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Material performance

Evaluation of the performance of extruded polystyrene boards – Implications for their application in earthquake engineering

Vojko Kilar [a], David Koren [a], Violeta Bokan-Bosiljkov [b], *

[a] Faculty of Architecture, University of Ljubljana, Zoisova 12, SI-1000 Ljubljana, Slovenia
[b] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, SI-1000, Ljubljana, Slovenia

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ABSTRACT

The paper summarizes the results of laboratory tests that were performed on samples of extruded polystyrene foam (XPS). The aim of the investigation was to determine the mechanical characteristics which are essential for the seismic analysis of modern low-energy building structures, where XPS boards are used as a thermal insulation layer beneath the building's foundations. As well as this, the shear behaviour of differently composed thermal insulation (TI) foundation sets was investigated, and their friction capacity estimated. The results showed that, in general, XPS material with higher compressive strength also possesses higher shear strength. Sliding between individual components of TI foundation set was revealed to be a likely failure mechanism in the case of building structures that are founded on a TI layer when subjected to strong earthquake loadings.

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1. Introduction

In recent years, more and more consideration has been given to the energy efficiency of buildings, as well as to their sustainable design and living conditions [1–3]. A low-energy building is characterised by the minimum or zero heating costs that can be achieved by the application of relatively thick thermal insulation (TI) layers and efficient ventilation systems. The new directives and standards on rational and efficient energy use strictly regulate that thermal bridges have to be avoided, and that the TI layer should run without interruptions all around the building – even under it or its foundations (Fig. 1).

For application of a TI layer beneath a building's foundations an appropriate TI material has to be used. Besides its thermal insulation characteristics, the selected TI material has to demonstrate sufficient compressive strength and water resistance, minimal long-term creep and good durability. In practice, the most commonly used materials are cellular glass gravel, cellular glass boards, and extruded polystyrene (XPS) boards (which are discussed in this paper).

XPS is based on the use of a polymerised polystyrol and a foaming agent. In general, rather limited research has been performed up until now into the behaviour of XPS foam, although in production the behaviour of this foam under monotonic compressive loading conditions is regularly controlled. In the relevant scientific literature, only a few references can be found in relation to the behaviour of XPS foam. Improved XPS foam insulation with better material efficiency (and lower thermal conductivity) was developed [4]. In [5] XPS foam was applied as part of a vibration isolating screen installed in the soil near a test public transport track. The long-term mechanical

* Corresponding author. Tel.: +386 1 4768663; fax: +386 1 4250681.
E-mail address: violeta.bokan-bosiljkov@fgg.uni-lj.si (V. Bokan-Bosiljkov).

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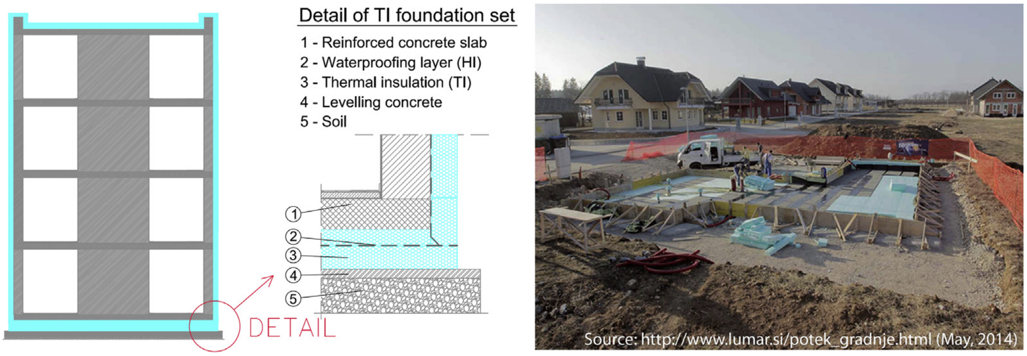

Fig. 1. The thermal envelope of the building must be uninterrupted: schematic presentation (left) and the construction of foundations on XPS boards in practice (right).

properties, which are of key importance for TI placed under foundations, have been analysed in [6]. In the same reference, the modelling of a foundation slab resting on a TI layer has also been schematically indicated. Vaitkus et al. [7] experimentally analysed XPS short-term compression dependence on exposure time. Significant changes in the XPS strength characteristics after 45 days were observed. The relationship between the XPS foam microstructure and its response under compressive load has been analysed in [8]. In the same reference, morphological data for the XPS boards were obtained by X-ray tomography imaging. It was shown that microstructure cell size has no impact on the mechanical properties of the XPS rigid boards when loaded in compression, as long as the density of these boards remains constant. On the other hand, the degree of cell anisotropy was found to have a crucial influence. Similar findings about the influence of the polymeric foam's density on mechanical properties in tension and compression are reported in [9], where the authors conclude that the foam's (e.g. XPS) deformation pattern beyond the yield point in compression is inhomogeneous.

As far as is known to the authors, the cyclic compressive and shear stress–strain behaviour of XPS foam, which is essential for its seismic response in earthquake engineering applications, has not yet been researched. From this point of view, extensive experimental research which would address the cyclic behaviour of XPS foam in compression, as well as in shear, is needed. On the other hand, the behaviour of expanded polystyrene foam (EPS), which is not used for TI below grade, has been extensively studied by means of laboratory static and dynamic tests [10–18]. Investigations into the creep of EPS under compressive loads [19,20] are much more numerous compared to the corresponding research preformed on XPS.

2. Seismic aspects of the insertion of a TI layer beneath the foundations of buildings

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 [6,21]. However, there is no guarantee that it can perform well also under cyclic earthquake loading. From the earthquake resistant building viewpoint, it should be pointed out that one of the consequences of the insertion of a flexible layer or layers of TI between the reinforced concrete (RC) foundation slab and the levelling concrete on the ground is that the fundamental period of the structure is prolonged, since due to the vertical (compressive) and horizontal (shear) deformability of the TI layer the building oscillates more slowly than if constructed on firm ground. Most passive houses are low-rise buildings with short fundamental periods, which could be further 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 might be increased by a factor of two or three in comparison with those of a corresponding structure on a fixed base. Such an increase might lead to damage of the superstructure or its contents, and should not be ignored [21–25]. On the other hand, for more flexible structures (with fundamental period already on the plateau of constant accelerations), the insertion of TI under the foundation slab prolongs the structural period, so that the seismic forces acting on the structure might be reduced. In such cases, the TI layer acts as a traditional seismic base isolation system and has beneficial effects on structural response.

The results of preliminary studies [21] have shown that the designers of multi-storey buildings founded on a TI layer placed beneath the foundation slab should pay extra attention to the seismic behaviour of such structures. In the case of stronger seismic excitation, exceeding the compressive and/or shear strength or ductility in the XPS layer could be expected. As a consequence of rocking behaviour, uplift of the superstructure and of the XPS layer might occur at one edge of the foundation, whereas at the opposite edge compressive strains and stresses in the XPS might, at the same time, significantly increase. In some extreme cases this could result in the toppling over of the whole structure. The study [21] also showed that control of the maximum shear stresses and maximum horizontal displacements of the XPS layer is much less critical than control of the behaviour of XPS in compression, which becomes of critical concern when severe uplifting takes place. It was shown that, during moderate seismic

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