARTHQUAKE SIMILAR TO VRANCEA, ROMANIA, MARCH 4th 1977

Romanian 1977 earthquake was an earthquake that occurred at 21:22:22 on 4 March 1977 with devastating effects. It had a magnitude of 7.2 on the Richter scale and duration of about 56 seconds (55 according to other sources) 1,570 victims, of which 1,391 only in Bucharest. At the country level there were 11,300 injured and 35,000 homes collapsed. Most of the damages were concentrated in Bucharest where over 33 buildings and big blocks collapsed [10, 11].

The earthquake also affected Bulgaria. In the town of Svishtov, three apartment buildings were destroyed and over 100 people died. The earthquake's epicenter was lo–cated in Vrancea, the most active seismic area in the cou–ntry, at a depth of about 100 km from the earth sur–face. The shock wave was felt in most of the Balkans [11, 12].

Based on the records made by INCERC Laboratory we obtained a digitalization of the March 4, 1977 earthquake in Excel format, and based on the data obtained, a chart in Figure 13 was made.

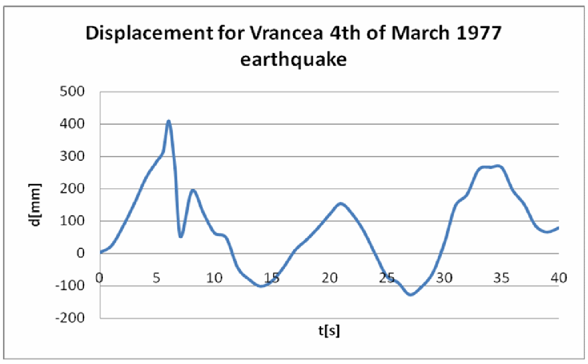

Figure 13. The digitalized diagram of displacement for the analyzed earthquake

To obtain the system analysis, during the earthquake, two main elements were considered: reinforced concrete structure of the building and the soil with dimensions of 50x50x5 m. These two elements were connected virtually through a linear motor, whose action was on the values from digitalization of the earthquake [10].

The action of the virtual motor that acts between the ground and the building is given by the displacement and acceleration shown in Figure 14 and are similar to Vrancea earthquake of March 4, 1977 [13-16].

After running the application, the determined ground reaction force during the 40 seconds of the virtual earthquake is shown in Figure 15.

Also, was obtained the building structure behaviour, based on FEM maps, for the north direction of the virtual earthquake (Figure 16). Using other directions, the results are almost similar.

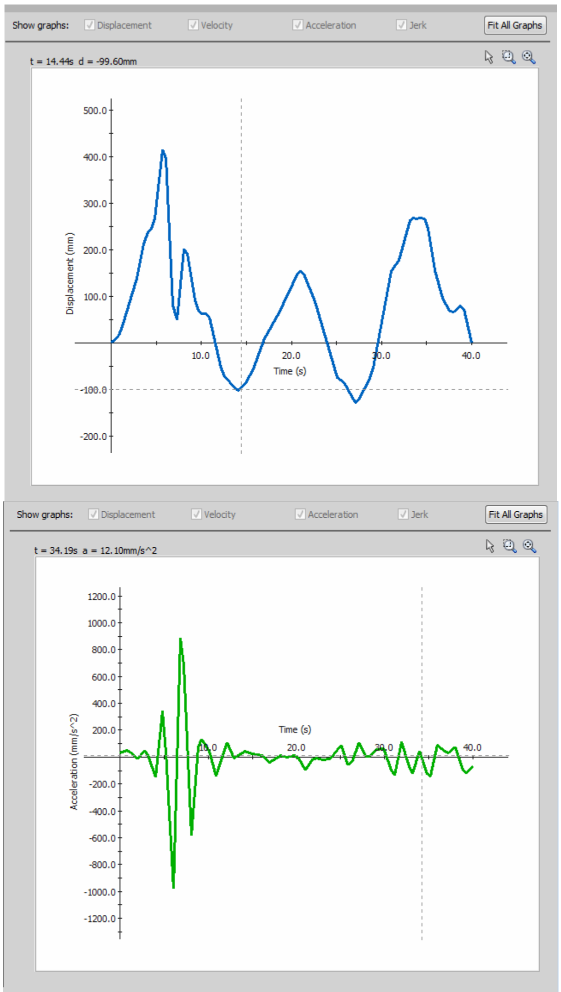

Figure 14. The kinematic parameters of the soil (displace–ment - blue and acceleration - green)

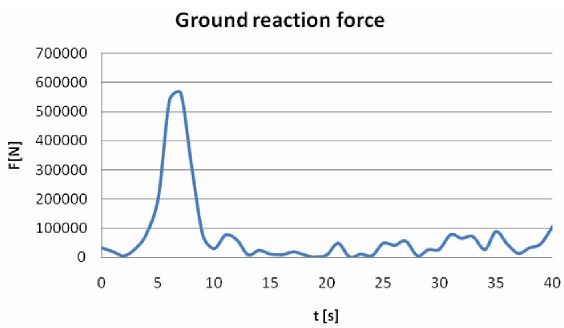

Figure 15. The ground reaction force during the virtual earthquake

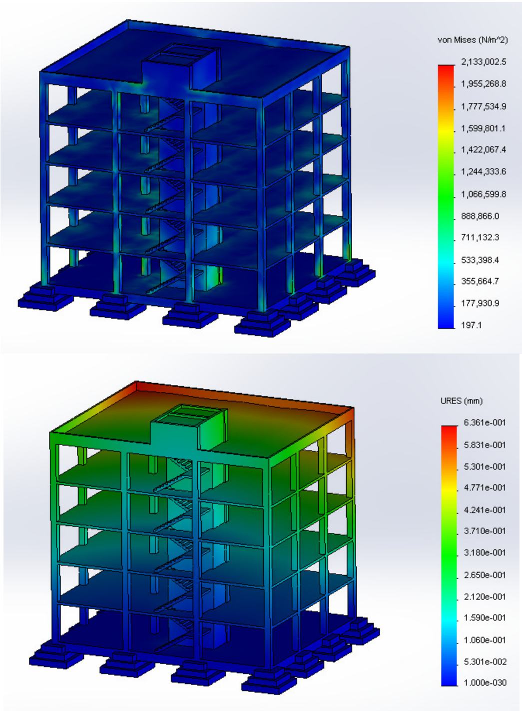

Figure 16. The FEM results for the earthquake simulation for the north direction (stress and displacement maps)

6. SIMULATION OF WIND ACTION OVER THE FIVE LEVEL BUILDING

To determine the effect of wind on a five level building, Flow Simulation Analysis module was used. It studied the effect obtained for air movements with a velocity of 150 km/h perpendicular to the south facade of the building [17].

We have obtained the results materialized in maps pressures, velocities, temperatures a.s.o. Ambient temperature was considered 20^{o} C. These results maps were presented in Figures 17-20.

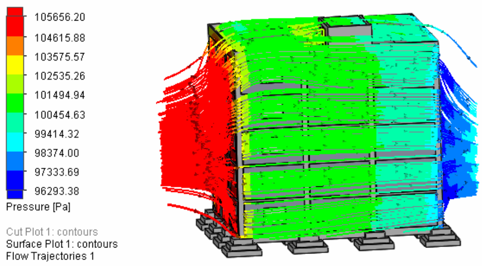

Figure 17. The pressure map

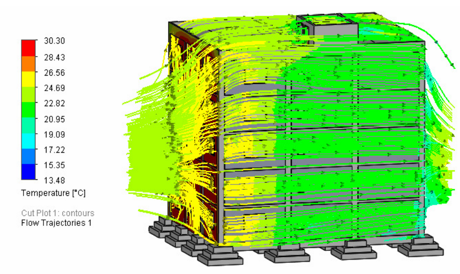

Figure 18. The temperature map

Also, wind simulations were developed with the air velocity of 150 km/h from other directions and similar map results were obtained.

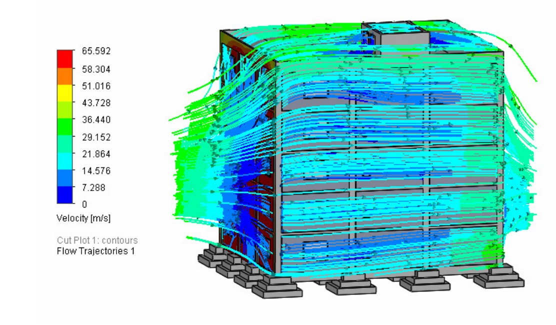

Figure 19. The velocity of air mass [m/s]

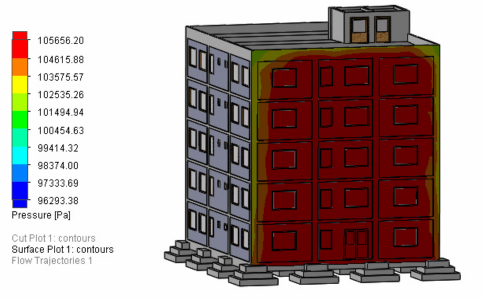

Figure 20. Normal pressure [Pa]

7. COMBINED LOADING SIMULATION (SNOW , EARTHQUAKE AND WIND) USING DIFFERENT ACTION DIRECTION

7.1. First combined loading simulation

The analysis of the situation that combined load consists of the following :

- Type Vrancea action earthquake from west direc–tion;
- Wind with the velocity of 150 km/h from west direction ;
- Snow pressure load of 2 kN / m^2.

Figure 21 presents the map results obtained after the first combined loading simulation.

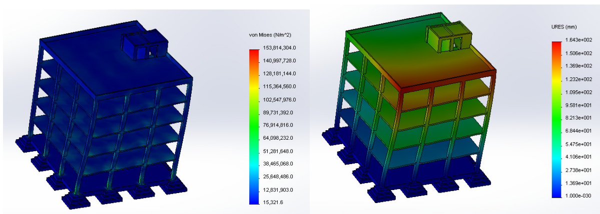

Figure 21. The FEM results for the first combined loading simulation (stress and displacement maps)

7.2. Second combined loading simulation

The analysis of the situation that combined load consists of the following:

- Type Vrancea action earthquake from west direction ;
- Wind with velocity of 150km / h from east direction ;
- Snow load pressure of 2 kN/m^2.

Figure 22 presents the map results obtained after the second combined loading simulation.

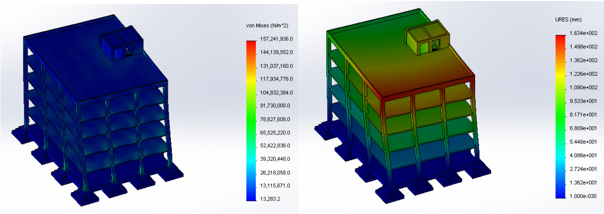

Figure 22. The FEM results for the second combined loading simulation (stress and displacement maps)

8. THE RAPID PROTYPING OF A SCALE MODEL FOR THE STUDIED BUILDING [18-21]

In the past decade, a new concept of manufacturing called "Rapid Prototyping" physical coating or without solid preform manufacturing became popular in the world. The operations included in Rapid Prototyping (RP) became relatively popular about twelve years ago with the advance of stereo lithography technology. Stereo lithography has a significant impact, in particular, on designing new products. The process started from a 3D CAD model involving ultraviolet sources, photosensitive polymers, melted plastic, metallic fine powders or laser systems [18-21].

The basic technique of this new method of rapid prototyping consists of a 3D model divided in thin layers, followed by physical realization of layers and their arrangement "layer upon layer". The materialization of 3D objects using stratified techniques is an idea as old as science and technology (the pyramids of Egypt were built block over block and layer over layer).

Using this printer we obtained fragments of levels building at the scale 1: 100 represented in the figures below. These elements were assembled with special glue, were completed using an air drying polymer clay and acrylic paint was used. Figure 23 presents different images with the scaled printed building.

Figure 23. The 3D printed scaled building (different views)

We obtained the printed model to test our 3D printing device for scale building model. Also, this device is available to produce plastic shapes for complicated or futuristic scaled models. During the printing operations the problems were identified and new methods were determined for complicated shape 3D printing used for any kind of building.

9. DISCUSSIONS

The five_level building was analyzed using both methods: with calculation given by the Euro Codes and using FEM techniques. The results were similar because a classical type of structure was used. For the earthquake calculation, the Euro Codes give only general verification calculus based on a supplementary average soil acceleration given by a map of values. For example, in our region, the Euro Codes give the calculation value for soil acceleration a=0.16 g. As we presented in Figure 14 the maximum acceleration (green map) is $a \approx 1000$ mm/s^2 or $a \approx 0.1$ g and it is reached after 6 seconds after the initiation of the virtual earthquake. The Euro Codes give only a supplementary calculation static load to be used in different cases, but FEM techniques give dynamic loads and parameters calculated in every moment of the virtual earthquake. Also, virtual simulation gives all the parameters in any location of the building during the earthquake. Very easily, the building can receive virtual verification for every kind of earthquake.

The Euro Codes calculation for wind gives only a supplementary load, but the FEM wind analysis can give a lot of parameters as pressure, temperature, velocity of the wind in any location on the virtual building. In addition, all the initial parameters can be changed and can be adapted to any values, very easily.

All these advantages recommend the FEM techniques to be used for all building structures, classical or futuristic.

10. CONCLUSIONS

Analyzing the two combined loading situations the following conclusions can be drawn:

- In both analyzed combined loading situations, displacements are very high, reaching 164.3 mm when wind acts in the direction of the earthquake from the west and to the value of 163.4 mm when the earthquake and wind have different directions ;
- Values of stress reach in the first case 153.8 MPa and 157.2 MPa in the second case ;
- Strain values are low, between $2.53 \cdot 10^{-3}$ and $2.47 \cdot 10^{-3}$ for the two analyzed situations;
- It is found that both conditions are unfavorable causing large displacements.

The method presented in this paper is a viable tool for the analysis of complex situations encountered in practice. This method can replace or complete the Euro Codes design calculation, which encounter difficulties to use in complicated or futuristic structures, increasingly used in practice.

Also, a scaled model was 3D printed and methods for complex shapes were determined.

REFERENCES

[1] Faur, N.: Finite elements. Fundamentals, in Romanian.

[2] http://www.solidworks.com/sw/resources/solidworks-tutorials.htm, [Accessed: June 2015].

[3] Agent, R. and Dumitrescu, D.: Guide for the calculation and composition of reinforced concrete structural elements, in Romanian, Ed. Tehnica, Bucharest, 1992.

[4] Design Code for foundation design in building structures, in Romanian, June 2005.

[5] Design code for masonry structures CR 6-2013, in Romanian, 2013.

[6] Standard for the design of direct foundation structures NP112-04, in Romanian.

[7] Standard on improving weak foundation grounds, mechanically; indicative C29-85, in Romanian.

[8] Bolt, B.A.: *Earthquakes*, W.H. Freeman and Company, New York, 1988.

[9] Design Code for evaluating action of snow on buildings, in Romanian, 2012.

[10] Scawthorn, C., O'Rourke, T. and Blackburn, F.: *The 1906 San Francisco earthquake and fire — Enduring lessons for fire protection and water supply*, Earthquake Spectra 22, S135–S158. Scawthorn, C., Yamada, Y. and Iemura, H., 1981. A model for urban post-earthquake fire hazard. Disasters 5, pp. 125–132, 2006.

[11] Mihai, M. X.: Evaluation of seismic territory of Craiova and the behavior of certain categories of buildings during strong earthquake on March 4th, 1977, in Romanian, PhD Thesis, 2014.

[12] P100-2013 seismic design code, in Romanian.

[13] Scawthorn, C., Eidinger, J. and Schiff, A.: *Fire Following Earthquake*, Technical Council on Lifeline Earthquake Engineering Monograph No 26, American Society of Civil Engineers, 2005.

[14] Scawthorn, C. and Khater, M.: Fire Following Earthquake: Conflagration Potential in the Greater Los Angeles, San Francisco, Seattle and Memphis Areas, EQE International, prepared for the National Disaster Coalition, San Francisco, 1992.

[15] Wenzel, F., Lungu, D., Novak, O.: *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitiga–tion.* Selected papers of the First International Workshop on Vrancea Earthquakes, Bucharest, November 1 – 4, 1997. Kluwer Academic Publishing, Dordrecht, Netherlands, pp. 374, 1998.

[16] Wenzel, F., Lungu, D.: *Earthquake risk mitigation in Romania*. Proceedings Volume, 2nd EuroConference on Global Change and Catastrophe Risk Management, Luxembourg, 2000.

[17] Design Code. Basics of designing and actions on construction. Wind action, in Romanian, 2012.

[18] Matthew B. Wall, Karl T. Ulrich and W.C. Flowers: *Evaluating prototyping technologies for product design*, Research in Engineering Design, Volume 3, Issue 3, pp 163-177, 1992.

[19] Wohlers, T.: Rapid prototyping state of the industry: 1997 worldwide progress report, RPA of SME, Dearborn, Michigan, 1997.

[20] http://masuratori3d.blogspot.ro/2010/05/prototipare-rapida-piese-injectate.html, [Accessed: May 2015].

[21] http://www.robofun.ro, [Accessed: May 2015].

ПОСТУПЦИ ВИРТУЕЛНОГ МОДЕЛИРАЊА И БРЗЕ ИЗРАДЕ ПРОТОТИПОВА У ГРАЂЕВИНАРСТВУ. СИМУЛАЦИЈЕ ДЕЈСТВА СНЕГА, ВЕТРА И ЗЕМЉОТРЕСА НА ПЕТОСПРАТНУ ЗГРАДУ

А. Попа, А. Могосану, Д. Попа, А. Дута, А. Теодореску

Рад приказује виртуелни модел зграде на пет нивоа на којој је извршено експериментално виртуелно испитивање. Резултати су приказани на сликама и дијаграмима. Такође је коришћен метод коначних елемената за симулацију оптерећења зграде снегом. На основу 3Д модела зграде и дигитализованог дијаграма померања вршена је кинематичка и динамичка симулација зграде, слична земљотресу који се догодио 4. марта 1977. у Вранцеи у Румунији и који се осетио на целом Балкану. Такође је вршена симулација дејства ветра на предњу страну зграде коришћењем модула за анализу тока симулације.

Резултати су приказани на мапама притиска, брзине и температуре. У циљу добијања сличних прорачуна изведене су симулације на згради за случајеве вишеструког оптерећења (снег, земљотрес, ветар). Приказан је поступак брзе израде прототипова на моделу зграде коришћењем штампача Prusa mendel 13 3D.