World Academy of Science, Engineering and Technology
International Journal of Architectural and Environmental Engineering
Vol:8, No:4, 2014

Energy Efficient Construction and the Seismic Resistance of Passive Houses

Vojko Kilar, Boris Azinović, David Koren

Open Science Index, Architectural and Environmental Engineering Vol:8, No:4, 2014 publications.waset.org/9997882/pdf

***Abstract*—**Recently, an increasing trend of passive and low-energy buildings transferring form non earthquake-prone to earthquake-prone regions has thrown out the question about the seismic safety of such buildings. The paper describes the most commonly used thermal insulating materials and the special details, which could be critical from the point of view of earthquake resistance. The most critical appeared to be the cases of buildings founded on the RC foundation slab lying on a thermal insulation (TI) layer made of extruded polystyrene (XPS). It was pointed out that in such cases the seismic response of such buildings might differ to response of their fixed based counterparts. The main parameters that need special designers' attention are: the building's lateral top displacement, the ductility demand of the superstructure, the foundation friction coefficient demand, the maximum compressive stress in the TI layer and the percentage of the uplifted foundation. The analyses have shown that the potentially negative influences of inserting the TI under the foundation slab could be expected only for slender high-rise buildings subjected to severe earthquakes. Oppositely it was demonstrated for the foundation friction coefficient demand which could exceed the capacity value yet in the case of low-rise buildings subjected to moderate earthquakes. Some suggestions to prevent the horizontal shifts are also given.

***Keywords*—**Earthquake Response, Extruded Polystyrene (XPS), Low-Energy Buildings, Foundations on Thermal Insulation Layer.

I. Introduction

THE implementation of the directive [1] has set new requirements for the buildings' energy efficiency. After the year 2020 it will not be possible to get a building permit unless the building will be near zero-energy. One of the Directive 2010/31/EU principles is that energy efficiency measures should not affect other requirements in buildings such as accessibility, safety and intended use of the building. On the subject of ensuring the safety of low-energy buildings there is no sufficient literature to investigate to what extent and in which cases can the construction of such buildings be dangerous in earthquake-prone regions. In those parts of Europe in which low-energy buildings have already become an established practice, earthquakes are for the most part unknown and therefore the verification of new construction details is not necessary. In recent years, however, the low-energy buildings standard has slowly been gaining ground in areas where earthquakes (including strong earthquakes) are frequent, such as Spain, Portugal, Italy, Greece, Croatia and Slovenia. The suitability of such details in earthquake areas needs to be verified, and appropriate solutions found. The paper describes the critical details of low-energy buildings and focuses on the prevention of ground floor slab thermal bridge. Under the given assumptions the conclusions of parametric analyses of buildings founded on a layer of thermal insulation (TI) are presented. A comparison between the response of models founded on a fixed base and models founded on a layer of TI with the same superstructure is presented.

V. Kilar is with the Faculty of Architecture, University of Ljubljana, Slovenia (phone: +386-1-2000-720; fax: +386-1-4257-414; e-mail: vojko.kilar@fa.uni-lj.si).

B. Azinović and D. Koren are with the Faculty of Architecture, University of Ljubljana, Slovenia (e-mail: boris.azinovic@fa.uni-lj.si, david.koren@fa.uni-lj.si).

II. Critical Details of Low-Energy Buildings from the Point of View of Earthquake Resistance

In practice there are no uniform requirements for thermal efficiency and construction detailing methods, which will define the unique low-energy buildings [2]. On the other hand, in the case of passive houses, these requirements are more accurately defined and determined by regulations of the Passivhaus Institute [3]. In order to achieve low-energy consumption passive houses must expose well isolated and air-tight envelope without thermal bridges. In this way, extremely low transmission heat losses are achieved. Furthermore passive houses must have a controlled ventilation system preheated with heat from the exhaust air, which also reduces ventilation losses. By achieving all of the Passivhaus Institute requirements the energy consumption of the building is reduced to the level, that no active heating system is required.

The demand of constructing buildings without thermal bridges is a trend, which applies to all new built buildings, regardless of the different definitions of low-energy buildings and the use of different passive and active systems to reduce energy consumption. Already a small thermal bridge can endanger the environmental concept of such buildings [4]. The problem exposed in this article relates to the fact that the construction of low-energy buildings is also present in earthquake-prone areas. However, the specific details to prevent thermal bridges have not been adequately verified on dynamic seismic loads [5]. Structural control for seismic load is necessary, because the majority of problematic junctions is resolved by inserting thermal insulative parts between the load-bearing structural elements and can cause weakening of the structure in the most crucial parts of the building. On the account of improving thermal comfort of the building structural integrity/stability can be threatened.

First low-energy buildings were low-rise buildings, which are not so vulnerable to the changes on the building envelope from the point of view of structural resistance [6]. The latter is the main reason, that structural seismic safety of low-energy buildings has not been thoroughly researched until now.

Open Science Index, Architectural and Environmental Engineering Vol:8, No:4, 2014 publications.waset.org/9997882/pdf

Solutions for new critical details in passive and low-energy buildings are mainly developed and experimentally tested by manufacturers of construction products and architecture designers according to the requirements of an individual building project.

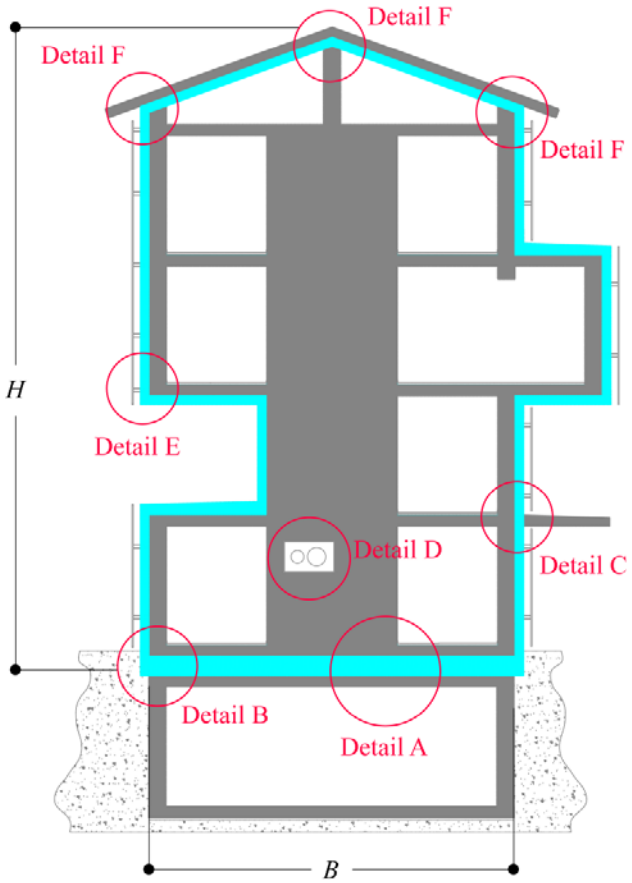


Fig. 1 Schematic representation of low-energy buildings' details critical from the point of view of earthquake resistance

The special details of passive and low-energy buildings, which could be critical in the case of dynamic seismic loads, are shown in Fig. 1 and can be divided as following:

A. Ground Floor Slab

Installation of a TI layer with suitable compressive strength beneath the ground floor slab, foundation slab or strip foundations. For this purpose most frequently used materials are extruded polystyrene (XPS) boards and foam glass boards/granulate. More details of the insertion of TI layers beneath the foundation slab and their influence on seismic response are presented in chapter III.

B. Insulation Base

Interruption of the thermal bridge at the junction of the outside wall with the strip foundation or foundation slab by means of a so-called insulation base made of a material with suitable compressive strength and thermal conductivity. Insulation base is usually a thermal insulating block produced from one of the following materials: aerated concrete, light concrete, foam glass, and extruded polystyrene (XPS). Such thermal insulation blocks can be mainly used in masonry structures and are not reinforced as it is in the case of load bearing TI elements (Detail C). For this reason thermal insulation blocks can be used only to withstand compressive stresses. The manufacturers of these elements usually limit their use regarding on the number of building stories, which is the main parameter for defining the axial compressive stress on each block. Insulation base is mostly suitable for low-rise buildings with less than three stories, because the compressive strength of thermal insulation blocks is limited on the account of their good thermal conductivity properties. The axial compressive stresses on the insulation base can be even further increased, if the building is exposed to seismic shaking. From the point of view of earthquake resistance the position of the blocks at the buildings' base is undesirable, because the seismic forces are as a rule largest at the base. Furthermore seismic shaking can also induce shear and tensile stresses in the thermal insulation blocks, which are not designed to overcome the combination of compressive and shear stresses or tensile and shear stresses.

C. Load Bearing TI Elements

In the case of preventing thermal bridges between the balcony cantilever and the internal slab, special innovative solutions of different load bearing TI elements were proposed by manufacturers of construction products. These products are experimentally tested on vertical loads and their results are published by manufacturers in the form of different material for building designers. Some research [7], which compares the experimental and analytical results, was obtained with an intention to present a variety of potentially dangerous failure mechanisms of such load bearing thermal insulation elements exposed to vertical loads. When exposed to seismic shaking other critical issues could emerge. In the case of long cantilever the induced vertical oscillating could result in the local failure of the load bearing thermal insulation element. Moreover, such a detail can also be of critical concern for the global structural seismic response in the case when it interrupts the load bearing shear wall or column. In this case the structural vertical integrity is affected and could result in the deteriorated overall structural response. The problem is similar as in the case of thermal insulating blocks (detail B).

D. Interruptions in the Structural System, Because of the Controlled Mechanical Ventilation System

The installation pipes used for the mechanical ventilation system are in most cases placed at the parts of the structure, which are crucial for their stability (structural walls, columns, slabs and beams). From the point of view of earthquake resistance, the interruptions in the structural elements cause a new weakening point, which can resolve in a different plastic mechanism under severe structure ductile behavior (e.g. soft story mechanism).

E. Façade Elements

In the process of energy efficient construction, the most effective measure is to increase the thermal insulation

Open Science Index, Architectural and Environmental Engineering Vol:8, No:4, 2014 publications.waset.org/9997882/pdf

thickness. However, the increased thermal insulation thickness of the outer wall can endanger the mounting of external façade elements, which is more difficult to assure. Furthermore, the thermal bridges through the façade elements are avoided by using special fixation elements with minimal thermal conductivity, which could prove to be critical in the case of strong seismic shaking.

F. Roof Fittings without Thermal Bridges

This detail could be more critical, when exposed to strong wind than in the case of strong earthquakes. However, the roof construction is usually considered as a stiff diaphragm, which binds the vertical construction elements to work as a whole in the case of a horizontal load. If a stiff diaphragm on top of the building is not assured, the seismic response of the whole building could be endangered.

III. Prevention of Ground Floor Slab Thermal Bridge

Most commonly used materials for preventing ground floor slab thermal bridge are cellular glass gravel insulation, cellular glass insulation boards, and extruded polystyrene (XPS) insulation boards. These materials are mainly used due to their high compressive strength and their water/frost resistance [8]. However, in the case of earthquake load, the mechanical requirements for the materials used as TI beneath the foundation slab become even stricter, due to the dynamic loads they are exposed to (described in Chapter IV).

A. Thermal Insulation Gravel (Aggregate)

The material for thermal insulation aggregate must perform under extreme conditions. In addition of carrying the weight of the whole building and thermally insulating the ground floor slab, it must be water and frost resistant. Furthermore it is demanded to be acid-resistant and alkali-resistant and also resistant to bacteria and vermin. The placement of thermal insulation aggregate below the ground floor slab can be described in the following basic points:

1) Construction pit excavation and laying the geomembrane.
2) The thermal insulation aggregate is transformed as a loose, scattered cargo and placed on the geomembrane with the help of a crane and a sheet. Blinding concrete and drainage layer to prevent capillary action of water are not necessary.
3) Compaction of the aggregate with vibration compacters and roller machines.
4) Placement of foil or geomembrane on the top as a protection layer.
5) Reinforcing and concreting the foundation slab.

Materials that correspond to the strict requirements of TI aggregates are cellular glass aggregate and to some extent expanded clay aggregate, which can be used only for low-rise buildings (Table I). Cellular glass aggregate is produced from waste glass by wet or dry-foaming procedure. In several stages of crushing and cleaning, the recycling glass is milled to the size of dust. The powder is stored temporarily in silos already mixed with mineral additives. From there it is forwarded to continuous industrial furnaces via conveyor belt. The thickness of the powder layer put onto the conveyor belt defines the resulting lump size. The furnace temperatures and the speed at which the glass powder goes through the furnaces, together with the additives (and their relative proportions) influence the properties of the produced insulation material. In the passage through the 10–15 m long furnaces with temperatures of 900–1000°C, the glass powder expands and finally after cooling down forms a granulate [9]. Expanded clay is similar as cellular glass produced at very high temperatures. Individual round shaped granules are produced in a rotary kiln at 1100–1200°C. Typical size of the granules varies from 0–32 mm and their density from 220–300 kg/m3. It is mainly used as a lightweight aggregate and as the insulation fill for flooring solutions.

TABLE I
Mechanical Properties of Thermal Insulation Gravel

	Cellular glass	Expanded clay[a]
Density [kg/m3]	100–150	220–300
Aggregate granulation [mm]	10–60	10–30
Thermal conductivity	0.060–0.080	0.065–0.120
Compressive strength	400–1600	700–2500
Friction angle [°]	40–50	35–40
Cohesion	0	0
*Energy for production [kWh]**	85	73–168
*Relative cost for production**	5.3–5.9	5.9–12.8

*Energy for production and relative cost are calculated for equal thermal conductivity value of U=0.4W/m2K for both materials. The price of EPS is used as a unit.

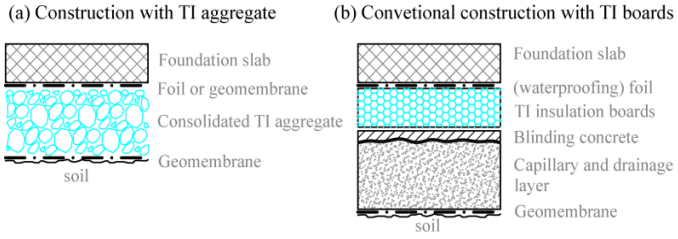


Fig. 2 Schematic comparison of TI foundation set. (a) Construction with aggregate; (b) Conventional construction with TI boards

B. Thermal Insulation Boards

As it was pointed out, special requirements for the compressive strength and resistance against the influence of water/frost need to be fulfilled by TI materials in underground applications. Both construction possibilities (Fig. 2) have some negative and positive aspects. In contrast to construction with TI aggregate, the application of TI in the form of boards requires a capillary/drainage layer and a flat bedrock, which can be time consuming, especially if the installation pipes need to be shifted in the TI layer. In this case the advantages of a pressure resistant construction with TI aggregate can be significant, because it can balance the uneven surface. On the other hand building sites with high underground water are not suitable for construction with TI aggregate, because the appearance of water eliminates the good thermal conductivity properties of the TI aggregate.

Open Science Index, Architectural and Environmental Engineering Vol:8, No:4, 2014 publications.waset.org/9997882/pdf

TI materials in the form of insulation boards were the first used to prevent ground floor slab thermal bridge. In Germany, where the first passive house was built, technical regulations for TI materials under the foundation slab already exist. However, none of the regulations includes material testing under cyclic loading conditions and its application in earthquake-prone areas. For this purpose, characteristics acquired according to the existing standards for different materials are presented and in the second part the evaluation of XPS boards performance according to cyclic loading, which was performed within the research project Seismic safety of passive houses at University of Ljubljana [10].

Expanded polystyrene boards (EPS) are produced by connecting expanded polystyrene granules in presence of saturated steam at 110–120°C. For production of 1m^3 of EPS approximately 400–1000 kWh of energy is needed, which classifies this material as one of the cheapest thermal insulating materials. In this article the price of EPS was chosen as a reference value, where in Slovenia the average price for 10cm of EPS with U-value 0.4 W/m^{2}K totals 10 €/m^2. In addition to its favorable price it exposes good thermal conductivity values between 0.035–0.04 W/mK. EPS boards must be properly protected, because they are not resistant to water, high temperatures (above 80°C) and organic solvents. Water resistance is problematic especially in the presence of constant moisture or underground water. EPS is one of the oil derivatives and is extremely hard to recycle [11]. In addition to dynamic tests of EPS [12]-[14], also the investigations on the compressive creep of the EPS [15], [16] are much more numerous compared to the corresponding research preformed on the XPS.

A different manufacturing process with the same base material as EPS is used to produce extruded polystyrene (XPS) boards. The consequence of different manufacturing process (extrusion) is mainly that cells in XPS material are closed and practically don't absorb water. So, despite a few times higher price compared to EPS, XPS is almost indispensable in the places where the TI is directly in contact with water (thermal protection of the basement walls, flat roof upside-down and TI below the ground floor slab). The production process is less environmentally friendly than in the case of EPS, because more energy is needed. In addition, CFC and HCFC gases were used in the past, which are bound to be replaced with less environmentally harmful substances as CO_2 and alcohols.

Compressive strengths and elastic moduli, which are presented in Table II, are obtained from the experimental tests, which are carried out according to the standard EN 826 [17]. On the other hand shear strengths and shear moduli were obtained on the basis of standard EN 12090 [18]. The values of different materials listed are therefore comparable with each other. Among all presented the most important value for TI under the ground floor slab is compressive strength, which is the main criterion for selecting the material. Standard EN 826 defines the maximum compressive strength of the TI σ_m (in the case when the $\sigma - \epsilon$ diagram does not have a pronounced maximum strength, σ_m is defined at 10% deformation). In addition to compressive strengthσ_m, compressive creep of the material is also an important characteristic. It is defined in the standard EN 1606 [19] for the intended life of the building 50 years at a compressive deformation equal to 2%. In Table II only the maximum compressive strength (σ_m) is shown, because other characteristics are more difficult to obtain for all materials, since the producers do not list all of the data in their catalogues.

TABLE II
MECHANICAL PROPERTIES OF TI BOARDS

	Cellular glass	Extruded polystyrene (XPS)	Expanded polystyrene (EPS)
Density [kg/m3]	100–165	25–35	15–30
Water Resistance	YES	YES	NO
Thermal Cond. l [W/mK]	0.040–0.050	0.030–0.040	0.031–0.043
Compressive Strength σ_m[kPa]	400–1600	300–700	50–200
Elastic Moduli [MPa]	100–500	15–40	4–6
Shear Strength [kPa]	80–300	100–200	10–40
*Energy for production [kWh]**	85	43–89	39–95
*Relative cost for production**	5.3–5.9	3.0–3.5	1

*Energy for production and relative cost are calculated for equal thermal conductivity value of U=0.4W/m2K for both materials. The price of EPS is used as a unit.

In addition to the material properties presented in Table II, also the cyclic axial and cyclic shear material properties are needed to perform nonlinear earthquake dynamic analysis. In general, limited research has been done until present on the behavior of XPS foam boards. In the relevant scientific literature only few references have been found. Improved extruded polystyrene foam (XPS) insulation with better material efficiency (lower thermal conductivity) has been developed in [20]. In [21] the XPS has been applied as a part of a vibration isolating screen installed in the soil near a test public transport track. The research provides some dynamic material characteristics of the used XPS: dynamic elastic modulus equals 35 MPa, the density 45 kg/m^3, Poisson's ratio 0.2, and the material damping 0.01. The long-term mechanical properties (compressive creep strains and moduli) that are of key importance for TI under ground floor slab have been analyzed in [22]. Based on the authors' knowledge, the cyclic compressive stress–strain behavior of the XPS foam that is essential for its seismic response in earthquake engineering applications has not yet been researched. Furthermore, the information about the cyclic behavior of this material in shear is currently completely unresearched issue. From this standpoint, an extensive experimental research addressing the cyclic behavior of extruded polystyrene foam (XPS) in compression as well as in shear is necessary in order to better understand the fundamental behavior of the XPS foam boards in its earthquake engineering applications. For this purpose several experimental tests on different XPS material and

Open Science Index, Architectural and Environmental Engineering Vol:8, No:4, 2014 publications.waset.org/9997882/pdf

different TI foundation sets (different compositions of the TI layer) was performed by authors of the present study in cooperation with Faculty of civil and geodetic engineering in Ljubljana [10]. The results for the selected material XPS400 are presented in Fig. 3. Besides the dynamic characteristics, the obtained values of axial elastic and shear moduli and corresponding strengths determined by monotonic compression and shear tests are also indicated and can be directly compared to the values in Table II. As can be seen from the Fig. 3 the investigated different specimens have shown very stable cyclic response with very low standard deviations. The axial compressive hysteresis loop proved to be stiffness degrading without changing the initial strength capacity. On the other hand shear hysteresis loop showed stiffness and strength degradation. The obtained results can be implemented in the numerical models of nonlinear contact springs.

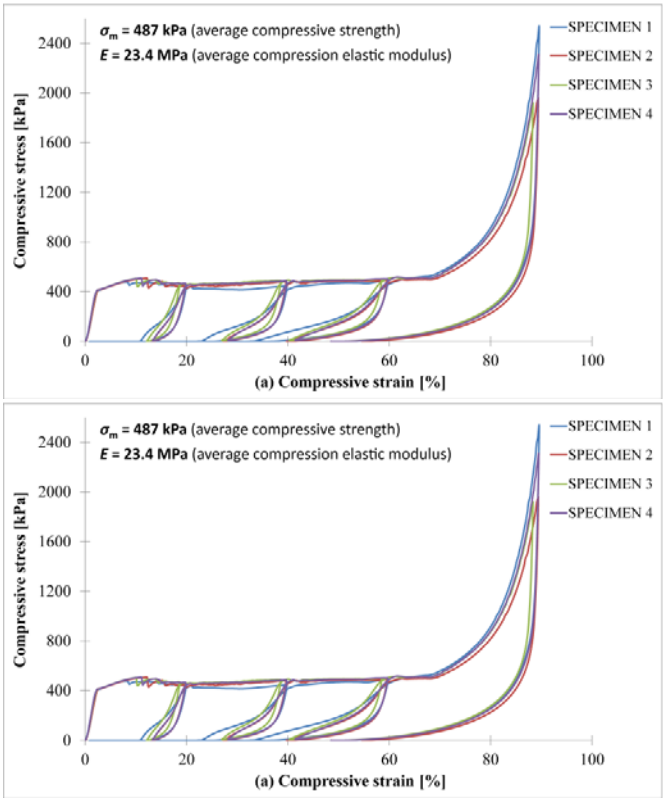


Fig. 3 Experimentally obtained cyclic characteristics for material XPS400: (a) Axial compressive stress-strain hysteresis loop; (b) Shear stress-strain hysteresis loop

IV. Seismic Aspect of the Insertion of the TI Layer beneath the Ground Floor Slab

The technology of modern low-energy or passive houses has mainly been transferred from western and northern Europe and has been adopted to sustain vertical and wind loading [22]. However, there is no guarantee that it can perform well also under cyclic earthquake loading. From the point of view of earthquake resistance, it should be pointed out that, by inserting the flexible layers of TI between the reinforced concrete (RC) foundation slab and the layer of blinding concrete on the ground, the fundamental period of the structure will be prolonged, since, due to the horizontal shear deformability of the insulation layer, the building will oscillate more slowly than on a firm ground. The fundamental periods are additionally increased by rocking effects, which are a consequence of the vertical deformability of the insulation layer. Most passive houses are low-rise buildings with short fundamental periods which could be elongated by the insertion of a TI layer, and thus moved into the resonance part of the design response spectrum (into the period of constant accelerations). In such cases the expected top accelerations of the structure could increase by a factor of two or three in comparison with a structure on a fixed base (Fig. 4). Such an increase could lead to damage to the superstructure or its content, which should not be ignored [5], [23]-[25]. However, if the fundamental period of the superstructure is already on the plateau of constant accelerations, the insertion of TI under the foundation slab might prolong the structural period into the descending branch, so that the seismic forces acting on the structure might be reduced. Only in this case will the TI layer act as a traditional seismic base isolation system, so that the earthquake induced forces would be reduced.

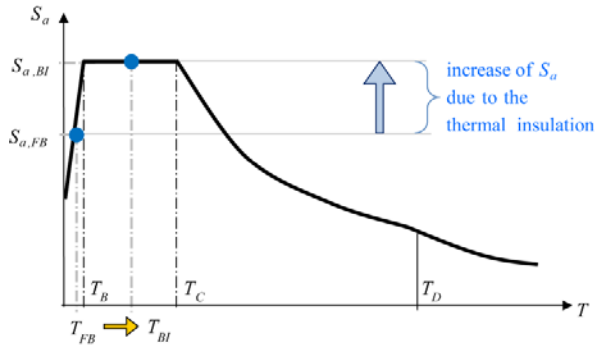


Fig. 4 Roof accelerations of the stiff superstructure in relation to its fundamental period – comparison of the fixed base (FB) and base isolated (BI) building

The results of the preliminary studies [5] and extensive parametric studies [25] have shown that the designers of multi-storey buildings founded on the TI layer under the ground floor slab should pay additional attention to the seismic behavior of such structures. In the case of stronger seismic excitation the following limit states (or their combination) could be expected: (i) formation of a plastic mechanism in the superstructure (i.e. the selected strength was too small), (ii) overturning of the superstructure (i.e. its selected slenderness was too high), (iii) exceedance of the allowable compressive strength of the TI (i.e. the selected weight or the selected slenderness of the TI slab was too large), and (iv) the allowable shear strength of the TI, or the allowable friction capacity between the TI layers, is exceeded. Both studies [5], [25] also proved that the control of maximum shear stresses and maximum horizontal displacements at the XPS layer is much less critical than the control of behavior of XPS in compression which becomes of critical concern when

Open Science Index, Architectural and Environmental Engineering Vol:8, No:4, 2014 publications.waset.org/9997882/pdf

severe uplifting takes place. It was shown that during moderate seismic excitation the edge compressive stresses in the XPS layer beneath the foundation slab could exceed the XPS nominal compressive strengths already in the cases of heavy concrete buildings with more than two or three storeys [5]. The allowable number of storeys depends on numerous parameters such as seismic intensity, the floor plan aspect ratio (slenderness) of the superstructure, its stiffness, strength and cyclic behavior, its seismic weight, quality and thickness of the XPS [25]. In authors' related study [24] also the soil type and the stiffness of the ground floor slab have been investigated and recognized to be essential parameters in governing the seismic response of the buildings founded on the TI layer.

V. Conclusion

The paper presents the critical issues of energy efficient construction on seismic safety of low-energy and passive houses. In the first part of the paper problematic details from structural point of view are recognized and their probable negative influence on buildings' seismic safety is presented. It has been pointed out that the most problematic detail from the point of view of earthquake resistance refers to the thermal insulation (TI) layer under the ground floor slab. In this case the dynamical characteristic of the building might have been changed, because the building on a soft TI layer will oscillate slower than on a firm ground. In the second part of the paper different TI materials for the ground floor insulation and their characteristics are presented. It was shown that only few TI materials fulfill the demand criteria to be used in underground applications (cellular glass and XPS). In contrast to construction with cellular glass aggregate, the application of TI in the form of boards requires a capillary/drainage layer and a flat bedrock, which can be time consuming, especially if the installation pipes need to be shifted in the TI layer.

The results obtained from authors' related studies [25] have shown that the insertion of a layer of thermal insulation beneath the ground floor slab of buildings could lead to the damage of the structure, its non-structural elements, or the TI layer itself. For this reason the transfer of such buildings from non earthquake-prone areas to earthquake-prone areas requires additional caution, and the negative effects of creating foundations on a TI layer should be accounted for appropriately in the structural model for seismic analysis and design. Negative amplifications, as expected, in general increase with the number of stories, the slenderness of the building, and the seismic weight of the building. It should be pointed out that the inelastic behavior of the superstructure appears to be favorable for the TI layer since it reduces the forces and transfers smaller moments onto the foundations. It was also shown that the negative amplifications are much bigger only in the case of buildings with shorter periods of vibration (i.e. stiffer buildings), that is in the case of buildings with periods shorter than T_C in the EC8 response spectra (0.4–0.6 s). The largest amplification factor was found in the case of buildings with very short periods, i.e. shorter that the period T_B in the EC8 response spectra (0.1–0.2 s). In the case of longer periods, the TI layer acts as a seismic isolator, and reduces the seismic forces. It should be pointed out that the amplifications themselves - even in the case of magnitudes several times greater which were recorded in the case of very stiff buildings - are not necessarily a threat unless they remain below the given building limit serviceability values or recommended values from the codes. The most important parameters that have to be controlled for every buildings founded on thermal insulation are:

1) The horizontal top (roof) displacement of the building: The largest displacement increase was obtained in the case of stiffer buildings with shorter periods of vibration (<0.3 s), where the increase was up to 5 or 10 times in comparison to FB buildings.
2) The ductility demand: The biggest differences occurred in the case of stiffer buildings with shorter periods of vibration (< 0.2 s), where the increase was up by a factor of several times. The greatest ductility demands were recorded in the case of BI models with low bearing capacities, which behave in a highly inelastic manner.
3) The maximum compressive stress in the thermal insulation layer: The largest compressive deformations in the TI could be expected in the case of slenderer structures with a larger number of stories, which are also heavier than buildings with fewer stories.
4) The rocking effect: It was concluded that the models with 4 or more stories might experience some overturning problems in the case of narrower building floor plans.
5) The friction problems: It has been found out that they are more critical in the case of lower structures which are lighter than the higher buildings. Friction capacity could also be increased by interconnecting the different layers of boards by gluing or other means so as to prevent the sliding between the layers (shear struts, side rails, etc.). Such solutions are, however, not yet commonly used in the construction of low-energy houses. It should be noted that the horizontal sliding effect might be also treated as a seismic isolation system to reduce the extreme seismic forces acting on a building, providing that the building and foundation system are designed to accommodate larger horizontal shifts.

Acknowledgment

The authors acknowledge the financial support from the Slovenian Research Agency (project No. L5-4319 and program No.P5-068). The financial support of other project's co-funders (Building and Civil Engineering institute ZRMK and companies FIBRAN NORD, DULC and BAZA ARHITEKTURA) is also gratefully acknowledged.

References

[1] *Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings*, 2010.
[2] X. Dequaire, "Passivhaus as a low-energy building standard: contribution to a typology," *Energy Efficiency,* vol. 5, pp. 377–391, August 2012.

[3] W. Feist, "Life-cycle energy analysis: low-energy house, passive house, self-sufficient house," in *International symposium of CIB W67*, Vienna, Austria, 1997, pp. 183–190.
[4] W. Feist, *Wärmebrücken und Tragwerksplanung - die Grenzen des Wärmebrückenfreien Konstruirens*. Darmstadt: Passivhaus Institut, 2007.
[5] V. Kilar, D. Koren, and M. Zbašnik-Senegačnik, "Seismic behaviour of buildings founded on thermal insulation layer," *Građevinar,* vol. 65, pp. 423–433, 2013.
[6] M. Zbašnik-Senegačnik, "Large buildings built as passive houses," *Građevinar,* vol. 63, pp. 903–906, 2011.
[7] T. Heidolf and R. Eligehausen, "Design concept for load bearing thermal insulation elements with compression shear bearings," *Beton- Und Stahlbetonbau,* vol. 108, pp. 179–187, March 2013.
[8] F. Méar, P. Yot, R. Viennois, and M. Ribes, "Mechanical behaviour and thermal and electrical properties of foam glass," *Ceramics International,* vol. 33, pp. 543–550, 2007.
[9] A. Zegowitz, "Cellular glass aggregate serving as thermal insulation and a drainage layer," in *Buildings conference*, 2010, pp. 1–8.
[10] V. Kilar, D. Koren, and V. Bokan-Bosiljkov, "Evaluation of extruded polystyrene boards performance – implication for earthquake engineering applications," *Submitted for publication in Construction and Building Materials* 2014.
[11] A. M. Papadopoulos, "State of the art in thermal insulation materials and aims for future developments," *Energy and Buildings,* vol. 37, pp. 77–86, January 2005.
[12] S. Vejelis, I. Gnip, S. Vaitkus, and V. Kersulis, "Shear Strength and Modulus of Elasticity of Expanded Polystyrene (EPS)," *Materials Science-Medziagotyra,* vol. 14, pp. 230–233, 2008.
[13] I. J. Gnip, S. I. Vaitkus, V. I. Kersulis, and S. A. Veyelis, "Deformability of expanded poly styrene under short-term compression," *Mechanics of Composite Materials,* vol. 43, pp. 433–444, September 2007.
[14] D. Wang and R. J. Bathurst, "Numerical Analysis of Earthquake Load Mitigation on Rigid Retaining Walls Using EPS Geofoam," *Open Civil Engineering Journal,* vol. 6, 2012.
[15] J. S. Horvath, "The compressible inclusion function of EPS geofoam," *Geotextiles and Geomembranes,* vol. 15, pp. 77–120, 1997.
[16] I. Y. Gnip, S. Vaitkus, V. Kersulis, and S. Vejelis, "Analytical description of the creep of expanded polystyrene (EPS) under long-term compressive loading," *Polymer Testing,* vol. 30, pp. 493–500, August 2011.
[17] CEN, "European standard EN 826:1996: Thermal insulating products for building applications - Determination of compression behaviour," ed. Brussels, 1996, p. 15.
[18] CEN, "European standard EN 12090:1997: Thermal insulating products for building applications - Determination of shear behaviour," ed. Brussels, 1997, p. 15.
[19] CEN, "European standard EN 1606:2013: Thermal insulating products for building applications - Determination of compressive creep," ed. Brussels, 2013, p. 15.
[20] F. Bunge and H. Merkel, "Development, testing and application of extruded polystyrene foam (XPS) insulation with improved thermal properties," *Bauphysik,* vol. 33, pp. 67–72, February 2011.
[21] S. François, M. Schevenels, B. Thyssen, J. Borgions, and G. Degrande, "Design and efficiency of a composite vibration isolating screen in soil," *Soil Dynamics and Earthquake Engineering,* vol. 39, pp. 113–127, August 2012.
[22] H. Merkel, "Determination of Long-Term Mechanical Properties for Thermal Insulation under Foundations," in *Buildings conference*, 2004, pp. 1–7.
[23] D. Koren, V. Kilar, and M. Zbašnik Senegačnik, "Seismic safety of passive houses founded on thermal insulation," in *17th International Passive House Conference 2013*, Frankfurt am Main, 2013.
[24] D. Koren and V. Kilar, "Seismic vulnerability of the reinforced concrete building structures founded on XPS layer," *Submitted for publication in Earthquakes and Structures, An Int'l Journal,* 2014.
[25] B. Azinović, D. Koren, and V. Kilar, "The seismic response of low-energy buildings founded on a thermal insulation layer – a parametric study," *Submitted for publication in Engineering Structures,* 2014.

Open Science Index, Architectural and Environmental Engineering Vol:8, No:4, 2014 publications.waset.org/9997882/pdf