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ANALYSIS OF THE FOUNDATIONS OF A FIVE-STOREY BUILDING ON EXTRUDED POLYSTYRENE

ANALIZA POSADOWIENIA PIĘCIOKONDYGNACYJNEGO BUDYNKU NA EKSTRUDOWANYM POLISTYRENIE

Abstract

This study presents the example of using extruded polystyrene for thermal insulation under the foundation slab of a building. Under the foundation slab of the thickness of 500 mm of a five-storey reinforced concrete building there was applied a layer of XPS of the thickness of 150 mm. The authors monitored the deformation of insulation under the load of the building from the moment of concreting the foundation slab until the completion of its development. Additionally, there were conducted laboratory tests of the σ–ε dependence and of material creeping. On the basis of the results of material properties, for the purpose of conducting the analysis of XPS deformations and effort, there was constructed a numerical model in the FEM system. This work includes the results of the conducted measurements and analyses with proper comments. They became the basis for drawing the conclusions which will be of use for future work.

Keywords: *extruded polystyrene*, *XPS*, *thermal isolation*, *concrete building*

Streszczenie

W pracy przedstawiono przykład zastosowania ekstrudowanego polistyrenu jako izolacji termicznej pod fundamentem budynku. Pod płytą fundamentową grubości 500 mm pięciokondygnacyjnego budynku żelbetowego zastosowano warstwę XPS o grubości 150 mm. Autorzy przeprowadzili monitoring odkształcenia warstwy izolacji pod obciążeniem budynkiem od momentu zabetonowania płyty fundamentowej aż do ukończenia jego realizacji. Dodatkowo przeprowadzono badania laboratoryjne zależności σ–ε oraz pełzania materiału. W oparciu o otrzymane rezultaty właściwości materiałowych w celu wykonania obliczeniowej analizy deformacji i wytężenia warstwy XPS zbudowano model numeryczny w systemie MES. W niniejszej pracy zamieszczono wyniki przeprowadzonych pomiarów i analiz ze stosownymi komentarzami, które mogą być przydatne w przyszłych realizacjach.

Słowa kluczowe: *polistyren ekstrudowany*, *XPS*, *izolacja termiczna*, *budynek żelbetowy*

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1. Introduction

Horizontal thermal insulation has been generally used for the floors of the lowest levels of reinforced concrete buildings. It is traditional in the construction industry to place the structure of the building directly on load bearing soil. Then only the space between the highly loaded foundation elements (foundation bases, strip foundations) is thermally insulated from the soil with hard EPS. In modern construction also the foundation elements are insulated from the soil. Then slabs of extruded polystyrene are placed under the non-highly loaded strip foundations and foundation bases of low buildings, sports halls and others. Such a solution improves the heating properties of the building and has a positive effect on its energy balance. Thermal insulation under the foundations is especially significant in passive buildings. The foundation base then accumulates heat and gives it back only to the rooms, not to the soil. Currently the produced insulation material, i.e. XPS (extruded polystyrene) with high resistance to compression and low deformability, allows to develop more effective thermal insulation of a building from the soil than in the past.

For the first time the authors of this work used XPS as thermal insulation under the foundation slab of a five-storey reinforced concrete skeleton building. The XPS producers declare that its compression resistance to be the stress under specific deformation. That resistance is specified as per PN-EN 826 [1] on cubical samples of the side length of 50 mm. However, it is obvious that the size of the sample has effect on the mechanical properties of materials. Therefore, XPS may behave totally differently under a foundation slab than in a small sample. For that reason, there was conducted the monitoring of deformations of the XPS layer under the foundation slab of a designed and constructed building. The measurements were started after concreting the foundation slab and finished after the end of construction (after completing the internal and external finishing layers). Additionally, laboratory tests on XPS were conducted for the purpose of determining the stress-strain dependence under full admissible stress, and short stability of deformations at continuous stress.

2. XPS characteristics

XPS (extruded polystyrene) is a modern material for thermal insulations, formed in the shape of slabs in the process of extrusion and foaming of polystyrene resins. It is a fine-grain foam of low density. The endurance classes of 30, 50 and 70 refer to the guaranteed compressive stresses of 300, 500 and 700 kPa, respectively, under the imposed strain of 10%. The compressive strength at 10% strain is defined by the norm [1]. The suppliers of XPS additionally define the compressive stresses upon the strain of 2 and 5% and the elasticity modulus. The technical specifications also provide information on the creep specified as per PN-EN 1605 [2].

XPS is recommended by producers for insulation of external walls, horizontal insulation of floors, insulation of industrial flooring and parking lots, as insulation of strip foundations and others.

3. Structural description of the building and its insulation

The building of the Energy-Saving Construction Laboratory was developed from August 2013 to May 2014. The five-storey building was constructed of flat reinforced-concrete slabs of the thickness of 0.25 m, supported on columns. The slabs are based on 3 internal columns of the intersection dimensions of 0.35 × 0.35 m, on external columns and 3 stiffening walls (Fig. 1). Along the two external borders of the building, there were applied external columns of the intersection dimensions of 0.2 5× 0.25 m, with the filling of cellular concrete between them. Such walls were covered with the external layer of clinker bricks of the thickness of 0.12 m, based on brackets (Fig. 2a)). Along the two remaining external borders, there were applied the columns of the intersection dimensions of 0.30 × 0.30 m with glass facade.

The building was constructed on a foundation slab of the thickness of 0.50 m. The slab was thickened to 0.60 m in the areas of internal columns (Fig. 1b)). The layer of weak soil under the slab of the thickness of 1.0 m was replaced with load-bearing sand and gravel soil. Moreover, in the layer of the replaced soil there was additionally installed a horizontal heat exchanger. On the replaced substrate there was placed a layer of leca concrete of the thickness of 0.30 m. On the leca concrete, directly under the foundation slab, there was placed the thermal insulation layer of the thickness of 150 mm made of Polish slabs Synthos XPS Prime 70 (Fig. 1b)). The XPS slabs of the highest strength are produced at the thickness of up to 100 mm. For that reason, the layer of the thickness of 150 mm was produced by combining the slabs of the thickness of 50 and 100 mm (Fig. 2b)).

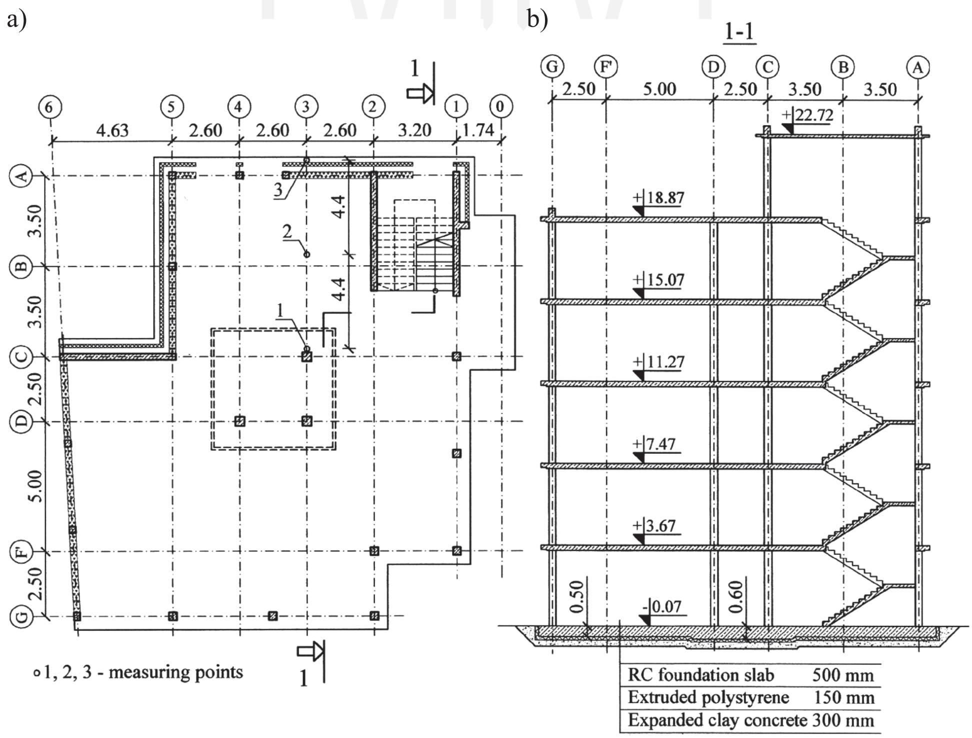


Fig. 1. a) Structural plan of the first floor, b) 1-1 vertical cross-section

a) b)

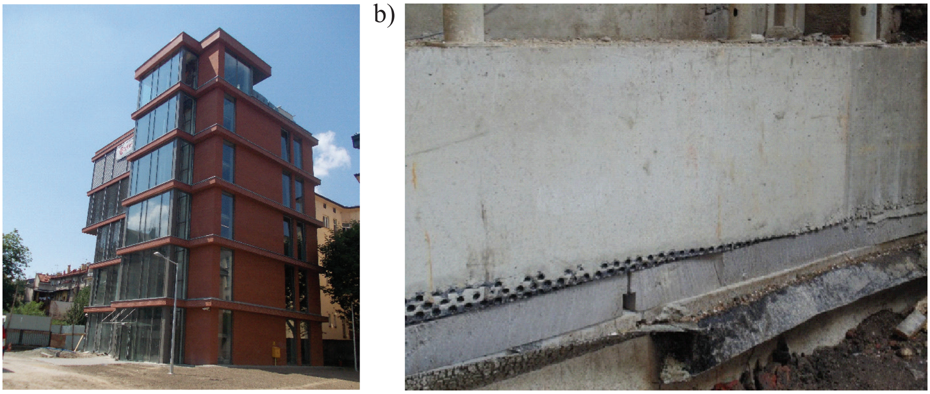


Fig. 2. a) The view of completed building, b) the view of XPS layer under the foundation slab

4. Tests program

The application of XPS under the foundation slab of such a tall building was a prototype solution in the authors' designing activities. For that reason, the decision was made to monitor the insulation material deformations under the load of the building. The purpose was to become familiar with the behavior of XPS at such a high load. Additionally, there were performed the laboratory tests on two samples of extruded polystyrene. The first one was used for determining the σ–ε dependence necessary for calibrating the FEM numerical model of the material. The second was used for determining the level of creep over a short period of time after application of load.

The tests were supplemented with the numerical analysis of the foundation slab together with substrate layers. All the tests were aimed at determining the limit of using XPS under the foundation elements in the buildings constructed in the future.

4.1. In-situ tests

Three measurements points were designated for the purpose of monitoring the insulation deformations (marked as 1, 2 and 3 in Figure 1a)). In those points there were installed ϕ10 mm threaded rods anchored in the substrate leca concrete (Fig. 3a)). The rods were insulated from the foundation slab concrete with a PVC pipe. The deformation of the XPS layer under the load of the building (that layer was situated between the leca concrete and the foundation slab) resulted in the rods moving out from under the foundation slab. That movement was registered with the mechanical sensors installed on the upper surface of the slab (Fig. 3b)). The measurement sensors were lined with steel boxes during the construction process, to protect them against damage. The only holes left were to allow the readouts. The first (zero) readout was performed right after concreting the foundation slab. The subsequent readouts were made no more often than every several days.

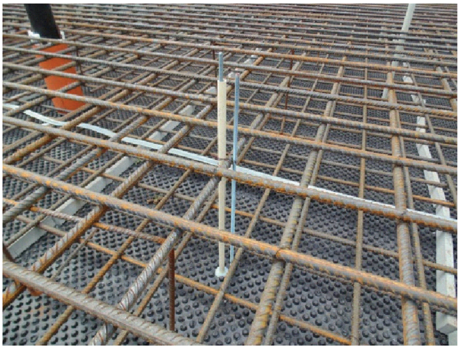
a)  b) 

Fig. 3. a) The view of reference rood anchored into expanded clay concrete layer and b) mechanical gauge installed at the foundation slab surface

4.2. Laboratory tests

Two identical XPS samples were subject to tests in a laboratory. Those tests were aimed at improving the modeling of XPS behavior under the foundation slab. For that purpose, there were prepared 2 samples of the dimensions of 0.5 × 0.5 × 0.15 m. In order to limit the horizontal deformation of samples, they were placed in a special steel ring (Figs. 4 and 5). The clearance between XPS and the ring, of the thickness of 7–8 mm, was filled with cement mortar. In order to facilitate the vertical sliding of the material in the steel frame caused by its vertical deformation between the mortar and the XPS sample, there were applied 2 layers of PE foil. The details of the prepared sample were presented in Fig. 4, while its view – in Fig. 5. The steel slab generating the load was 500 × 500 mm in size. It was 4–6 mm smaller than the XPS sample.

The first sample was used to test the σ–ε dependence. The load was applied with continuous increase in the XPS thickness loss of 0.5 mm per minute, until gaining the highest load capacity of the material.

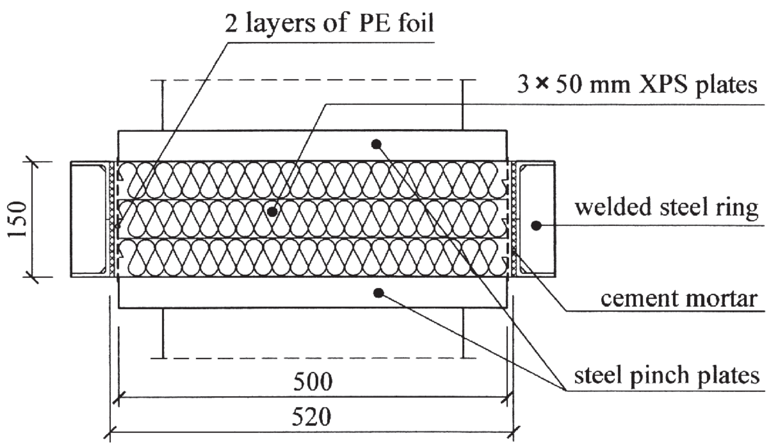


Fig. 4. The samples of Synthos XPS 70 prime inside the steel ring

The second sample was used for testing the stability of deformation (creep) at stable loads (increased gradually). The first load was 200 kPa. During the test, the stress was increased in 100 kPa increments. Each value of the stress was maintained until the moment when the deformations stabilized (stabilization of deformations was assumed to be the loss in thickness over time smaller than 0.01 mm over 5 minutes).

Fig. 5. The view of sample prepared to test

4.3. Numerical analysis

There was constructed a numerical model of the foundation slab together with a polystyrene layer in the FEM system. The ABAQUS software was used for that purpose. The numerical model was constructed based on three-dimensional finite elements. The analysis assumed elastic substrate and friction between the slab and XPS.

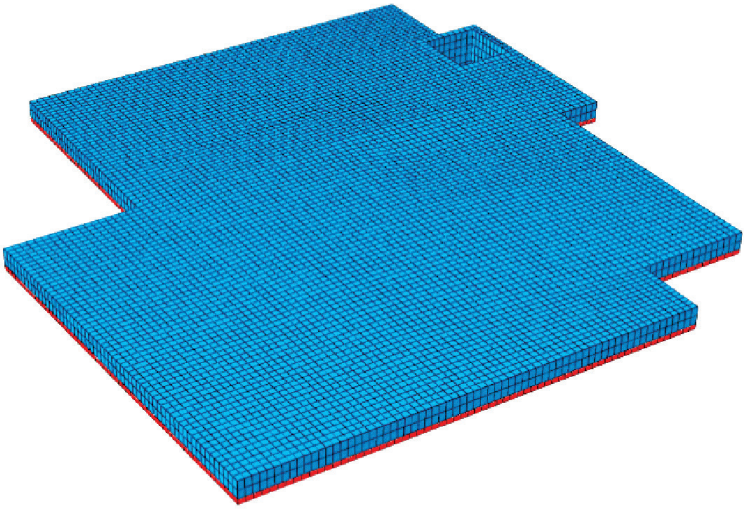


Fig. 6. FEM model of foundation slab and insulation layer

A contact layer was applied in order to provide the physical conditions of contact between the two materials. That meant absence of zero or negative values of substitute forces in contact surface nodes. It is necessary to provide the condition of contact and the geometrical compliance of the adjacent elements (the shape function must be continuous on the contact of those elements). For that reason, the C3D8R finite elements were used for all the parts of the model. These are 8-node elements with linear shape function and reduced contact points. Those elements are available in the ABAQUS/Standard library. The friction coefficient was assumed as $\mu = 0{,}3$. The constructed FEM model was presented in Fig. 6.

The numerical analysis was conducted in 6 steps. Each step was consistent with the suitable stage of the construction of the building. The load was applied in the form of concentrated forces from columns and linear load from the walls. There was assumed the elastic work of the foundation slab with the parameters $E = 32$ GPa and $\nu = 0.3$ consistent with the concrete of class C25/30. XPS was modeled as an elasto-plastic material. The elasto-plastic model in the ABAQUS program required the separation of the elastic and inelastic elements [3]. In the most general form, that compound may be presented as:

$$F = F^{el} \cdot F^{pl} \tag{1}$$

where F is the total deformation gradient, F^{el} is a fully reversible part of deformation in the considered point, and F^{pl} is defined as:

$$F^{pl} = \left[F^{el}\right]^{-1} \cdot F \tag{2}$$

The above division of elements may be directly used in formulating the plastic model. The XPS material model, constructed based on von Mises yield surface, was used for conducting a numerical analysis. The properties of the XPS material were assumed based on the σ–ε dependence received from laboratory tests (Fig. 8). To define the material properties it is necessary to know the Cauchy stresses and the logarithmic deformations. In this case of results of laboratory tests, there were known the dependence between nominal stress and strain. For the purpose of obtaining the actual stresses and logarithmic deformations, there was a simple conversion:

$$\sigma_{true} = \sigma_{nom}\left(1 + \varepsilon_{nom}\right) \tag{3}$$

$$\varepsilon_{\ln}^{pl} = \ln\left(1 + \varepsilon_{nom}\right) - \frac{\sigma_{true}}{E} \tag{4}$$

5. Tests results

Figure 7 presents the results of reducing the thickness of thermal insulation under the foundation slab registered in 3 measurement points marked in Fig. 1a). Two characteristic points were marked on the time axis. These are the time of completing the construction of the reinforced concrete structure (16 November 2013) and the time of completion of the finishing layers, such as the cement leveling, filling walls, glass and clinker lining (5 March 2014) which time was crucial for the load for the foundation slab. What may be observed that the change in insulation thickness is different in different points. The closer we are to the external edge, the higher the value is.

Figure 8 presents the σ–ε dependence obtained in the laboratory tests. A non-linear dependence may be observed in the whole scope of loads. The highest compressive stresses amounted to 664 kPa and were recorded at the strain equal to 4.57%. They were maintained until the deformations reached the level of 5.2%, after which they began to fall.

The stresses were maintained until the strain reached the level of 10%, but the high speed of creep did not allow to record the stresses with required precision.

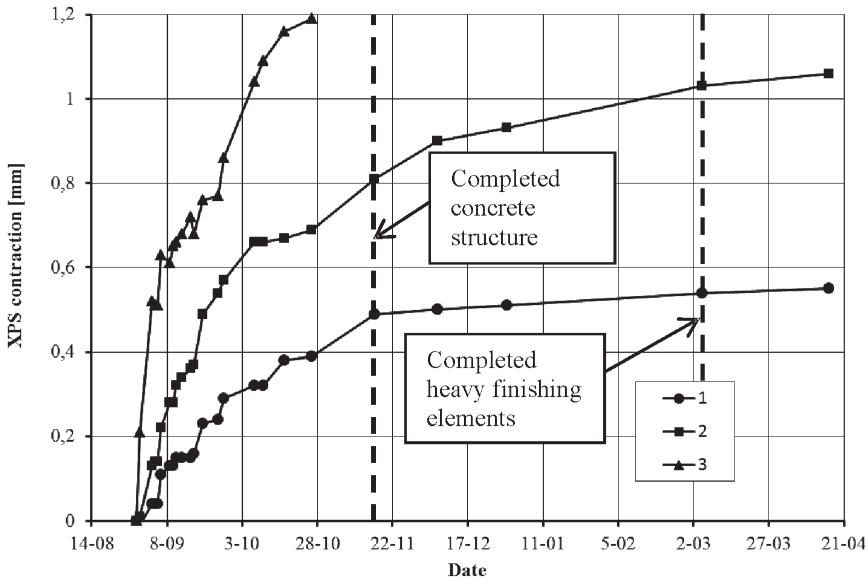


Fig. 7. Results of XPS layer thickness reduction in 3 measurements points marked in Fig. 1a)

The curve in Fig. 8 presents the high value of the secant elastic modulus. It amounted to 62.5 MPa at the stresses equal to 200 kPa; 48.5 MPa at 300 kPa and 40.1 MPa at 400 kPa. It should be noted that the average value of the elastic modulus amounts to 25 MPa in the declaration of the producer of XPS.

Figure 9 presents the results of the laboratory tests of short-term XPS creep. The upper diagram shows the load program, while the lower diagram – the change in strain over time. The horizontal markers on the strain curve signify the end of increasing the stresses in the respective steps (beginning of creep). The assumed criterion for stabilization of deformations over time was described in point 4.2. At the stresses equal to 200 kPa, the deformation stabilization over time lasted about 1 hour. Over that time the deformations increased by 4.4%. The same values amounted respectively to 1 hour and 9.1% at the stresses of 300 kPa and 2.6 hours and 28.7% at 400 kPa. The stresses of the value of 500 kPa were maintained for over 4 hours. The deformations over that time increased from the value of 0.0234 to 0.0364. Therefore, the increase was 37.9%, but it was far from stabilizing the deformations. What should be emphasized is that the deformations were approaching the value of 4.57% fast. It is the value at which the highest load-bearing capacity of XPS was reached in the tests of the σ–ε dependence.

The maps of lowering the insulation thickness obtained from the numerical analysis were presented in Fig. 10. The vertical stresses in the XPS layer are presented in Fig. 11.

The highest value of the stresses under the internal thickened fragment of the foundation slab amounted to 82 kPa. The highest local values of stresses amounted to 180 kPa in the area of the staircase and 196 kPa under the external wall. Figure 12 presents the results of the calculated change in thickness in the measurement points marked in Fig. 1a). Those values were designated in 6 analysis steps, after concreting each floor and after completing the construction of the building. The results were compared with the measured values. It may be noted that only point "1" recorded the satisfactory compliance of less than 20%. It may result from the fact that the loads were not estimated precisely enough and that the creep in the numerical analysis was neglected. The presented comparison between the results shows the necessity to improve the modeling of that issue.

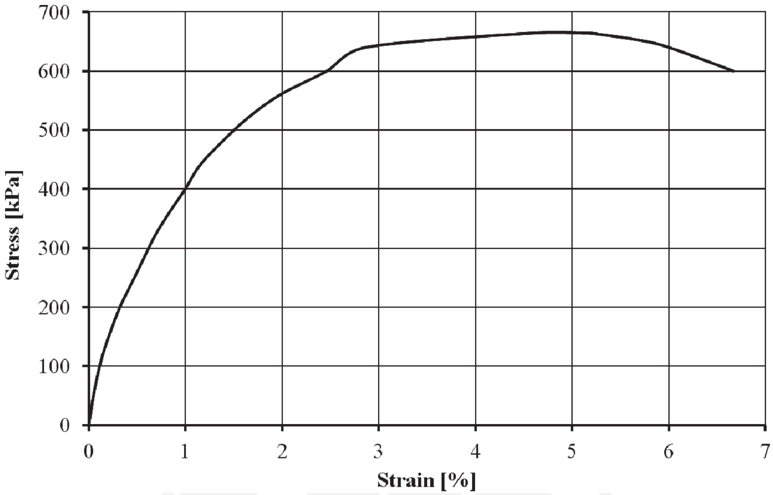


Fig. 8. Stress-strain dependence from laboratory test

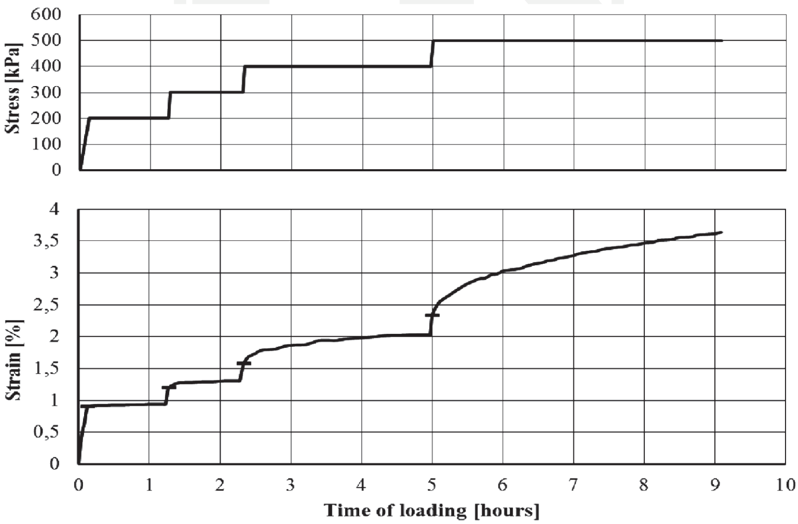


Fig. 9. Short time creep of XPS sample from laboratory test

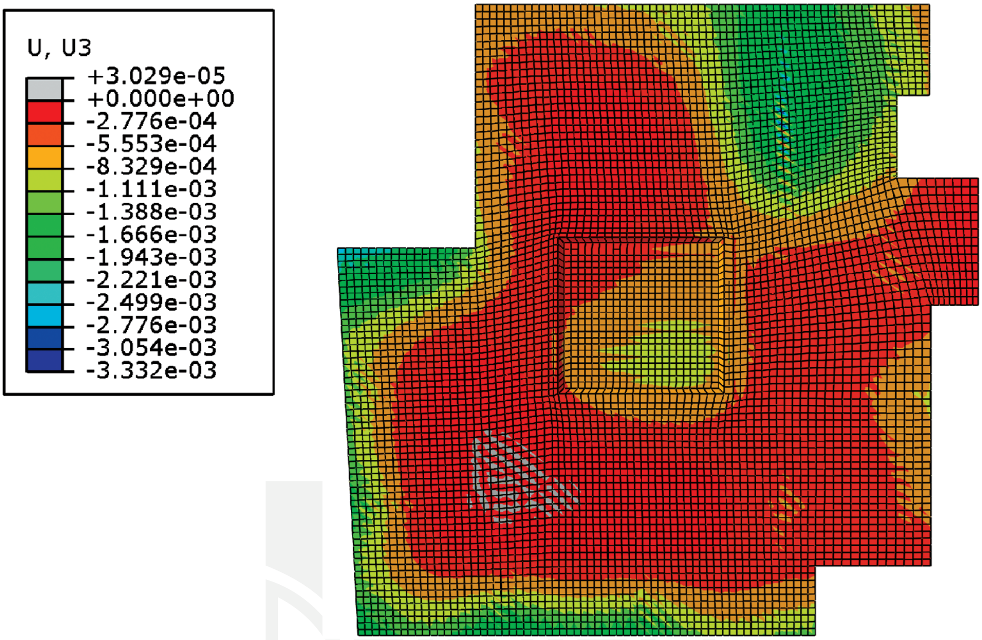


Fig. 10. The map of vertical contraction of XPS layer in final stage [in meter]

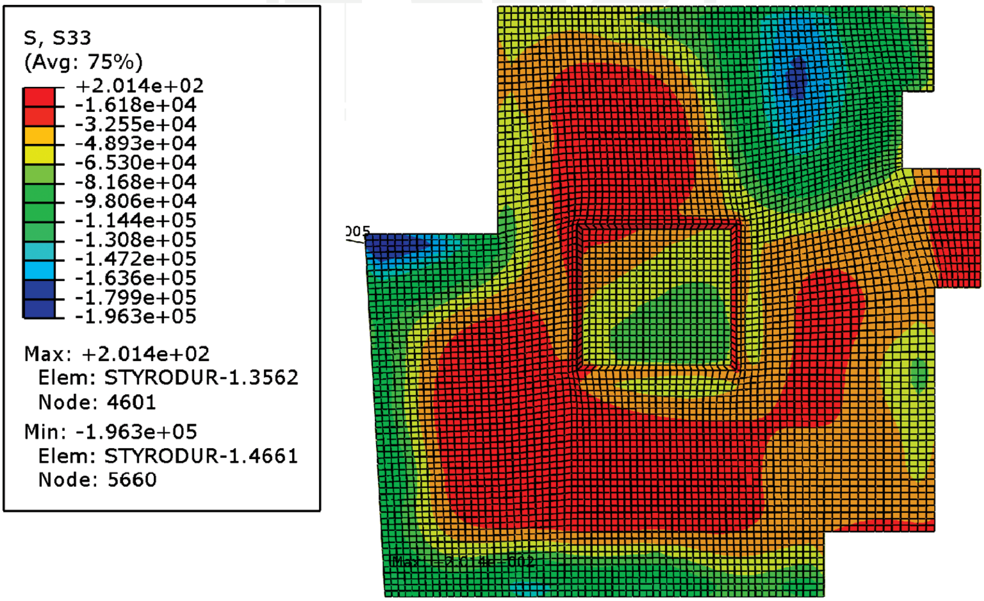


Fig. 11. The map of vertical stresses in XPS [in Pa]

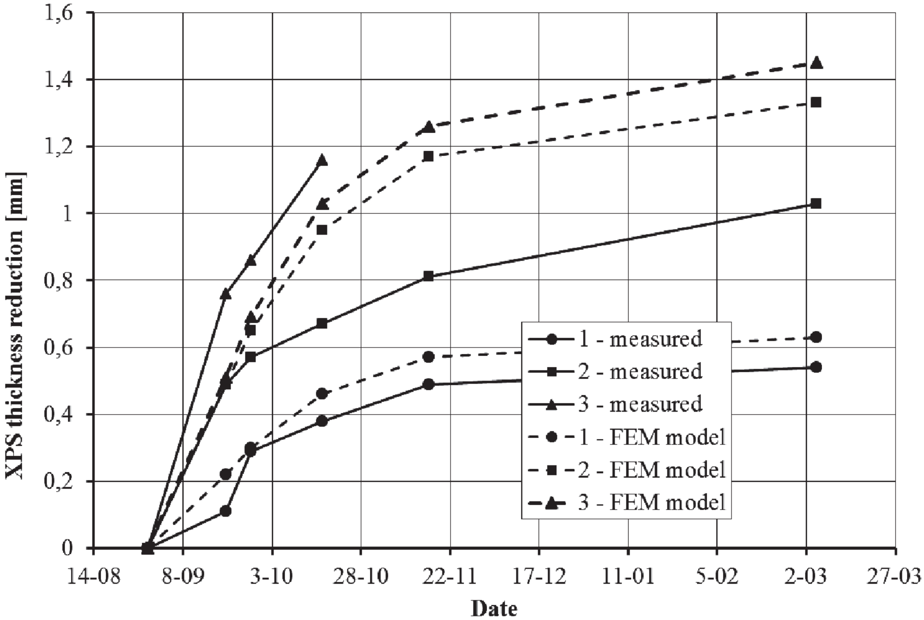


Fig. 12. Results of XPS thickness reduction (calculated and measured)

6. Final conclusions

On the basis of the obtained analysis and measurement results it may be concluded that:

- The change in the thickness of the 150 mm layer of XPS under the foundation slab of the five-storey reinforced concrete building exceeded slightly 1 mm (1.19 mm; $\varepsilon = 0.79\%$ – point "3"). That value was reached at the stresses equal to 115 kPa (value from numerical calculations). Such a small change in insulation thickness is not significant for the total settlement of the building.
- The laboratory tests of creep of XPS indicated that the deformations stabilize at the stresses of 400 kPa. That value seems too high to allow it when applying insulation under a building without additional creep tests over a long period of time. However, it may be determined that the safe level of stresses is the value of 300 kPa.
- The above conclusions indicate that it may be assumed that it would be safe to apply the analyzed XPS material under the foundations of a 10-storey building.
- However, it is certain that the modeling of the issue presented in this work should be improved. For that purpose, a plastic soil model should be applied. Additionally, it is necessary to prepare the model of the whole building in order to take into account the impact of stiffness of the building on the behavior of the foundation slab.

Literature

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[2] PN-EN 1605: 2013-07E *Thermal insulating products for building applications – Determination of deformation under a given compressive load under specified temperature* (in Polish), 30-07-2013.

[3] *ABAQUS User's Manual*, 2011.

[4] Synthos XPS Prime 70 (I, L, N), *Technical Manual*, Synthos S.A., July 2013.