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EDITOR-IN-CHIEF'S WORD

Dear readers,

already traditionally, our Academy's Bulletin Engineering Power features achievements of its members, renowned scientists, in their field of expertise.

Guest-Editor of this issue is Zoran Veršić, PhD, Associate of the Academy in the Department of Architecture and Urban Planning. Therefore I believe You will read presented professional papers with great interest, since they are intriguing from the technical as well as the artistic perspective.

Editor-in-Chief
Vladimir Andročec, President of the Croatian Academy of Engineering

EDITOR'S WORD

Dear readers,

Architecture has always been a special field of human creativity where engineering expertise meets artistic inspiration as well as sociological, historical and other conditions of modern life.

To this end, it is my great pleasure to present this edition of Academy's Bulletin Engineering Power dedicated to Architecture, and its Guest-Editor, Zoran Veršić, Associate of the Academy of the Department of Architecture and Urban Planning.

Editor
Zdravko Terze, Vice-President of the Croatian Academy of Engineering

FOREWORD

The University of Zagreb, Faculty of Architecture is the oldest and in terms of its diverse activities the leading institution of higher education in the field of architecture, urban planning and design in the Republic of Croatia. The present Faculty of Architecture is based on the academic formation of architects that has followed the tradition of engineering education since 1919. In addition, the artistic aspect of architectural education has also been built into the academic programmes of the Faculty. The Faculty comprises four departments (Department of Architectural Design, Department of Urban and Physical Planning and Landscape Architecture, Department of Architectural Technology and Building Science, Department of History and Theory of Architecture). These organisational units are in charge of scientific and artistic activities and education. Each department has a corresponding institute (Institute of Architecture, Institute of Urban Planning, Physical Planning and Landscape, Institute of Building Construction and Building Physics, Institute of Architectural Heritage) established for the purposes of research projects and activities related to the architectural profession. Conducted independently or in collaboration with investors and contractors, these activities entail the application of knowledge grounded in the most recent theoretical and empirical research in architecture and urban planning. A very significant aspect of the Faculty's work is interdisciplinarity, being a specific quality of the Department of Architectural Technology and Building Science whose staff, in addition to architects, includes civil and mechanical engineering experts, facilitating thereby a comprehensive approach to teaching, research and professional work.

This issue comprises papers written by members of the Department of Architectural Technology and Building Science and the Department of History and Theory of Architecture, and their corresponding institutes (the Institute of Building Construction and Building Physics and the Institute of Architectural Heritage). The papers cover a wide range of topics that include energy efficiency in building construction, reconstruction of existing buildings, energy renovation and structural strengthening. During their lifetime buildings decay due to atmospheric conditions and their use, the latter of which is closely related to constantly changing social, cultural and economic circumstances. After several decades of continuous us, buildings occasionally require a thorough refurbishment when their structural elements are repaired and partially replaced, which helps them adapt to contemporary needs and demands as well as to comply with valid technical regulations.

In the last several years, energy efficiency improvement has been one of the major enticements for building reconstruction and refurbishment. It resulted from the European Union's directives obliging the member states to carry out plans for the reduction of greenhouse gas emissions, the improvement of energy efficiency and of the ratio of renewable resources in new and already existing building stocks. In terms of technical possibilities for implementing diverse measures of energy efficiency improvement and the use of renewably energy resources, Nearly-Zero Energy Building (nZEB) has been chosen as a cost-effective model for building refurbishment. However, it is important to mention a feature related to the model that is specific to the Republic of Croatia, namely that energy performance of buildings depend on the climatic conditions of the region in which they are located. Reconstruction and energy renovation of buildings necessarily require analyses, and most frequently, there is a need to improve their mechanical resistance and stability. Buildings that are included in the Register of Cultural Property of the Republic of Croatia or form part of protected cultural and historic ensembles, require a more elaborate reconstruction approach because of different measures that limit the improvement of their qualities in order to safeguard their original and authentic characteristics.

Guest-Editor
Zoran Veršić, University of Zagreb, Faculty of Architecture

CONTENT

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Energy Efficiency and Architectural Heritage: The Reconstruction of the French Pavilion in Zagreb

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Abstract

The exhibition pavilion of the Republic of France was built for the Zagreb Fair during the years 1936 and 1937 at 25 Savska Street 25 in Zagreb according to the design of the French architect Robert Camelot and the civil engineer Bernard Lafaille. The French Pavilion represents a unique engineering innovation, since a thin steel shell was applied for the first time as a load-bearing structure in high-rise building. Therefore, it is a building of exceptional cultural and historical, as well as technical and technological value. The reconstruction design envisaged that the Pavilion would keep its original use as an exhibition space with the possibility of holding some other public events such as lectures, promotions, round-table discussions and smaller performances. In order to enable the use of the Pavilion all year round, it was necessary to adapt the Pavilion appropriately to contemporary standards. In this process, special attention was given to energy efficiency with a contemporary treatment of the perimeter elements of the Pavilion structural system (non- and load bearing structures), which did not damage the authenticity of its idea and design in any segment.

Keywords*: energy efficiency, reconstruction, cultural heritage, the French pavilion, Bernard Lafaille.*

1. Introduction

The relocation of the *Zagreb Fair* to the grounds of the furniture factory "Bothe & Ehrmann" in Savska Street in 1934, enabled its spatial development on approximately 30,000 m^2 of a mostly vacant lot. This in turn provided an opportunity for the international activities of the *Zagreb Fair* once the national pavilions, financed by parent countries, were built. At the end of 1935, an architectural competition for the *Zagreb Fair* was launched. The first prize was won by the architects Hinko Bauer and Marijan Haberle, who were also entrusted with the realisation of the project. Until October 1936, when the first exhibition on the new location was held, according to the competition design only the first phase of the building of the Zagreb Fair complex had been finished. The national exhibition pavilions of France, Italy, Germany and Czechoslovakia were designed by foreign architects and they were built in the period between 1936 and 1938. The exhibition pavilion of the Republic of France was built in 1936 and 1937 according to the design of the French architect Robert Camelot (Reims, 1903 – Pariz, 1992), who worked for the Jacques and Paul Herbé architectural bureau, and the civil engineer Bernard Lafaille (Reims, 1900 – Pariz, 1955). The construction was completed by Zagreb craftsmen.

The French Pavilion represents a unique engineering innovation, since a thin steel shell was applied for the first time as a load-bearing structure in high-rise building. Therefore, it is a building of such exceptional cultural and historical, as well as of technical and technological value, that it transcends the boundaries of local significance. This statement was supported by the work of Bernard Lafaille and Robert Camelot in the period after the Second World War, when they frequently applied technical and technological achievements of their developmental phase of which the French Pavilion in Zagreb was an initial part. While Lafaille was dedicated to industrial architecture (hangars, silos, bridges and dams), as well as to the cooperation with the leading architects of the post-war period, for example with Le Corbusier, on the projects of Unité d'Habitation, Camelot has been remembered as one of the designers of the Paris Centre for New Industries and Technologies (CNIT, 1950), the nucleus of today's business centre of Paris – La Défense. Apart from the French Pavilion in Zagreb, he also designed a pavilion for the world exhibition in New York (1939) with the Herbé brothers.

Under the directive of the Regional Institute for the Protection of Cultural Monuments in Zagreb, the French Pavilion was preventively protected in 1987, while under the directive of the Administration for the Protection of Cultural Heritage of the Ministry of Culture of the Republic of Croatia in 2003 it was listed in the Register of Cultural Assets of the Republic of Croatia.

2. The original design and construction of the French Pavilion 1936-1937

The national exhibition pavilion of the Republic of France was erected in the centre of the *Zagreb Fair* complex. Its position and shape were already defined in the first-prize winning architectural competition design of the tandem Bauer – Haberle.

In the period between August and December 1936 all design documentation was created, while the obtaining of necessary building permits for the construction of the Pavilion was prolonged as long as to the spring of 1937. The preliminary design was signed by the architects Robert Camelot together with Jacques and Paul Herbé, while the structural designer was the civil engineer Bernard Lafaille. The development of the detailed design was entrusted to Vjekoslav Faltus, architect from Zagreb. The contractors were Zagreb craftsmen who also carried out the contract designs. These were the Construction Company *Braća ing. Faltus* (concrete details), the Carpentry Šoch & Sakra (the details of the wooden structure and façade), and the Engineering Workshop and Foundry *Braća Ševčik* (details of the steel structure). Under deadline pressure the Pavilion was built during the six winter months. The opening ceremony took place on 17 April 1937 at the beginning of the “XXVII. International Specialized Sample Fair”. The opening of the Pavilion and the spring fair were followed by two years of additional work and repairs caused by the untimely opening of the Pavilion as well as by design and construction flaws. Most problems were caused by moistening and water dripping into the interior of the Pavilion, because of the condensation on the soffit of the steel tin roof. The analysis of the designing and construction of the Pavilion, including the choice of the contractors and building methods, informs us about a tight deadline in which the project was conceived and realized, the kind of deadline which is certainly a common characteristic of the organisation of large fairs.

The Pavilion is conceived as a cylindrical single-space structure of an irregular curved surface, covered with a suspended roof (*la voile mince*) in the shape of a reversed shallow cone 32.30 m in diameter made of trapezium steel tin panels 2 – 3 mm thick.

The roof rests at a height of 13.50 m above the ground on a ring-like series of 12 steel tubular columns 80 cm in diameter and 3 mm thick, fixed on short reinforced-concrete bars that stick out from the concrete base. The roof structure is stretched under the weight of the central circular skylight which also functions as a precipitation collector, while the whole structure system is stabilized with a concrete ring beam in a steel tin box, laid directly on the columns. This construction represents the first tensile stress roof structure of a modern conception in the history of Croatian architecture, and in the area of weight (18 kg/m^2 of a roof over area) it is a kind of record. The cylindrical walls are made of concrete to the height of 4.9 m, while the upper zone is made of wooden frames with outer and inner panelling divided by ventilated cavity. Within the wooden structure, narrow vertical window openings are alternatively interpolated, while additional natural light is provided by a circular skylight in the middle of the roof structure. The Pavilion has three equally important entrances emphasized by glazed, wooden railing of almost the full height of the Pavilion. The mentioned window and door openings were glazed originally with single-layered glass, while the roof skylight was composed of two glass membranes in separate steel frames. The floor surface of the Pavilion is raised above the ground with 8 steps and it was made of concrete with shallow, geometric graphics. In the basement area, there are three separate spaces and only one is connected directly with the Pavilion interior. The volumes of the basement spaces can be observed on the cylindrical perimeter wall of the Pavilion.

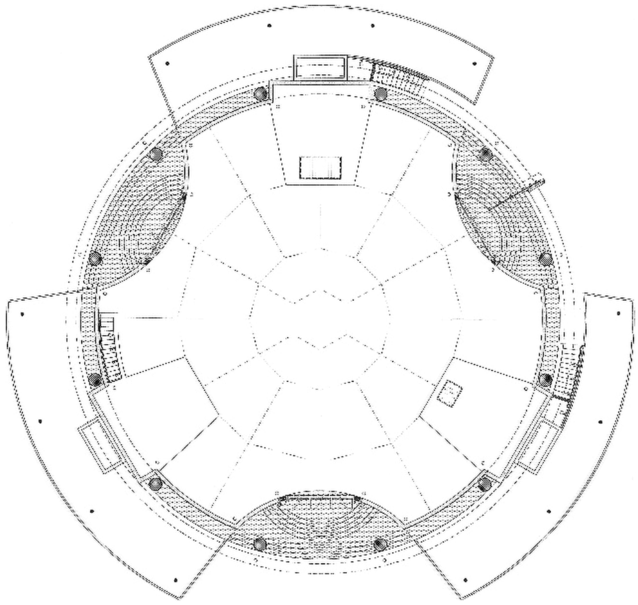


Fig. 1. The French Pavilion, ground-floor plan (contract design, 2010.)

The building is characterised by the combination of the architectural idea about a representative central space, enabled by an innovative construction solution, with the application of building industry materials that normally characterize a building of limited duration.

3. The history of use and former renovation and adaptation designs of the French Pavilion

This masterpiece of modern architecture kept its original use as an exhibition space for the latest technical achievements for a very short time. Ever since the *Zagreb Fair* was moved to its present location in New Zagreb in 1956, the French Pavilion has not been given more appropriate use within the Student Centre but the one of the storage of the nearby Theatre &TD. Inappropriate use of the attractive space of the Pavilion in the second part of the 20th century was occasionally accompanied by the initiatives for its renovation. As a matter of fact, three designs for its renovation and adaptation were made, there were several studies of the whole complex including the Pavilion, as well as numerous exhibitions about the creation, history, possible use, and renovation of the Pavilion. In the early 1990s, the Pavilion entered the period of relatively intensive new use as a theatrical stage. Recognized as an exceptionally valuable theatrical space, owing to the geometry of its interior, the Pavilion aroused great interest of cultural workers. However, the poor condition of the Pavilion questioned any further use for public performances without previous renovation. Since the renewal did not take place, at the end of the 1990s the French Pavilion was definitely closed for any kind of public use due to safety reasons and until 2009 it was used as storage.

4. The design of renovation and reconstruction of the French Pavilion between 2007 and 2011

The latest initiative for the renovation of the French Pavilion was a part of "The Strategy Proposal of the Renovation and Revitalization of the Student Centre of the University of Zagreb". The group of experts concluded that the French Pavilion as a unique building had to be reconstructed to its initial state with some necessary technical alterations which would enable the implementation of contemporary standards.

Within the task that was defined by the mentioned Strategy Proposal, the Institute for Built Heritage of the Faculty of Architecture of the University of Zagreb made a detailed architectural survey of the French Pavilion current state in the spring 2007 with all the damages delineated in it, including the evidence of corrosion damages on the load-bearing steel structure. Six columns reachable from the scaffolding were probed and the damages of the steel tin roof were evidenced on the basis of visual examination. The results of this preliminary research showed that the entire surface of the columns and more than one quarter of the surface of the roof were suffering from corrosion. At the meeting of the project coordination in July 2007 with the participation of the French conservator Pierre-Antoine Gatier, it was concluded that a segment of 1/12 of the Pavilion had to be examined in its entirety, both the part of the load-bearing steel structure and the part of the concrete base and wooden panelling.

The research was carried out by the Croatian Conservation Institute and the Croatian Society for Materials and Tribology in March and April 2008. Researches of the Croatian Conservation Institute included the analysis of the composition of the steel and the welds on the columns, the research of the plaster layers and the kinds of binders on the concrete base, as well as the research of the painted layers and the kinds of wood on the surface, so that the same kinds of materials, paint coats, paints, binders and alloys would be used during the reconstruction.

Fig. 2. The French Pavilion after completion in 1938 (top), the state in 2007 (middle) and after reconstruction in 2014

The examination of the Croatian Society for Materials and Tribology on a segment of the load-bearing steel structure indicated a damaging influence of corrosion in the form of holes in steel tin and the thickness reduction of the column walls up to 40% in comparison with the originally designed thickness. Similar results were obtained by the measuring of the thickness of the roof steel tin plates. In comparison with the originally designed thickness, the reduction of the section amounted to 30%. The latter researches enabled the making of calculation models for the load-bearing structure which indicated an increased main strain due to advanced corrosion of the load-bearing structure which exceeded permitted limits.

All the mentioned researches as well as the calculation model of the present condition of the load-bearing structure suggested the need of a complete reconstruction of the steel load-bearing structure and the wooden surfaces, except for the concrete base of the Pavilion that was scheduled for repair work.

The preliminary design of the renovation and reconstruction of the French Pavilion (The Institute for Built Heritage, July 2008) defined the use of the Pavilion as an exhibition space with partially polyvalent character which created possibility of holding lectures, presentations, university graduation ceremonies, and potentially performances in accordance with unpretentious technical capabilities of the Pavilion, determined by the need for the preservation of the original spatial qualities of the interior. The spatial and functional disposition of the utility rooms, in fact of the three basement volumes, was also defined. The design envisaged modern toilets replacing the original ones, a heating substation and a technical equipment and furniture storage.

The aspect of saving thermal energy and thermal protection was also included in the preliminary design. The calculations of the heat transfer coefficient and the steam diffusion in terms of saving thermal energy were made. All existing perimeter structures showed dissatisfying values of thermal protection and energy saving according to contemporary standards. The occurrence of condensation on the inner surface of the roof structure and windows was proven. Therefore modified sections with additional layers for the purpose of fulfilling the basic requirements of thermal protection and saving the energy of the building were proposed.

The detailed design of the renovation and reconstruction from April 2009 included the design of an overall thermal protection and energy efficiency system. According to the requirements of the Institute for the Protection of Cultural Monuments and Nature of the City of Zagreb, it was decided that because of the preservation of the authenticity of the Pavilion additional layers of thermal insulation on its reinforced-concrete base would not be applied. The base of the building should be preserved in its original thickness, after a possible repair with a thin plaster in order to protect the structure. According to the *Construction Act*, after obtaining a written consent of the Ministry of Culture, it is allowed to depart from the basic requirements for a building (in this case from thermal protection and saving energy), if they would disturb the important features of the monument. The design envisaged the heating of the whole space of the Pavilion including the basement area. The room temperature planned in the design for the heated part of the building was estimated at an average between +18 and 20°C. Thermal energy for heating is provided by hydronic radiant floor heating.

Anticipated changes in the way the building will be used and the resulting microclimate changes are not expected to lead to building damage (the degradation of the structure and section layers).

The design of the Pavilion from the aspect of saving thermal energy and thermal protection was made according to the *Technical Regulations about Thermal Energy Savings and Thermal Protection in Buildings* that were valid at the time as well as on the standards to which these regulations referred.

The design envisaged that the light, wooden panels had to be thermally insulated in the section with a layer of rock wool lined with glass fleece on the ventilated cavity. On the warmer side of the thermal insulation it was necessary to build a vapour barrier.

The walls below the ground in the basement area remained in the previous condition and on the accessible parts waterproofing protection and thermal insulation with extruded polystyrene XPS panels impregnated on the outer side with an HDPE membrane (for protection) were applied. Drainage was laid around the building. The parts of the basement walls inaccessible from the outside were thermally insulated on the inner side with extruded polystyrene XPS panels with the obligatory application of a vapour barrier.

The new floor on the ground of the Pavilion, below which floor heating was installed, includes thermal insulation on a new waterproof layer laid on the existing levelled off concrete base and in the same way the floors on the ground of the basement area of the Pavilion were made. Thermal insulation with extruded polystyrene XPS panels was applied. The ceiling over the basement area (inter-storey construction) remained in its previous state. The roof of the building made of steel tin was thermally insulated with a layer of sprayed up urethane expanding foam with the final layer of sprayed up waterproofing material. The thermal insulation is self-adhesive and sticks to the surface. The layers and the insulation of the roof were applied in accordance with the detailed instructions and descriptions of the producers. The three cross gutters draining under the roof were covered with a layer of rock wool covered with aluminium foil to prevent condensation on the superficial area of the pipe. The flat roof over the basement area was thermally insulated with extruded

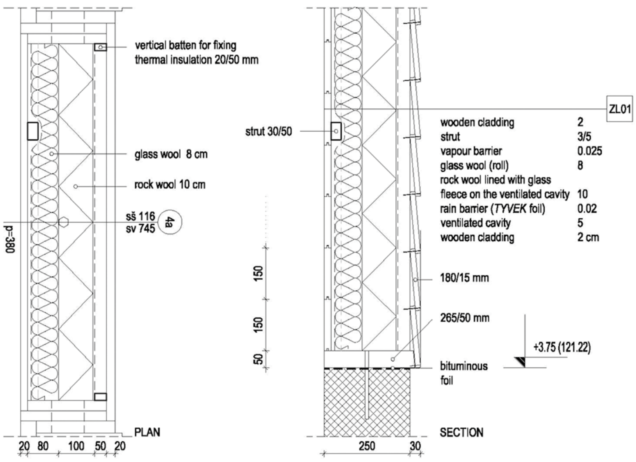


Fig. 3. Section of the perimeter wooden walls showing the application of thermal insulation and supporting layers within the originally hollow cavity of wooden panels.

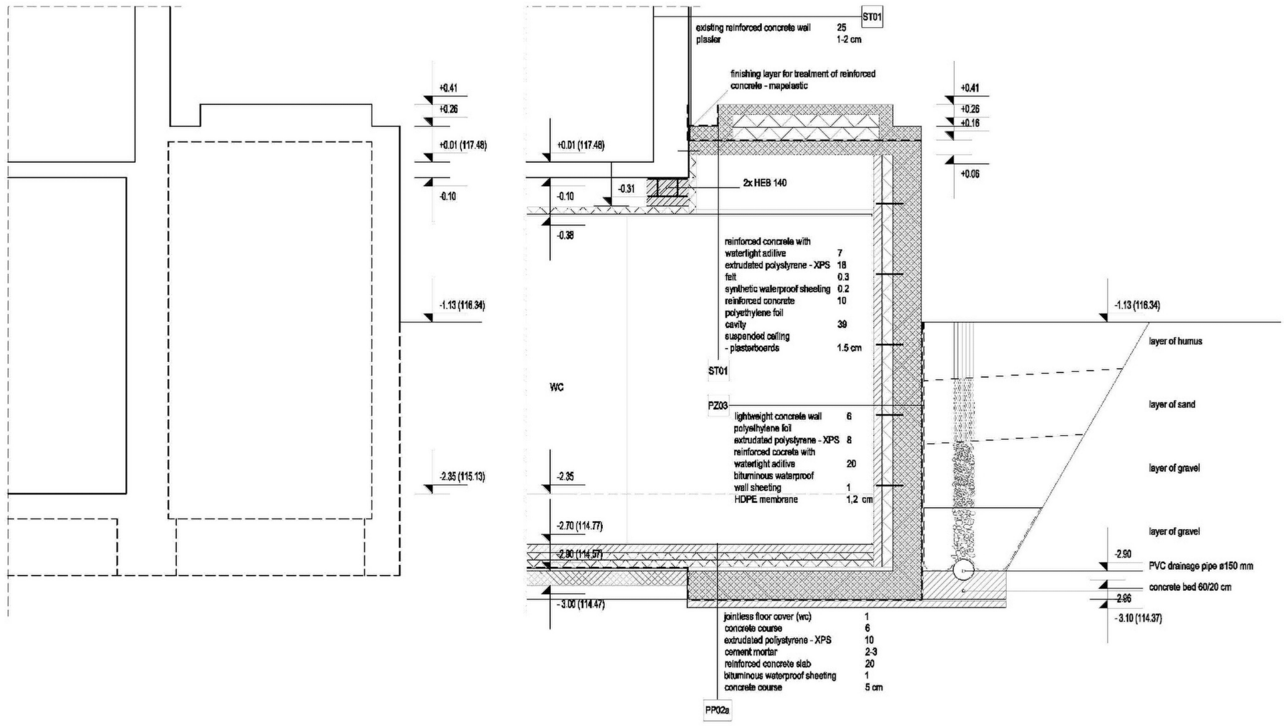


Fig. 4. Longitudinal section through one of the reconstructed basement segments showing the outer walls insulated on the inner side, partially insulated roof slab and new drainage layers.

polystyrene XPS panels and protected with synthetic waterproof insulation.

The wooden frames of fixed windows are glazed with insulating glass LOW-E 4+9+4 mm. The wooden entrance door has a thermally insulated wing and is glazed with insulating glass LOW-E. The roof skylight is made of a double metal frame. The upper frame is glazed with double laminated safety insulating glass LOW-E 4+12+4+4 and the lower one with single glazed laminated safety glass.

Due to the planned improvement of the thermal insulation values the heat transfer coefficients (U-values) are lower than values required by the Technical Regulations, except for the reinforced-concrete outer wall to which it was not allowed to apply any layers for the purpose of thermal protection and energy saving. This departure from U-values does not cause building damage (condensation).

All perimeter structures were designed in such a way that they reach satisfying values of thermal protection (except for the reinforced-concrete wall), that the ones exposed to great temperature changes are stable and that within their composition and on their surface there are no occurrences of unwanted condensation of steam.

Due to the impossibility of complete thermal insulation repairs of the building the transmission heat loss coefficient per surface area unit of the building heated part H_T' [$W/(m^2 \cdot K)$] is higher for app. 30% than the permitted values as well as the annual thermal heat demand per volume of the building heated part unit Qh' ($kWh/m^3 \cdot a$) which is higher for app. 21% than the permitted values.

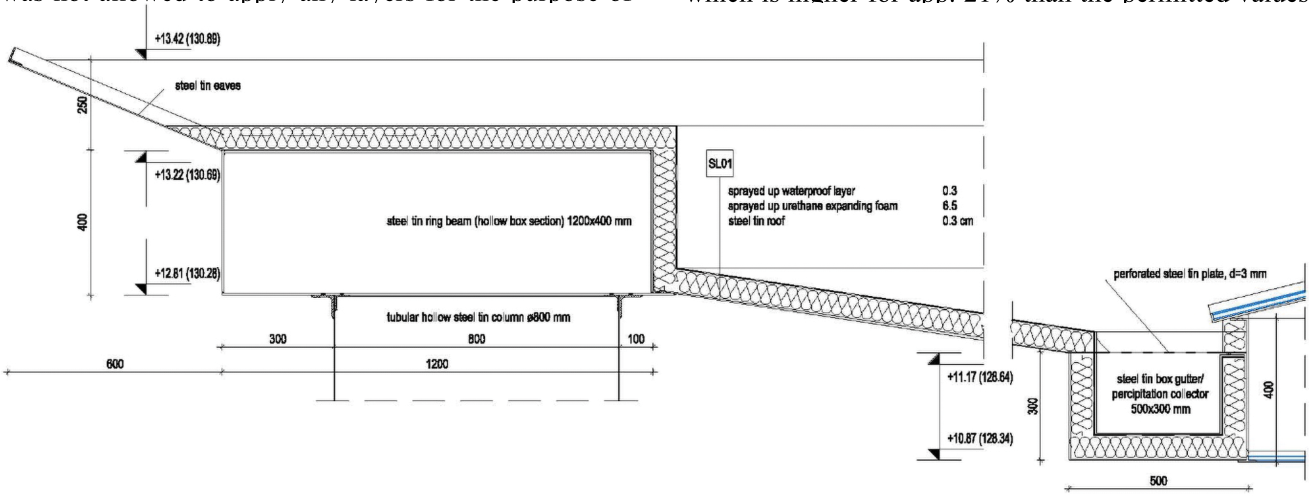


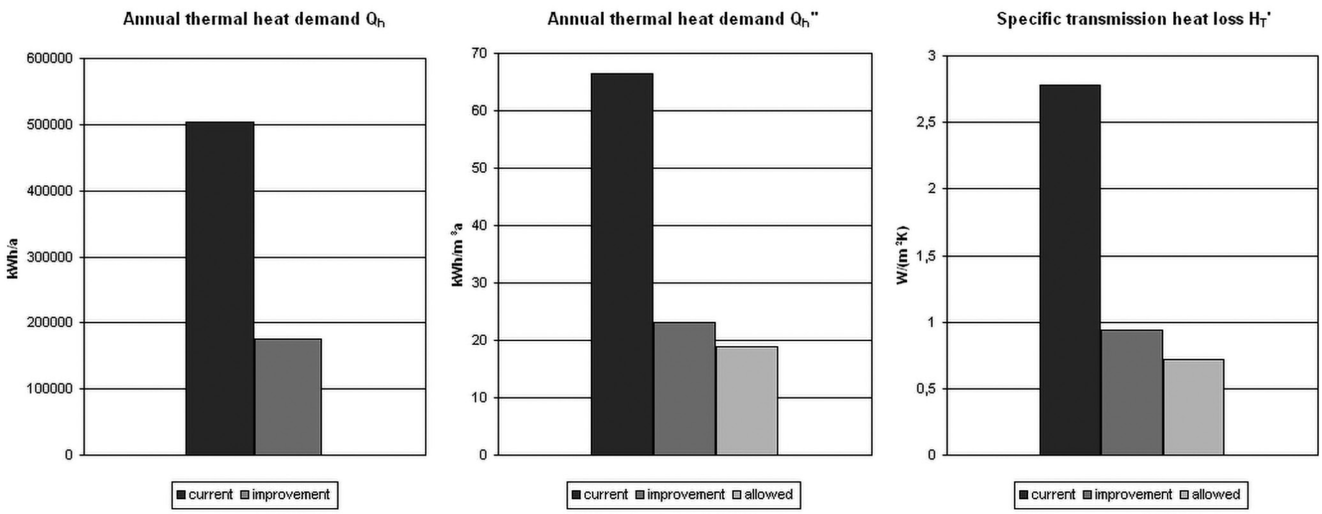
Fig. 5. Section through a segment of steel tin roof showing the application of sprayed up thermal and waterproof insulation; perimeter steel tin ring beam is shown to the left and the box gutter, adjacent to the roof skylight, to the right.

Table 1. Comparison between current and improved U-value.

Type of building structure	U-value current (W/m^2K)	U-value impro-vement (W/m^2K)
ZM01-wall structure-reinforced concrete	3.76	3.42
ZL01-wall structure-wooden	1.25	0.18
PZ01-basement wall-reinforced concrete	3.75	0.50 – 0.58
PP01-floor structure-the pavilion	3.55	0.32
PP02-floor structure-basement	4.33	0.32
ST01-flat roof-reinforced concrete	4.90	0.39
SL01-steel tin roof	5.46	0.29
roof skylight	3.50	1.80
window	5.10	1.80
door	2.90	2.00

Table 2. The review of the Pavilion energy consumption

Characteristic			
superficial area-building heated part A (m^2)	2,664.09		
volume-building heated part V (m^3)	7,501.58		
shape factor f_o (m^{-1})	0.36		
usable building area A_K (m^2)	674.00		
	current	*impro-vement*	*allowed*
annual thermal heat demand Q_h (kWh/a)	503,230	176,133	–
annual thermal heat demand Q_h'' (kWh/m^3a)	66.47	23.02	18.97
specific transmission heat loss H_T' [$W/(m^2K)$]	2.78	0.94	0.72
coefficient transmission heat loss H_T (W/K)	7,416.17	2,495.16	–



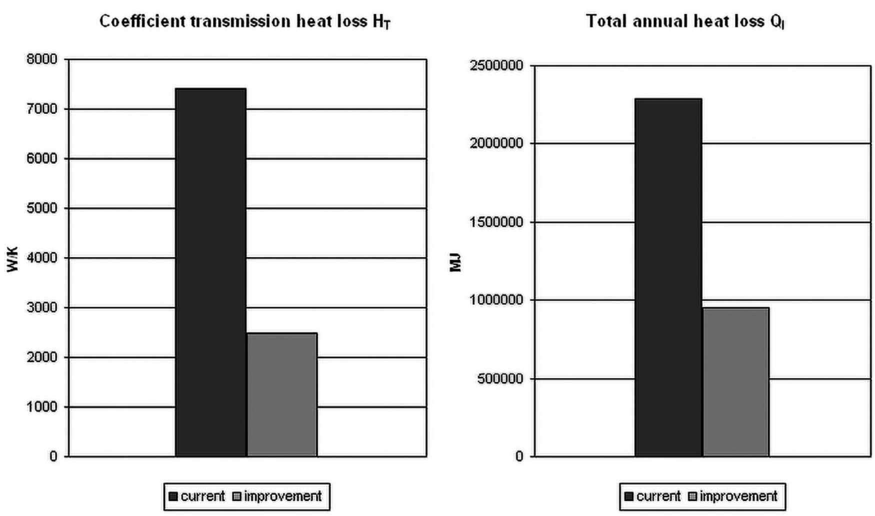


Fig. 6. Graphs showing improvements regarding heat demand and loss.

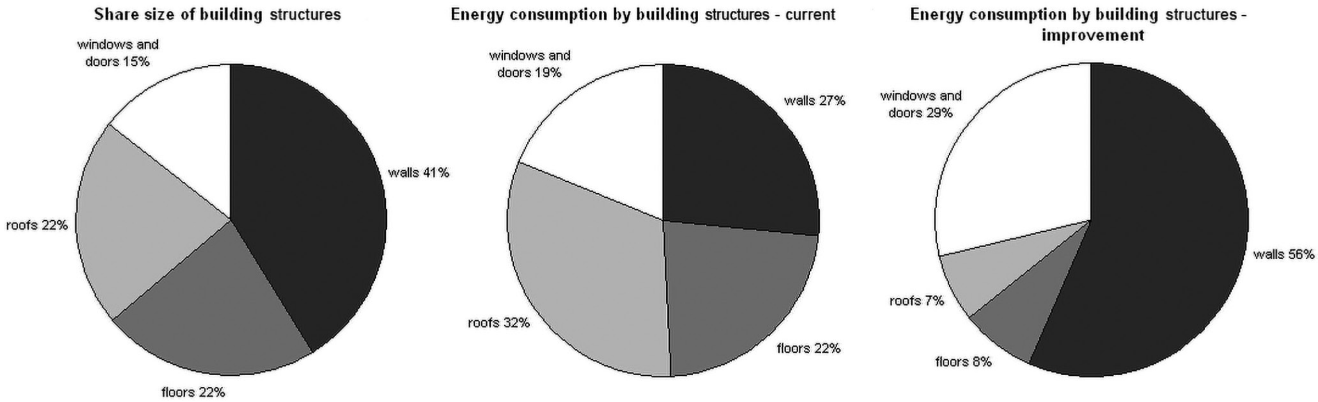


Fig. 7. Graphs showing percentage of building structures and their previous and improved energy consumption.

Conclusion

Exceptionally proportional, particularly impressive in its interior the French Pavilion entered the history of building because of its specific load-bearing metal structure, the author of which was Bernard Lafaille: 12 hollow tubular columns 80 cm in diameter and made of only 3 mm thick steel support at a height of 13.50 metres a ring beam on which a membrane in the shape of a reversed truncated cone 32.30 m in diameter is suspended. A membrane of 820 m^2 in area and 2 mm thick is made of trapezium steel tin panels that were prepared in advance in a workshop and then welded on the spot. As far as the weight is concerned this construction represents a kind of record – 18 kg/m^2 of a roof overall area. Designed in such a way as to bear only tensile stress, the roof structure is suspended under the weight of the central circular skylight and it therefore represents the first tensile strain roof structure of a modern conception. The building is characterized by the combination of the architectural vision of a monumental central space, enabled by an innovative constructional solution, with the construction work of the Pavilion done by the application of some common materials of the building industry that normally characterize a building of limited duration.

The design of the renovation and reconstruction of the French Pavilion at the Student Centre Zagreb envisaged restoring the original use of the building, the one of an exhibition space, with the possibility of occasional organisation of some other public events within the framework of university activities. In order to enable the use of the Pavilion all year round, ultimate technical solutions were found in the treatment of perimeter structures with special emphasis on energy efficiency. Since the French Pavilion is a protected cultural asset, it was impossible to intervene by adding the layers of thermal insulation in order to satisfy the prescribed thermal insulation features on all perimeter structures without threatening its authenticity. The outer reinforced-concrete walls had to be preserved in its original thickness and under the existing conditions without the possibility of adding thermal insulation layers at the request of the Institution for the Protection of Cultural Monuments. For this reason, the heat transfer coefficient U of some walls does not satisfy the prescribed values. By calculation of the condensation it was proved that on and in the reinforced concrete walls the occurrence of unwanted amounts of condensation will not happen.

According to the *Design of the building in regard to saving thermal energy and thermal protection*, all other building elements and building structures under the planned exploitation conditions satisfy the demanded requirements.

Because of the inability to secure complete thermal insulation repairs of the building, the transmission heat loss coefficient per surface area unit of the building heated part H_T' [$W/(m^2 \cdot K)$] and required annual thermal heat demand per unit of the volume of the building heated part Q_h' ($kWh/m^3 \cdot a$) are higher than the permitted values. However, since it is a case of a protected cultural asset according to the *Construction Act*, after obtaining a written consent of the Ministry of Culture, it was allowed to depart from the basic requirements for a building, in this case from thermal protection and saving energy.

Translated by: Dunja Vulić Krpanec, prof.

References

[1] Androić, B., Francuski paviljon u Zagrebu, Primjer umjetničke kreativnosti inženjera, *Glasnik AMCA-FA*, Vol. V, No. 1, pp. 26-27, Građevinski fakultet, Zagreb, 2005.

[2] Baletić, B., Prijedlog strategije za obnovu i revitalizaciju Studentskog centra Sveučilišta u Zagrebu, Arhitektonski fakultet, Zagreb, 2004.

[3] Nogue, N., Bernard Lafaille, mathématicien et constructeur, *Techniques et architecture*, No. 406, pp. 120-125, Paris, 1993.

[4] Radović-Mahečić, D., Moderna arhitektura u Hrvatskoj 1930-ih godina, Institut za povijest umjetnosti and Školska knjiga, Zagreb, 2007.

[5] Radović-Mahečić, D., Pohvala konstrukciji – uz 70. Godišnjicu Francuskog paviljona na Zagrebačkom zboru, *Radovi Instituta za povijest umjetnosti*, No. 31, pp. 297-312, Institut za povijest umjetnosti, Zagreb, 2007.

[6] Šneler B., Stanje konstrukcije i mogućnosti rekonstrukcije Francuskog paviljona u Zagrebu, Zavod za arhitekturu Arhitektonskog fakulteta Sveučilišta u Zagrebu, Zagreb, 1992.

[7] *** Francuski paviljon – prvih 70 godina, Bojan Baletić (ed.), Sveučilište u Zagrebu, Zagreb, 2007.

[8] *** *Godine*, časopis za kulturu, tematski broj posvećen Francuskom paviljonu, Vol. 8, No. 13/14, Studentski centar Sveučilišta u Zagrebu, Zagreb, 1997./1998.

Stanka Ostojić[1], Zoran Veršić[1], Iva Muraj[1]

Energy analysis and refurbishment strategy for Zagreb University buildings: former Faculty of Technology in Zagreb by Alfred Albini

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Abstract

In the year 2012 the University of Zagreb started the process of energy audits and energy certification of all university buildings with the intent to improve their energy performance. As a property owner, the University of Zagreb encompasses approximately 130 buildings (465,000 m^2). The first phase of this research project involves the audit of 23 faculty buildings, which make up 30% of all faculty buildings area belonging to the University. One of the largest buildings audited in the first phase is the building of the former Faculty of Technology in Zagreb built from 1958 to 1964 and designed by the esteemed 20th century Croatian architect Alfred Albini. This classic work is the last of Albini's accomplishments and is a protected cultural heritage monument. Today the building belongs to the Faculty of Food Technology and Biotechnology and the Faculty of Mining, Geology and Petroleum Engineering. The paper presents results of the energy audit and energy certification of Albini's modern architecture building and determines the energy balance in contemporary usage. The paper also suggests possible energy efficient improvement measures and profitability calculations.

Keywords: *energy audit; energy refurbishment; cultural heritage; former Faculty of Technology; University of Zagreb; Alfred Albini*

Introduction

The Republic of Croatia's Ordinance on Energy Audits of Construction Works and Energy Certification of Buildings[1] prescribes the introduction of energy audits of buildings which are necessary for determining energy performance and management in buildings with energy and water consumption, measures for energy-efficient improvements and their cost – effectiveness, and energy certification of buildings [1]. The ordinance also prescribes energy certification deadlines, which was for public use buildings with a total useable floor area greater than 1.000 m^2 scheduled for 31st December 2012. The deadline for buildings with the total use of floor area more than 500 m^2 was set on 31st December 2013, whereas for building exceeding 250 m^2 was 31st December 2015. Energy performance certificates provide information on the energy features of buildings and facilitate comparative analyses of buildings on the basis of their energy features, efficiency of their energy systems and the quality and features of their exterior walls. An energy performance certificate can be obtained only after a detailed energy audit of the building which also includes gathering the information necessary for energy efficiency evaluation. A building's energy consumption report contains conclusions, a chapter which lists recommendations and the order in which economically justified measures should be adopted in order to improve energy efficiency and energy performance of the building. The energy efficiency status of the building complex of the former Faculty of Technology was calculated using a software programme (*Toplinska zaštita Novolit 2009*) in 2013 according to valid technical regulations.

[1] Ordinance on Energy Audits of Construction Works and Energy Certification of Buildings (Official Gazette 81/12, 29/13, 78/13)

1. Refurbishment Strategy for Zagreb University Buildings

Given the legal requirement of the certification process, the University of Zagreb decided to perform energy audits of its faculty buildings. Altogether 32 faculties are housed in more than 130 buildings whose gross floor area amounts to approximately 412.000 m^2, which, if the buildings housing Rector's offices are included, reaches approximately 465.000 m^2.

The project of energy audit and certification of the university's buildings has been headed by a coordination team. The assignment of auditing was, however, entrusted to individual teams from the Faculty of Architecture, Faculty of Civil Engineering, Faculty of Electrical Engineering and Computing and the Faculty of Mechanical Engineering and Naval Architecture. The five teams consisted of one expert from each of the mentioned institutions. The first round of energy audits included the buildings of the eight following faculties: Faculty of Architecture, Faculty of Geodesy and Faculty of Civil Engineering which all share the building at 26 Kačićeva Street (gross floor area ~21.300 m^2), Faculty of Humanities and Social Sciences at 3 Lučićeva Street (~23.850 m^2), Faculty of Food Technology and Biotechnology and Faculty of Mining, Geology and Petroleum Engineering at 4 and 6 Pierottijeva Street (~17.150 m^2), Faculty of Electrical Engineering and Computing at 3 Unska Street (~43.100 m^2), Faculty of Mechanical Engineering and Naval Architecture at 1 and 5 Lučićeva Street (~30.570 m^2). The buildings of all these faculties make up more than 30% of the total floor area of all Zagreb University's buildings.

The buildings audited in the first phase are either located in the protected historical centre of the City of Zagreb or they are protected as individual immovable cultural properties. The first phase of the project of energy audit and certification began at the end of 2012.

2. Former Faculty of Technology in Zagreb

The former Faculty of Technology in Zagreb and the present Faculty of Food Technology and Biotechnology and the Faculty of Mining, Geology and Petroleum Engineering comprise two buildings: the building at 4 Pierottijeva Street and the building in 6 Pierottijeva Street that was constructed at a later date (Fig. 1, 2).

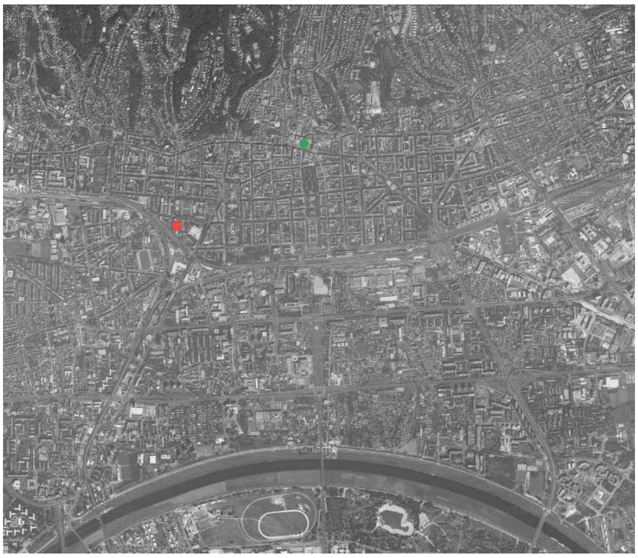

Fig. 1. Position of the former Faculty of Technology in Zagreb (red dot) and main city square of Ban Josip Jelačić (green dot). Source: Google Maps (https://maps.google.com/)

The older building at 4 Pierottijeva Street, which used to house the Society of Engineers and Technicians, was built in 1937 (architects M. Haberle and H. Bauer). Its L-shaped plan comprising ~1,138 m^2 gross floor area is divided into a south and north wing. The building has a ground floor, mezzanine and three storeys housing lecture halls and offices of the Faculty of Mining, Geology and Petroleum Engineering. All the building's architectural parts show the formal features typical for the period in which it was built: reinforced concrete skeleton and brick infill walls, plaster applied to internal and external walls with openings, multi-ribbed reinforced concrete floors and flat roofs. The southern and western gable walls are attached to the subsequently built structure designed by Alfred Albini[2].

[2]Alfred Albini was a Croatian architect (Graz, 1896 – Zagreb, 1978). He studied at Vienna's University of Technology (former Technishe Hochschule) in 1919, and graduated from the Polytechnic of Zagreb in 1923. From 1923 to 1962, he worked at the Faculty of Architecture in Zagreb, first as teaching assistant to Viktor Kovačić and later as professor. In the period from 1928 to 1964, Albini designed and completed several residential and commercial buildings: the Žerjavić Fundation House (Zagreb, 1928-1930/32), the building of the Town Savings Bank (Osijek, 1930), Meixner House (Zagreb, 1933), the Arko House (Zagreb, 1940), the Croatian Cultural Centre in Sušak (Rijeka, 1941), the Residential and Commercial Building in Zadar (1954) and the Faculty of Technology in Zagreb (1964). He was the laureate of the City of Zagreb Award (1962), Viktor Kovačić Award for life achievement (1966) and Vladimir Nazor Award (1968). [2] [3]

Fig. 2. Aerial view of the older building at 4 Pierottijeva Street (1) and subsequently added building at 6 Pierottijeva Street (2a – Large Building and 2b – Small Building). Source: Google Maps (https://maps.google.com/)

Albini was a prominent protagonist of Croatian modern architecture who moderately and creatively built on the tradition accepting numerous modernist impulses and integrating them in his personal architectural expression. He took special interest in the issues of urban planning and protection of cultural heritage and expressed his views in newspaper articles and theoretical papers. [4]

The building at 6 Pierottijeva Street, also a part of the former Faculty of Technology, was built in 1958-1964 according to the design by Alfred Albini. His associates on this project included A. Dragomanović, D. Ložnik, B. Krstulović, J. Meniga, and E. Erlich, the last of whom was also responsible for designing the architectural structure. Clearly demonstrating Albini's architectural signature this building, last in his career, forms part of the anthology of Croatian architecture and is today a protected cultural property.

It consists of two separate structures (Large and Small Building) elongated in the north – south direction and connected with two glazed volumes (Fig. 3). The two-storey Small Building comprises a gross floor area of ~2.994 m^2 and it has a basement, mezzanine and one storey. Large Building has a gross floor area of ~12,736 m^2 and, in addition to a basement and mezzanine, has six storeys and a machinery room on the flat roof. The ground floor of Small Building contains an entrance volume, library, student cafeteria with accompanying facilities while the first floor contains a large amphitheatre (lecture hall). Large Building consists of a central corridor and rooms facing west and east (seminar rooms, small lecture rooms, labs and offices), two staircases and lifts. The plan, which is based on a modular grid of 1.75 m, provides a functional spatial organisation and adaptability of the space on all floors (Fig. 4).

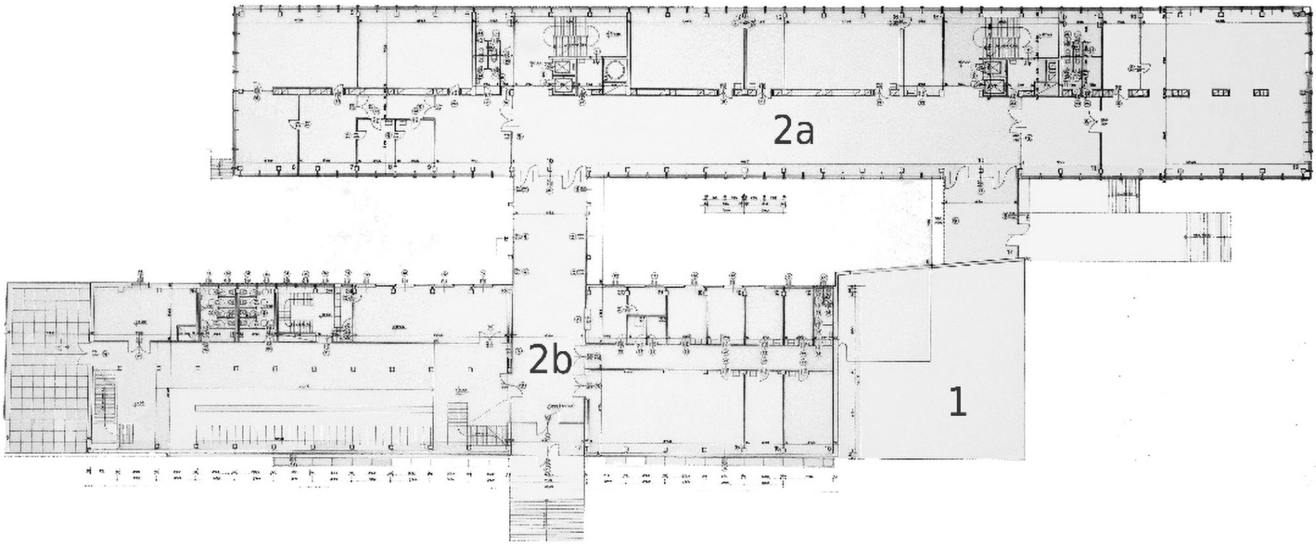

Fig. 3. Present situation of the former Faculty of Technology – Large and Small building (south-eastern façade)

Fig. 4. Ground floor plan of the former Society of Engineers and Technicians (1) and the former Faculty of Technology (2a – Large building, 2b – Small building). Source: Faculty of Food Technology and Biotechnology, University of Zagreb

Fig. 6. View of Large Building's north-western façade (present situation)

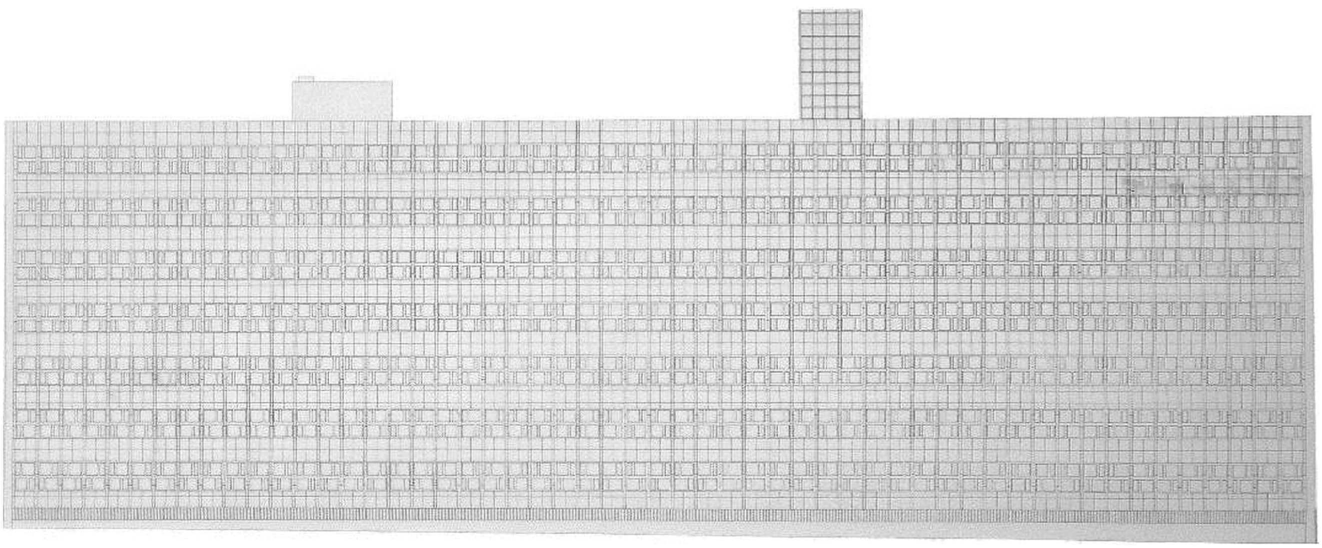

Fig. 5. Western façade of Large Building at 6 Pierottijeva Street (original Albini's drawing). Source: Faculty of Food Technology and Biotechnology, University of Zagreb

The wall bearing structure is a reinforced concrete skeleton composed of columns and transverse beams. The ceiling is constructed as a multi-ribbed reinforced concrete slab. The modular grid concept is adjusted to the façades and windows. The exterior walls of Large Building are coated with stone slabs placed at a distance from the main load bearing structure and supported by reinforced concrete elements. The façade pattern created by continuous alteration of windows and stone slabs, corners with contrastingly dark edges and window panes represent the main elements of the building's visual expression (Fig. 5, 6). [5] The facades of Small Building are all plastered except for the east façade which is coated with stone slabs rising up to the walls bellow mezzanine windows.

The process of determining architectural elements of the buildings included the use of original design plans created in 1958 by architect Albini as well as sketches and information collected during the energy audit of the buildings. [6]

Material components of architectural elements and their U-values[3] were presumed according to the construction date of audited buildings, which was the period 1958-1964.[4] [7]

3. Refurbishments Over the Years

The flat roof of Large Building was partially refurbished in the 1980s. However, since no surviving documents about the refurbishment could be found, it was impossible to determine which parts of the roof were repaired. The refurbishment included thermal insulation with 5 cm thick plates of mineral wool and covering of the substructure with corrugated sheet-metal. According to the building manager the roof leaked at places even after it had been refurbished. In the last several years, the leaks have been periodically repaired (in segments of about 50 m^2 depending on financial circumstances). These newly refurbished roof sections have not been thermally insulated but only covered with corrugated sheet-metal (ventilated covering).

The flat roof above the library in Small Building was refurbished in 2000 and in this case as well, the lack of documentation of this refurbishment made it difficult to precisely determine roof layers during the energy audit. For the purposes of calculation, the layers were presumed just as in the case of the roof on Large Building. The flat roof covering of the lecture hall was repaired in 2009. It was refurbished with a vapour barrier, a 10 cm polystyrene insulation layer and a synthetic waterproofing membrane.

Old deteriorated windows and doors were replaced with new double glazed aluminium or 5-chamber PVC windows and doors (1999-2009). Characteristics of PVC windows are: Uframe – value = 1.10 W/m^2K, Uglass – value = 1.40 W/m^2K with overall Uwindows – value = 1.31 W/m^2K.[5] Some openings have not yet been replaced and still have old wooden, aluminium or steel frames with extremely poor thermal characteristics.

Continued use of certain decayed openings and a periodical replacement of windows and doors resulted in the installation of various types of sun shading systems. The majority of openings have the interior sun protection mechanisms (venetian blinds) combined with heat reflective glazing. The exceptions are stairwells, sanitary facilities and spaces in the basement on the north, west and south facades of Large Building which do not have any sun protection systems. The openings on the south volume connecting Small and Large Building have also been left unprotected. The openings on the north volume – which connects the building at 4 Pierottijeva Street with Large Building – are protected from the sun with venetian blinds in the interior and fixed horizontal aluminium brise-soleils on the exterior. The calculation included the additional shading of individual openings with the neighbouring higher building or eaves.

The last reconstruction of Small Building in 2008 involved the removal of the door that served as wind protection (Fig. 7). Improper installation of some windows and the removal of the door resulted in increased air leakage at the building envelope which, consequently, led to greater energy consumption for heating and affected the feeling of comfort due to draught.

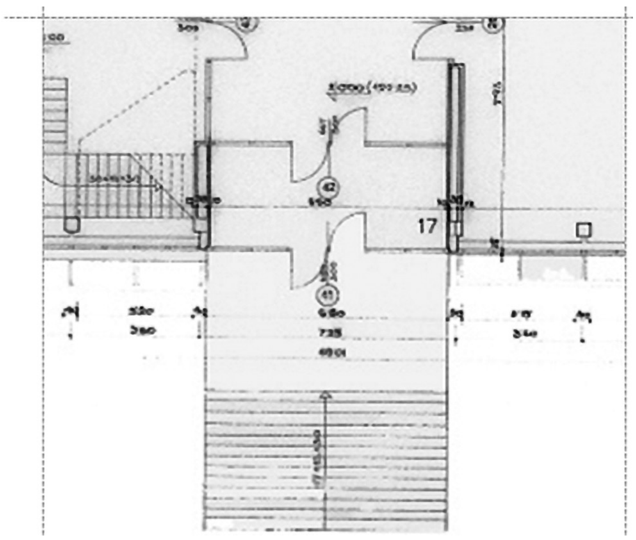

Fig. 7. Original Albini's ground floor plan of Small Building. The drawing shows the position of the wind-protection door which was removed in the 2008 reconstruction of the building. Source: Faculty of Food Technology and Biotechnology, University of Zagreb

[3] U-value is the coefficient of heat transmission or thermal transmittance [W/(m^2K)].
[4] *** (2012a): 68-73

[5] According to Technical Regulation on Rational Use of Energy and Heat Retention in Buildings (OG 110/08, 89/09, 79/13, 90/13) the biggest permitted U-value for translucent façade elements on buildings heated at +18°C or more is 1.80 W/(m^2K). [8]

4. Calculation of the Building's Energy Performance

Regardless of specific purposes of each of the described buildings, they are considered as a whole when speaking about thermal protection and energy savings. The amount of thermal energy required for heating of the building has been calculated according to the currently valid Croatian norms.

The energy efficiency status of the building complex of the former Faculty of Technology was calculated using a software programme (*Toplinska zaštita Novolit 2009, version.1.06*). The required amount of thermal energy for heating was calculated according to the HRN EN ISO 13790 standard[6]. The calculation included the climate data provided by the Zagreb Maksimir Weather Station, and the average climate data for continental Croatia[7]. [9] [10]

All the rooms except for certain labs and chemical storage rooms were defined as heated spaces. In order to simplify the procedure the calculation of ventilation losses included an assumed natural ventilation of all spaces although some lecture rooms have been ventilated through mechanical systems enabling thereby waste heat recovery. Thermal bridges were also taken into consideration and the calculation of linear heat losses included defined types of thermal bridges and a selection of suitable details from a catalogue of thermal bridges[8].

The defined heat losses comprised the losses through exterior walls, walls adjacent to unheated spaces, openings, flat roofs, portions of ceilings that are cantilevered beyond the exterior wall, ceilings over unheated spaces, floors on the ground and foundation walls above the ground level. The total amount of energy required for heating was calculated on the basis of the following entry data: heating regime of 10 hours per day, 7 days a week with the estimated average indoor temperature of 20°C.

According to the calculation of the overall thermal energy necessary for heating, which amounts to 30.8 kWh/m^3a, the building belongs to the E energy efficiency class[9].

[6] Technical Regulation on Rational Use of Energy and Heat Retention in Buildings (OG 110/08, 89/09, 79/13, 90/13) determines that the level of heat protection and energy saving is calculated by the annual thermal energy required for heating buildings whereas the energy spent on cooling, lighting etc. is disregarded.
[7] The building's energy consumption is (for the purposes of energy certification) calculated on the basis of climate data for specific weather station and reference climate data for a certain region.
[8] The catalogue contains illustrations of successfully reduced or eliminated thermal bridges and is an integral part of the new Technical Regulation on Rational Use of Energy and Heat Retention in Buildings (OG 97/14). [11]
[9] The maximum permitted amount of energy used for heating buildings is 17.2 kWh/m^3a.

5. Architectural Measures for Energy-efficient Improvements

The results obtained through the calculation of energy required for heating and the recognized energy saving potential formed the foundation of the proposal of architectural measures for energy-efficient improvements. Each measure, and the way it contributes to energy efficiency, corresponds to the specific calculation of the amount of energy required for heating. The results have been compared to the existing conditions and the return on investment periods have been estimated for each of the proposed measures (Table 1). [6] In addition to the proposed architectural measures, energy-efficient improvements are possible to achieve with the measures that are related to mechanical and electric installation equipment.

The calculated savings of the required heating energy, reduction of carbon emission and the return on investment period lead to the conclusion that the most suitable energy-efficient improvement measure for the buildings is M7. It comprises the M1, M3 and M5 measures: thermal insulation of walls and roofs, replacement of old windows and doors and installation of a door for wind protection (Table 2).

Exterior walls make a considerable part of the building envelope[10] and a lack of thermal insulation of the walls presents the problem of a great heat loss. Since the building complex of the former Faculty of Technology is an immovable cultural property, refurbishment of the existing exterior walls from the outside was not an option. An additional reason for proposing refurbishment of the exterior walls from the inside may be the fact that the infill walls are recessed in relation to the load-bearing reinforced concrete structure of Large Building and as such they form niches in the interior spaces which contain radiators. A great number of radiators were made from cast iron with no thermostatic valves which prevents the regulation of heat in individual spaces.[11] Installation of thermal insulation on the Large Building's infill walls from the inside would not present a barrier in the interior. The installation can therefore be done simultaneously with the replacement of the old and outdated radiators.

This measure also includes thermal insulation of infill walls in Large Building with 15 cm thick plates of mineral wool which could improve thermal characteristics of the walls and reduce the U-value from 4.00 W/(m^2K) to 0.22 W/(m^2K). (Fig. 8) The building could thereby meet the standard set by the Technical Regulation on Rational Use of Energy and Heat Retention in Buildings for the highest permitted value of the U-value for exterior walls is $U \leq 0.45$ W/(m^2K).

[10] The surface of infill walls between the load-bearing reinforced concrete parts in the exterior walls (columns and beams) of Large Building is 2.606 m^2. The overall surface of the exterior envelope of Large Building is 7.160 m^2.
[11] One of the proposed engineering measures is the replacement of old and outdated radiators.

Table 1: Architectural measures and achieved savings

Architectural Measure	Measure Description	$Q'_{H,nd}$ [b] [kWh/m³a]	Energy Efficiency Class [-]	Carbon Dioxide Emission [$kgCO_2/a$]	Return on Investment Period [years]
Existing Condition	/	30.8	E	404.360	/
M1	Thermal insulation of walls[a]	20.4	D	267.840	3.0
M2	Replacement of decayed windows and doors	28.5	E	372.935	7.3
M3	Thermal insulation of roofs	29.8	E	390.445	38.8
M4	M1 + M2 + M3	17.0	C	223.410	6.5
M5	Replacement of decayed windows and doors and installation of door for wind protection	26.8	E	351.750	8.4
M6	M1 + M3	19.4	D	253.890	6.3
M7	M1 + M3 + M5	15.5	C	202.915	6.0
M8	M1 + M2	18.1	D	237.135	3.8

[a] Measure M1 proposes thermal insulation of the inner side of the exterior walls of Large Building in order to avoid changes in the original appearance of the facades.
[b] Specific annual requirement of heating energy; maximum allowed = 17.2 [kWh/m³a]

Table 2: Calculated U-values of envelope structures and elements

Type of Envelope Structures and Elements		U-value [W/(m²K)]	U-value[a] [W/(m²K)]	U_{max}-value[b] [W/(m²K)]
VZ1	load-bearing parts in exterior wall (columns and beams)	2.75	–	0.45
VZ2	infill walls	4.00	0.22	0.45
VZ3	building plinth	3.15	–	0.45
VZ4	stone coated wall (Small Building)	4.35	–	0.45
VZ5	infill wall (Small Building)	1.55	–	0.45
VZ6	exterior wall or wall adjacent to unheated space	3.10	–	0.45
VZ7	partition wall adjacent to unheated space	2.60	–	0.45
K1	refurbished flat roof – corrugated sheet-metal covering	0.55	0.25	0.30
K2	refurbished flat roof – membrane covering	0.30	0.30	0.30
K3	flat roof (building at 4 Pierottijeva Street)	1.95	0.25	0.30
K4	flat roof – terrace	1.70	–	0.30
S1	ceiling above unheated space	1.20	–	0.30
S2	ceiling above open space	1.20	–	0.30
S3	ceiling adjacent to unheated space	1.45	–	0.50
P1	ground floor	2.55	–	0.50
VR1	aluminium exterior door or door adjacent to unheated space	2.00	–	2.90
VR2	wooden door adjacent to unheated space	2.00	–	2.90
VR3	PVC exterior door or door adjacent to unheated space	2.00	–	2.90
PR1	new windows (aluminium frame)	1.60	–	1.80
PR2	new windows (PVC frames)	1.30	–	1.80
PR3	old windows (aluminium frame)	2.90	1.30 (PVC frames)	1.80
PR4	old windows (steel frame)	5.90	1.61 (aluminium frames)	1.80
PR5	old windows (wooden frame)	3.40	1.30 (PVC frames)	1.80

[a] U-values calculated after implementing M7 architectural measure
[b] According to Technical Regulation on Rational Use of Energy and Heat Retention in Buildings (OG 110/08, 89/09, 79/13, 90/13)

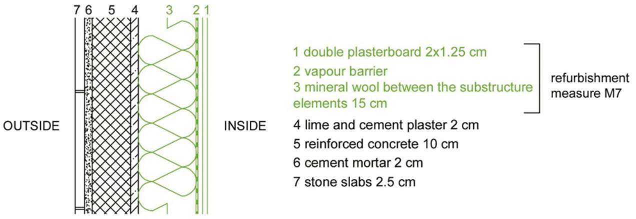

Fig. 8. Refurbishment of the infill walls in Large Building proposed by M7 measure (green colour marks the layers added in the course of refurbishment).

Heat losses through the uninsulated flat roof cause a great problem in the overall energy balance of the buildings belonging to the former Faculty of Technology. An additional reason for the roof refurbishment can be found in frequent problems with rainwater leakage in Large Building. The M7 measure therefore proposes refurbishments of the flat roofs: replacement of the existing waterproof membrane with a new one (Fig. 9). The waterproof layer would be topped by 12 cm thick plates of mineral wool between the metal substructure elements. It is necessary to protect the mineral wool from the ventilated air layer with a rain barrier and to reinstall the existing corrugated sheet-metal roof. Since the decayed openings (wooden windows, steel doors and windows and aluminium windows) on façades of the former Faculty of Technology cause increased heat losses, the problem can be solved by the application of the M7 measure. It proposes the replacement of old and worn out elements and the installation of PVC double glazed windows and doors with Low-E coating whose U-value equals 1.31 W/(m^{2}K). (Fig. 10)

The exception is the eastern entrance into Small Building, built as a single glazed glass wall with steel frames which does not meet the present heat retention standards. The M7 measure proposes the replacement of this glass wall with a new one: double glazed, with aluminium

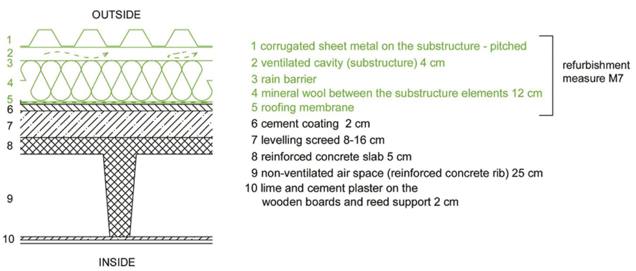

Fig. 9. Flat roof refurbishment proposed by the M7 measure (green colour marks the layers added in the course of refurbishment)

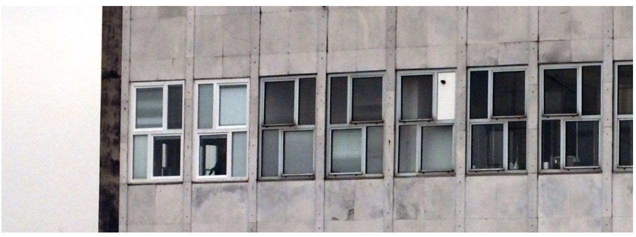

Fig. 10. A part of Large Building's northern façade (present situation)

frame, thermal break, Low-E coating and the overall U-value of 1.61 W/(m^{2}K). The measure also includes the application of sealants on each door and window if they have been warped due to long-time use and UV radiation exposure, which could help in achieving a better level of envelope air tightness.

In addition to the replacement of decayed openings the M7 measure envisages the construction of a door for wind protection or the installation of glass partition between Small and Large Building (within the south volume connecting those two buildings). This would lead to the reduction of ventilation losses which currently contribute to the considerable difference in the temperature of 4°C between the corridor, offices and classrooms. The wind-protection door would also reduce the air flow rate (and ventilation losses) in both Small and Large Building. The adoption of this measure envisages decreased air flow rate from 1.0 [h-1] to 0.60 [h-1].

Conclusion

Based on the energy audit and calculation the buildings formerly housing the Faculty of Technology (architect Albini) and the Society of Engineers and Technicians (architects Haberle and Bauer) belong to the energy efficiency class E and their values do not meet the standards proscribed by the Technical Regulation on Rational Use of Energy and Heat Retention in Buildings.

The proposed architectural measures for energy-efficient improvements have taken into consideration the fact that the building of the former Faculty of Technology is a protected cultural property. Comparative analysis has been conducted with the results of only those architectural measures whose application does not disturb the original appearance of the façade of Albini's building. The calculated savings of the required energy for heating, carbon emission reduction and the return on investment period lead to the conclusion that the most suitable energy-efficient improvement measure for the buildings is M7. It includes thermal insulation of the inner surface of Large Building's exterior walls, thermal insulation of all flat roofs, replacement of the remaining decayed windows and doors and the installation of a door for wind protection.

In addition to energy savings and decrease in maintenance costs, implementation of energy-efficient improvement measures contributes to a better quality of life and work of people and extends the lifetime of building.

References

[1] Pravilnik o energetskim pregledima građevina i energetskom certificiranju zgrada (NN 81/12, 29/13, 78/13) / Ordinance on Energy Audits of Construction Works and Energy Certification of Buildings (OG 81/12, 29/13, 78/13)

[2] Uchytil, A.; Šerman, K.; Barišić Marenić, Z. (2010), Arhitekt Alfred Albini – rani radovi / Architect Alfred Albini – Early Works, "Prostor", 18[2010], 1[39]: 80-91, Zagreb

[3] Uchytil, A.; Barišić Marenić, Z.; Kahrović, E. (2011), Lexicon of Architects – Atlas of 20th Century Croatian Architecture, Sveučilište u Zagrebu, Arhitektonski fakultet: 10-13, Zagreb

[4] Uchytil, A.; Štulhofer, A. (2007), Arhitekt Alfred Albini / Architect Alfred Albini, Sveučilište u Zagrebu, Arhitektonski fakultet, Zagreb

[5] Čavlović, M.; Uchytil, A. (2013), Arhitektonske kompozicije Alfreda Albinija / Architectural Compositions of Alfred Albini, "Prostor", 21[2013], 1[45]: 26-43, Zagreb

[6] Carević, I.; Duplančić, V.; Raič, S., (2013), Izvještaj o provedenom energetskom pregledu građevine Rudarsko-geološko-naftni fakultet i Prehrambeno-biotehnološki fakultet Sveučilišta u Zagrebu, Pierottijeva 4 i 6, Zagreb / Report on Energy Audit of the Faculty of Mining, Geology and Petroleum Engineering and Faculty of Food Technology and Biotechnology at 4 and 6 Pierottijeva Street, Zagreb

[7] *** (2012a), Metodologija provođenja energetskog pregleda građevina / Methodology of Conducting Energy Audit of Buildings, MGIPU, Zagreb

[8] Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama (NN 110/08, 89/09, 79/13, 90/13) / Technical Regulation on Rational Use of Energy and Heat Retention in Buildings (OG 110/08, 89/09, 79/13, 90/13)

[9] *** (2010), Priručnik za energetsko certificiranje zgrada / Handbook for buildings energy certification, [eds. Pavković, B.; Zanki, V.], UNDP, Zagreb

[10] *** (2012b), Priručnik za energetsko certificiranje zgrada – dio 2 / Handbook for buildings energy certification – part 2, [eds. Pavković, B.; Zanki, V.], UNDP, Zagreb

[11] Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama (NN 97/14) / Technical Regulation on Rational Use of Energy and Heat Retention in Buildings (OG 97/14)

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Nearly Zero-Energy Buildings in Croatia: Comparison of Thermal Performance in Different Climatic Regions

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Abstract

In recent years energy efficiency has become one of the most challenging themes for architects around the world. Energy problems and climate changes are more and more in charge of the future development of architecture. Energy-efficient approaches are incorporated into architecture as technical innovations, a particular use of materials based on the location or as utilisation of climatic conditions. Consequently, it is interesting to see what is actually built and how architects approach architectural themes in relation to climate and energy in Croatia.

The paper presents a national approach to Nearly Zero-Energy Buildings (nZEB) and way in which to meet the EU 2020 energy and climate policy targets. This research focuses on the evaluation of energy-efficient design strategies of residential buildings in different climatic regions of Croatia.

Keywords: *Energy Performance of Buildings, nZEB, Residential Buildings, Climate Regions, Croatia*

1. Introduction

Energy efficiency has become one of the most challenging themes for architects around the world. Energy problems and climate changes are increasingly becoming in charge of the future development of architecture. New technologies, new materials and changes in social structures have changed the way buildings have been designed and constructed. Today, new energy sources are necessary for architecture to develop, as the housing we build today will remain standing for at least 50 years.

As energy efficiency becomes an important aspect in building design, all participants in the building sector are confronted with numerous regulation changes in the field of energy efficiency. Consequently, it is interesting

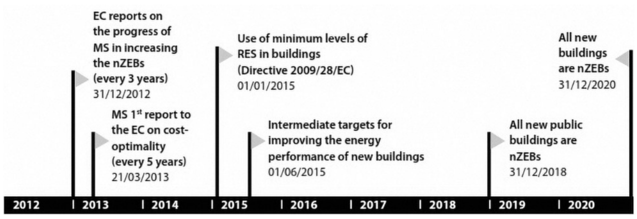


Fig. 1. Key years for nearly Zero-Energy Buildings (Directive 2010/31EC). [1]

to see how architects approach architectural themes in relation to climate and energy in Croatia.

The paper does not offer an answer to what energy efficient architecture should be, but rather asks the question: How do we design and build architecture with low energy consumption? The paper brings forth an evaluation of energy efficient design strategies of residential buildings in different climatic regions of Croatia.

2. EU 2020 Energy and Climate Policy Targets

The building sector holds high potential for energy demand reduction. As a measure to realize this potential, the European Parliament approved the Directive on the Energy Performance of Buildings in 2010 (*Energy Performance of Buildings Directive 2010/31/EU EPBD*). All the member states of the European Union have an obligation to reduce energy consumption by 20% by the year 2020. Each member state needs to develop a national scheme for achieving the required level of energy savings, in a way that best suits respective national circumstances and is at the same time in line with the common EU goals related to energy savings.

Nearly zero-energy buildings (nZEB) have very high-energy performance. The low amount of energy that these buildings require comes mostly from renewable sources.

The Energy Performance of Buildings Directive requires that after 31 December 2020, all new buildings in the EU will be nearly zero-energy buildings and member states should stimulate the transformation of the existing buildings under refurbishment into nearly zero-energy buildings. For public buildings the deadline is set for 31 December 2018. Although the concept of "nearly zero-energy buildings" is not defined, the objective of this directive is to promote design of buildings with improved energy performance in all EU member states. EU countries have to draw up national plans to increase the number of nearly zero-energy buildings.

2.1. National Approach to Nearly Zero-Energy Buildings

Climate and energy are closely bound together. The greater part of the CO_2 emitted in Croatia – and in the world in general – comes from energy consumption in buildings. The government has a long-term vision of making Croatia completely independent of fossil fuels. What is required to fulfil this vision is both political actions and actions on the part of individual citizens. The Republic of Croatia's Energy Strategy is focused on the period before 2020, which corresponds to the period covered by all adopted EU energy strategies. This facilitates the comparison between national goals and EU goals. Buildings account for as much as 42.3% of the total energy consumption. Therefore, reaching the goal will require a concerted effort to reduce energy consumption in buildings. Households are the largest individual energy consumers in Croatia, about 30% of the overall final energy consumption, and the largest users of electricity, over 40% of the overall final electricity consumption. The energy efficiency policy in the residential building sector is based on raising public awareness of possible savings and incentives to plan and build residential buildings in harmony with the principles of energy efficiency [2].

As an EU member state, Croatia has honoured its obligation of establishing the nearly zero-energy building standard (nZEB) and has laid down requirements in the document entitled *Technical Regulation on the Rational Utilisation of Energy and Thermal Insulation of Buildings* (Official Gazette 128/2015) which has been in effect since 1 January 2016 [3]. The Technical Regulation sets the deadline for design of nearly zero-energy buildings, which is 31 December 2020. From that date, all new buildings must be nearly zero-energy, while the deadline for the new buildings that are owned by public institutions is 31 December 2018.

In addition to new buildings constructed in line with the Long-Term Strategy for Mobilising Investment in the Renovation of the National Building Stock of the Republic of Croatia (OG 74/2014), the building renovation model following the nZEB standard was chosen as cost-effective. According to said strategy, apartment buildings and family houses in continental and coastal areas of Croatia are expected to undergo refurbishment in accordance with the standard from 1 January 2021.

Numerical requirements for the annual thermal energy demand for heating and the annual primary energy are different depending on the type and uses of individual buildings. These values have been determined by the Technical Regulation. According to the document, residential buildings are divided into family and apartment houses. A family house is a residential building with the maximum of three individual housing units and with the gross floor area less than or equal to 600 m^2. An apartment building is a residential building with four or more apartments.

Nearly zero-energy buildings must also meet the requirement of relying on renewable energy sources for at least 30% of the annual primary energy supply.

Table 1. The highest allowed values for new buildings and nearly zero-energy buildings heated and/or cooled to the temperature of 18 °C or more. [3]

requirements for new buildings and nZEBs	$Q''_{H,nd}$ [kWh/(m^{2}a)]						E_{prim} [kWh/(m^{2}a)]			
	new buildings and nZEBs						new buildings		nZEBs	
building category	continental zone, $\Theta_{min} \leq 3°C$			coastal zone, $\Theta_{min} > 3°C$			contin. $\Theta_{min} \leq 3°C$	coast $\Theta_{min} > 3°C$	contin. $\Theta_{min} \leq 3°C$	coast $\Theta_{min} > 3°C$
	$f_0 \leq 0{,}20$	$0{,}20 < f_0 < 1{,}05$	$f_0 \geq 1{,}05$	$f_0 \leq 0{,}20$	$0{,}20 < f_0 < 1{,}05$	$f_0 \geq 1{,}05$				
apartment build.	40,50	32,39+40,58f_0	75,00	24,84	19,86+24,89f_0	45,99	120	90	80	50
family house	40,50	32,39+40,58f_0	75,00	24,84	17.16+38,42f_0	57,50	115	70	45	35

2.2. Climatic Conditions in Croatia

Meteorological and climate data are important for modelling energy consumption in buildings. Croatia's climate is determined by its geographical position in the northern temperate zone, which is in terms of relief characterised by a mixture of mountains, plains, forest and a long littoral belt. The topography of Croatia is geographically diverse and climatic conditions are not uniform, which makes analyses and estimations of energy saving possibilities in the residential building sector a complex matter. A specific feature of Croatia's housing stock is rationality, which can be defined in terms of climatic conditions. The northern, north-western and eastern parts of Croatia have a continental climate, and this area, together with the central part of the country which has an alpine climate accounts for 64% of the housing stock. The coastal area (Istria, Kvarner bay and Dalmatia) with a Mediterranean climate accounts for the remaining 36%. The annual amount of energy needed for heating homes therefore varies considerably by location.

The first regulation on thermal insulation of buildings, introduced in 1970 (*Ordinance on Technical Measures and Conditions for Thermal Insulation of Buildings* – Official Gazette of the Socialist Federal Republic of Yugoslavia 35/70) divided the Croatian territory into three building climate zones. Each zone had the highest allowed U-values (W/m^{2}K) prescribed for individual elements of the exterior building envelope. The division stemmed from general climatic conditions and the temperatures in the coldest months of the year. The division had been in use until early 2006, when the new *Technical Regulation on Thermal Energy Savings and Thermal Insulation in Buildings* (OG 79/2005) was implemented. From then on, the Republic of Croatia was divided into two zones. The first included cities and places whose average outdoor air temperature of the coldest month measured at the building's location was ≤ 3°C. The second comprised cities and places whose average temperature of outdoor air of the coldest month at a building's location was >3°C, which in fact corresponded to the continental and costal climate zones. *The Ordinance on Energy Certification of Buildings* (OG 113/2008) introduced a new division into two zones: the continental and coastal climate zones. This division was based on the number of heating degree days in a year. There were cities and places in the continental climate zone that had 2200 and more heating degree days per year, and in the coastal climate zone that had 2200 and less heating degree days per year.

The currently adopted *Ordinance on Energy Audits and Energy Certification of Buildings* (OG 88/2017) has divided the country into zones according to the monthly average outdoor air temperature of the coldest month measured at the location of a building. The continental climate zone now includes cities and places whose average monthly outdoor air temperature of the coldest months measured at the location of the building is ≤3°C. The coastal climate zone includes cities and places whose average monthly outdoor air temperature of the coldest months measured at the location of the building is >3°C

Since 2006, climatic data used for the calculation of energy performance of buildings could be found enclosed in the *Technical Regulation on the Rational Utilisation of Energy and Thermal Insulation of Buildings* (OG 128/2005). Since 2015 meteorological data comprising meteorological values measured at authorised weather stations, which are necessary for calculations based on physical building features in terms of rational energy consumption and thermal insulation, have been published on the web site of the Ministry of Construction and Physical Planning [4]. Considering the great difference between the climate zones in Croatia, the difference can also be discernible in the energy performance of buildings in individual zones.

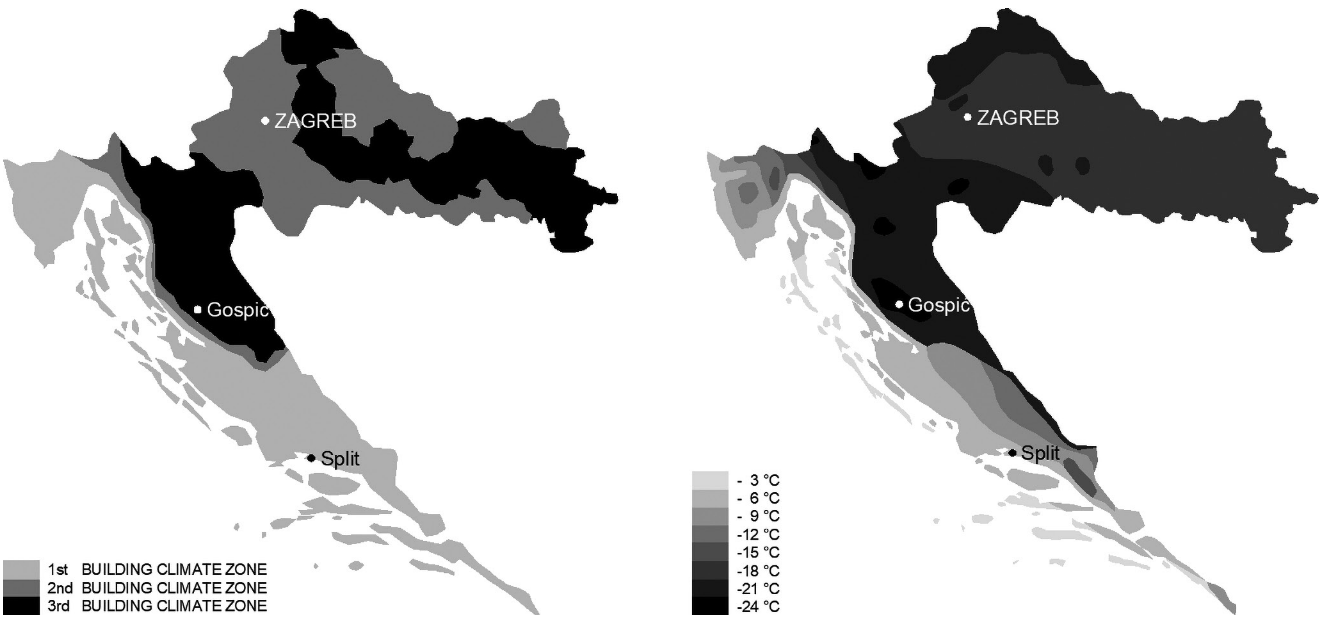


Fig. 2. Division of the Republic of Croatia into three building climate zones (left). Outdoor design temperatures (right). [8]

3. Chosen Models of Residential Buildings

For the purposes of this study, the authors compared energy performance of a model of the reference family house and a model of the reference apartment building, both of which are located in Gospić and Split, two cities with extremely different climatic features. The lowest temperature in the coldest month in Gospić is -17.2°C, and in Split -3°C. The global irradiance values (southern orientation, 30°) for Gospić is 4930 MJ/m^2, and for Split 6295 MJ/m^2 [6]. The analysis was done in line with the current Technical Regulation and with the use of En-Cert-HR v.2.37 software.

All the models of the reference buildings have favourable surface-to-volume ratio, which means that the surface area of their external envelope (parts of the building that separate the interior from the exterior and unheated spaces) is relatively small compared to the volume of the heated space of the building. In contrast to buildings with complex plans, compact buildings have smaller surface area through which heat can escape, which consequently reduces heating energy consumption as well as construction prices.

The model of the family house is a one-storey house with a loft and covering 160 m^2 of the useful floor area. The dominant orientation of the rooms is on the east-west axis. The south-facing side would be the most suitable for using solar gains in winter. However, statistically, the more frequent are east or west oriented buildings, which have been adopted as the assumed orientation of the models of the family houses and apartment buildings. The apartment building is a four-level structure with four apartments on each floor connected by an inner staircase, all levels are used for housing purposes and apartments covering floor area between 42 and 60 m^2. Half apartments have two-sided orientation, and half are only east or west facing [7].

3.1. Research Results

The use of the structural elements in the models complies with the requirements of the Technical Regulation (OG 128/2015). The thickness of specific insulation materials corresponds exactly to the values prescribed by the Technical Regulation. Thicker insulation materials would improve energy efficiency, but would also raise the construction price and would result in a longer return on investment. Using thermal insulation twice the size prescribed by the Regulation would decrease the heating energy demand per square unit of the useful floor area Q’’H,nd (kWh/(m^{2}a) for the family house in Gospić by

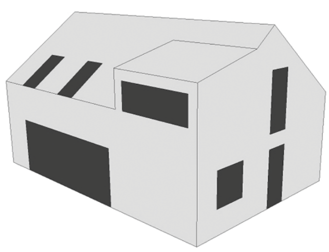
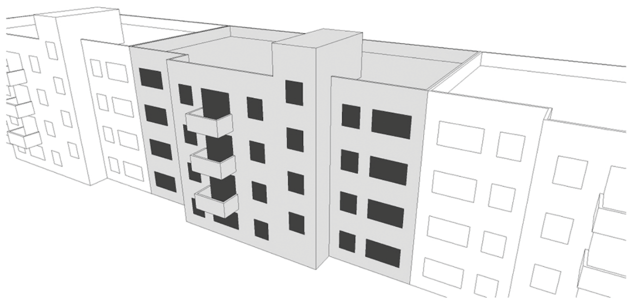
Models of reference residential buildings in Gospić and Split	
	
model of the reference family house surface-to-volume ratio = 0,79 m^{-1} usable floor area = 160 m^2 1 housing unit	model of the reference apartment building surface-to-volume ratio = 0,46 m^{-1} usable floor area = 886 m^2 16 housing units, usable floor area = 42-60 m^2

Fig. 3. Chosen models of the reference family house and the reference apartment building.

Table 2. Structural elements: description, real and the highest allowed U-values.

Structural element	Structural element description	U [W/m^{2}K]	U_{max} [W/m^{2}K]	
			Gospić	Split
Exterior wall	Clay block wall / Reinforced concrete insulated with 12 cm ETICS EPS	0,27-0,30	0,3	0,45
Slanted roof	Wooden roof insulated with 12 cm MW between the rafters + 5 cm MW in dropped ceiling	0,23	0,25	0,3
Flat roof	RC slab insulated with 15 MW	0,23	0,25	0,3
Ground bearing floor	Concrete slab isolated with 8 cm EPS + 2 cm EEPS	0,33	0,4	0,5
Windows	PVC window with double-glazed insulated windows one LOW-E pane, filled with argon gas, shutters	1,28	1,6	1,8

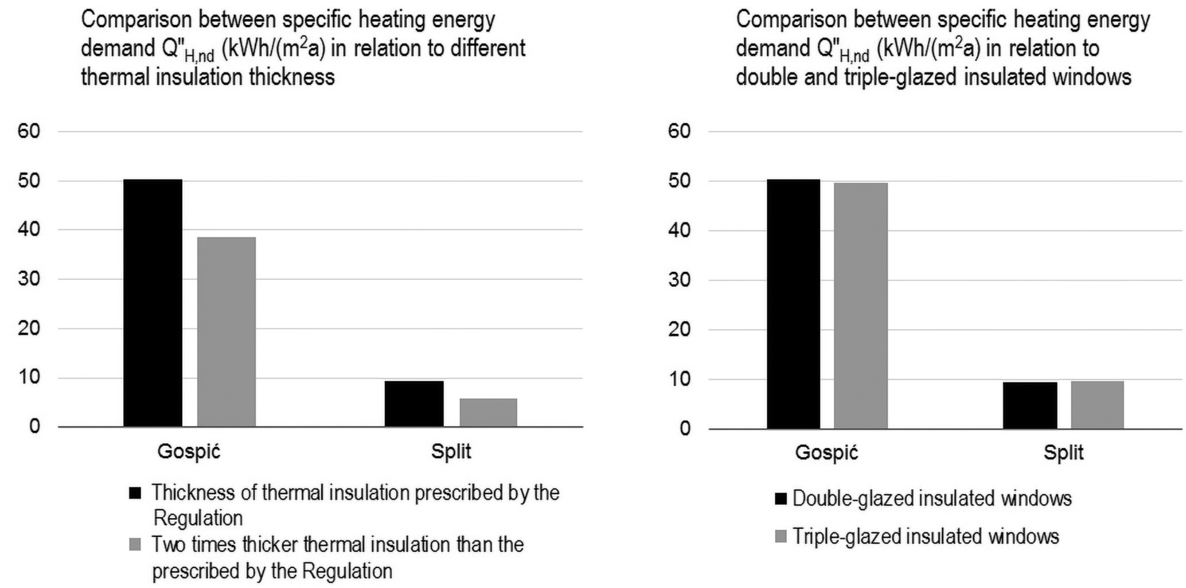


Fig. 4. Comparison between specific heating energy demand Q”H,nd (kWh/(m²a) in relation to different thermal insulation thickness and in relation to double and triple-glazed insulated windows on the family houses in Gospić and Split.

23.3% and for the house in Split by 37.8%. Although the percentages represent considerable savings, the difference in the annual cost of heating is still relatively small in relation to the initial investment.

Due to higher prices of windows than walls, the average size of glazed surfaces on family houses and apartment buildings does not exceed the dimensions of most commonly used windows. When the total amount of glazing on building envelopes is relatively low, heating costs, which would be saved by the use of triple-glazed insulated windows, would be very small, which would also result in a long return on investment. For the house in Gospić, the annual savings of heating and cooling would rise by 1.5%, and for the house in Split, the costs would actually increase by 2.5% per year. For buildings with large glazed surfaces and different orientation the impact would be much higher as well as the cost-effectiveness of triple glazing installation.

In addition to heat loss due to transmission through walls, windows, floors and the roof, a considerable amount of heat loss is due to ventilation. In comparison with naturally ventilated family houses, the use of 80% efficient heat recovery ventilation system reduces the thermal energy demand for heating per square unit of the useful floor area for the family house Q”H,nd (kWh/(m²a) in Gospić by 36.2% and of the house in Split by 56.7%.

For the houses with average or low energy consumption such systems are rarely cost-effective, but necessary when lower consumptions is wanted. Cost-effective benefits of using heat recovery ventilation during heating seasons can exceed 20 years for the house in Gospić and 80 years for the house in Split.

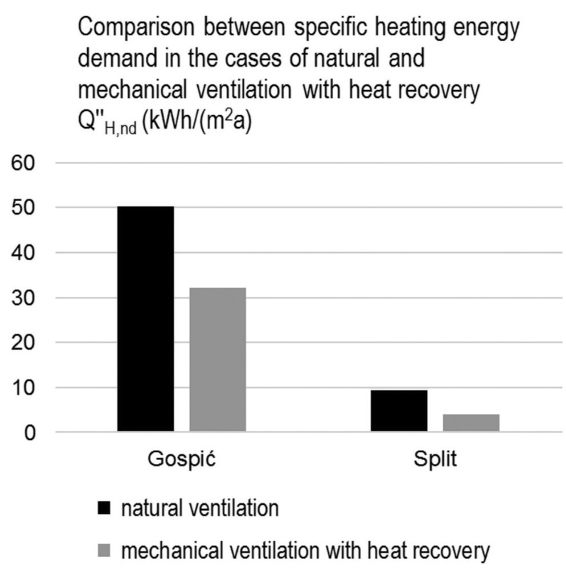


Fig. 5. Comparison between specific heating energy demand in the cases of natural and mechanical ventilation with heat recovery in the family houses in Gospić and Split.

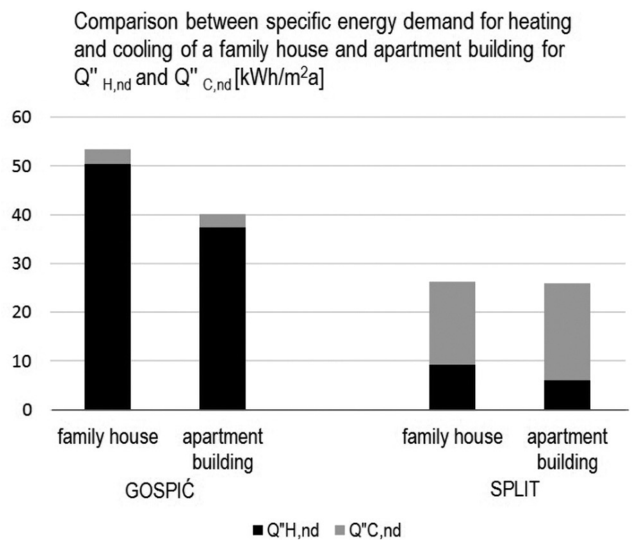


Fig. 6. Annual amount of energy needed for heating (Q” H,nd) and cooling (Q” C,nd) per square unit of useful floor area based on real climatic data for a family house and apartment building in Gospić and Split.

Table 3. Comparison between the annual thermal energy demand for heating (Q" H,nd) and cooling (Q" C,nd) per square unit of useful floor area based on actual climate data for the family houses and apartment buildings in Gospić and Split.

Building category	$Q''_{H,nd}$ (kWh/(m²a))		$Q''_{C,nd}$ (kWh/(m²a))	
	Gospić	Split	Gospić	Split
Family house	50,36	9,27	3,10	17,06
Apartment building	37,33	5,98	2,75	19,99

In the comparison between the values of annual thermal energy demand for heating per square unit of useful floor area of buildings based on actual climate data Q"H,nd (kWh/(m²a)), it has been shown that the naturally ventilated family house in Gospić (continental climate zone) demands 5.4 times more energy for heating in order to create the same microclimatic conditions as the house in Split (coastal climate zone), which has the same orientation and the same characteristics of construction elements.

In the comparison between the values of the annual thermal energy demand for cooling per square unit of useful floor area of buildings Q"C,nd (kWh/(m²a)), the results show that the family house with an installed cooling system in Split needs 5.5 times more thermal energy for cooling in order to create the same microclimatic conditions.

In a comparison between the total values of the annual thermal energy demand for heating and cooling per square unit of useful floor area for identical family houses, it has been shown that the family house in Gospić needs 2.0 times more thermal energy than the family house in Split.

The comparison between the values of annual thermal energy demand for heating per square unit of useful floor area based on actual climate data Q"H,nd (kWh/(m²a)) has produced the following results. The naturally ventilated apartment building in Gospić in relation to the same apartment building in Split needs 6.2 more thermal energy for heating for the creation of the same microclimatic conditions. When the values of the annual thermal energy demand for cooling per square unit of useful floor area of buildings Q"C,nd (kWh/(m²a)) are compared, the results show that the apartment building with a cooling system in Split needs 7.3 more thermal energy for cooling in order to create the same microclimatic conditions as the identical building in Gospić.

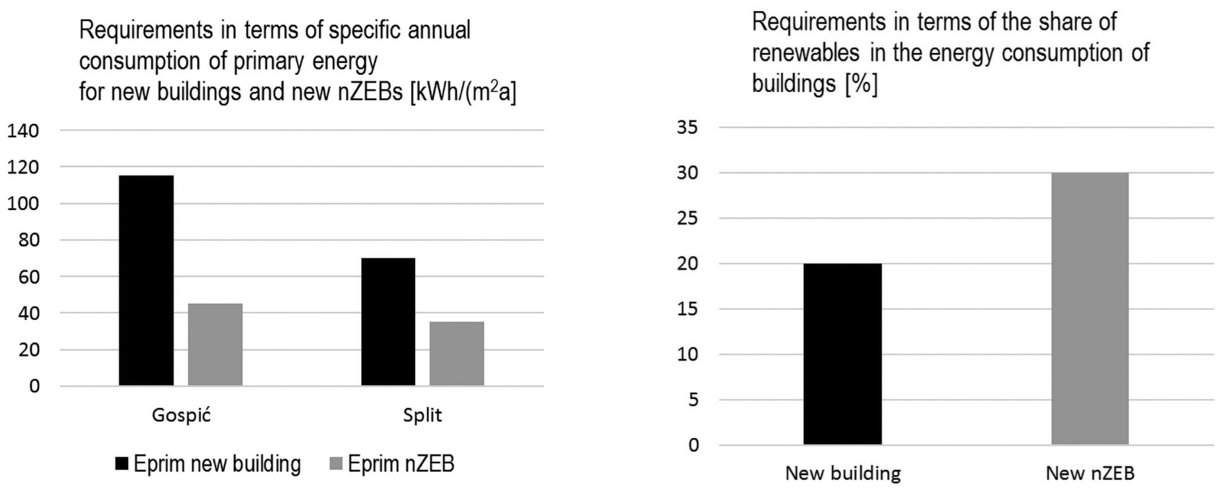


Fig. 7. Requirements in terms of specific annual consumption of primary energy for new buildings and new nZEBs [kWh/(m²a] and in terms of the share of renewables in the energy consumption of buildings [%].

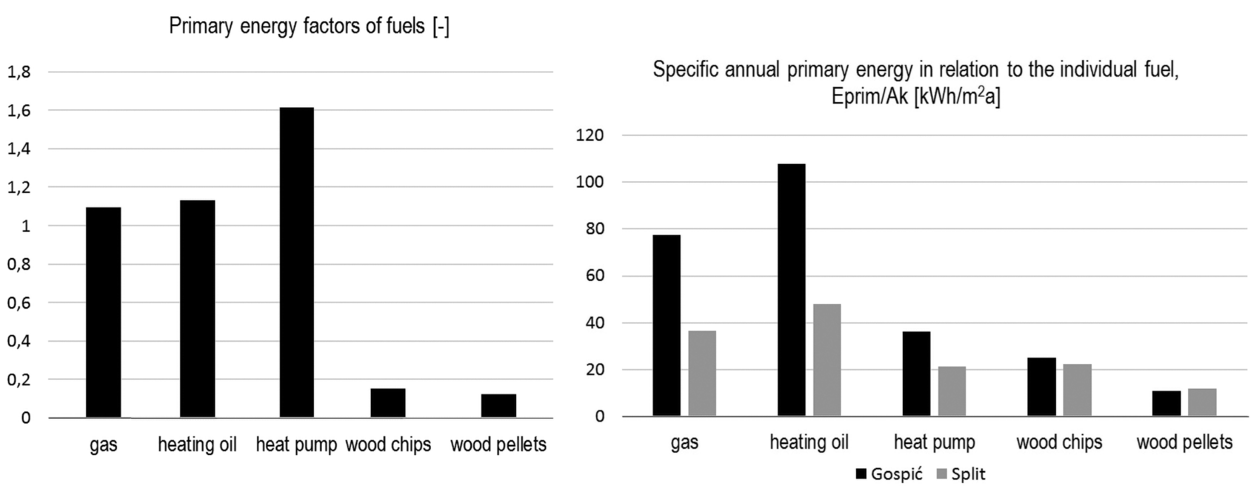


Fig. 8. Primary energy factors of fuels and specific annual primary energy in relation to the individual fuel used by family houses in Gospić and Split.

Table 4. Versions of the use of energy sources and systems in the cases of family houses and apartment buildings in Gospić and Split, which fit the nZEB criterion according to the Technical Regulation (NN 128/15)

Use	City	Primary heating systems	Spec. annual delivered energy, E_{del} [kWh/m^{2}a]	Spec. annual primary energy, E_{prim} [kWh/m^{2}a]	Share of energy from renewable sources [%]
Family house	Gospić	Heat pump	22,88	36,39	44
		Wood pellet boiler	78,44	10,97	82
	Split	Heat pump	13,17	21,26	45
		Wood pellet boiler	38,07	11,95	69
Apartment building	Gospić	Heat pump	19,9	32,11	43
		Wood pellet boiler	77,23	10,67	81
	Split	Heat pump	14,37	23,2	45
		Wood pellet boiler	40,35	13,48	68

* Central boiler room and preparation of domestic hot water

The comparison between the total values of the annual thermal energy demand for heating and cooling per square unit of useful floor area for identical apartment buildings has shown that the building in Gospić needs 1.5 times more thermal energy than the same building in Split.

In relation to present-day buildings, the Technical Regulation requires that the nZEB has much lower specific annual primary energy a greater share of renewable energy sources in the annual primary energy. The annual consumption of primary energy highly depends on energy resources, and less on the efficiency of the heating system and the buildings' consumption. Figures show comparisons between primary energy factors of certain fuels, specific annual primary energy for the family houses in Gospić and Split in relation to the fuel, a comparison of the share of energy from renewable sources and a comparison between specific delivered energy. [9]

Fuels with a low primary energy factor or the utilisation of highly efficient heating systems will most certainly meet the nZEB requirements determined in the Technical Regulation. These include renewable sources, and heat pumps which become increasingly popular.

Consumption results in relation to the use of different fuels and heating systems are shown in Table 4.

It is clearly evident in Table 4 and Figure 9b that the annual delivered energy demand for heating, cooling and domestic hot water (DHW) has the lowest value when the heat pump is used. Heat pumps use electrical energy only for transferring heat from, or to the environment. That is the reason why they have far greater useful efficiency than the heating systems using thermal energy that is contained in the fuel itself. Heating pumps can be used for heating, cooling and preparation of DHW. The total useful efficiency of such systems varies and is η~3-5, which means that 1 kWh of consumed electrical energy produces ~3-5 kWh of efficient thermal energy.

The initial investment for such a system is considerable, but it is possible to apply for subsidies for the use of renewable energy sources. As heat pumps are highly efficient and use only electricity, this relatively small energy consumption can be compensated with photovoltaic systems especially for cooling and DHW during summer. As well as in case of heat pumps, investment is considerable but subsidies can be applied. Even if subsidies are not possible, in case of Gospić with less irradiation reaching the surface payback period for most optimal photovoltaic systems is around 10 years, and in Split around 6 years.

Figure 10 compares annual electricity production of PV system and electricity consumption of heat pumps for the reference models with applied PV systems.

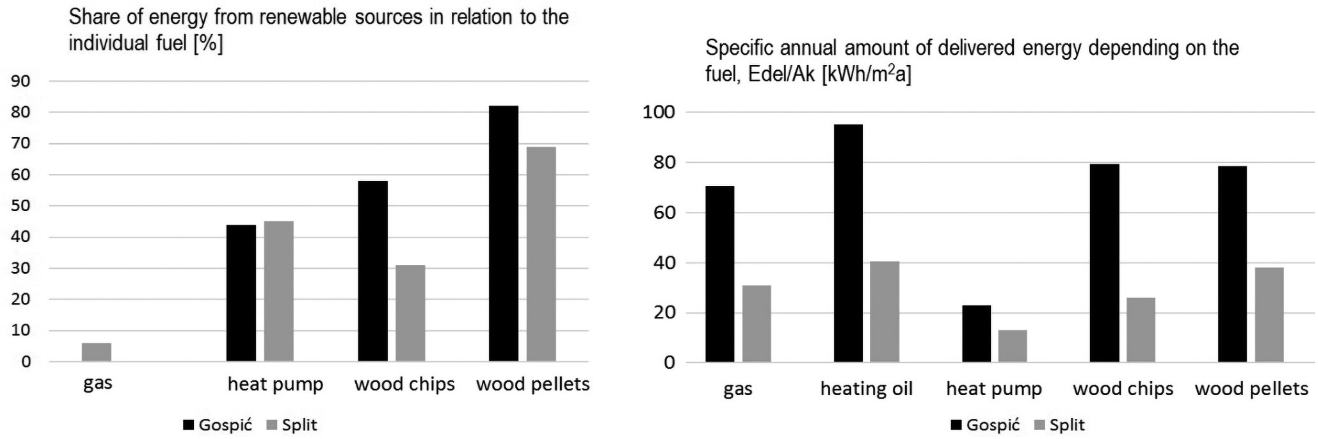
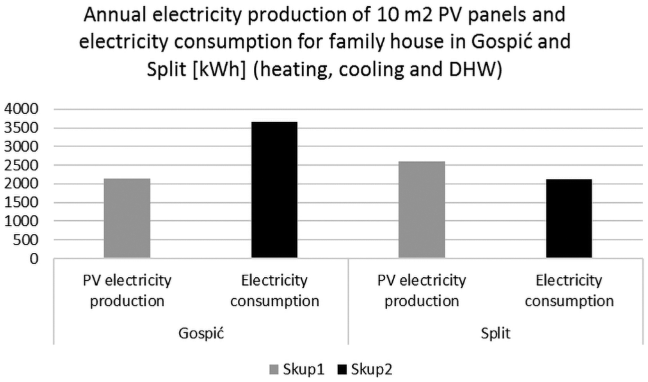


Fig. 9. Share of energy from renewable sources in relation to the individual fuel [%] and specific annual amount of delivered energy depending on the fuel used by family houses in Gospić and Split.



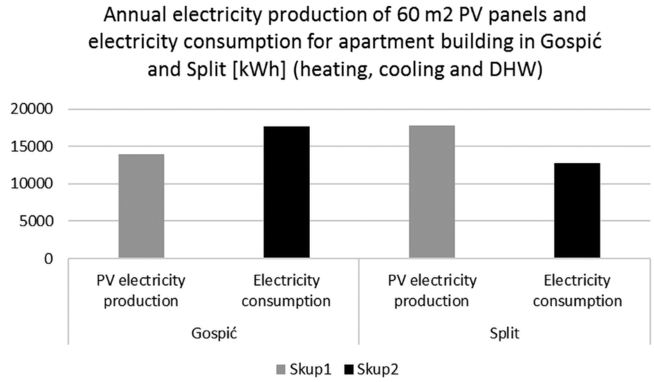


Fig. 10. Electricity production and consumption for the family house and apartment building with PV system in Gospić and Split [kWh] (for heating, cooling and DHW).

4. Conclusion

Energy efficient and resource conscious approaches are incorporated into architecture in many different ways. It may be a technical innovation, a particular use of materials based on the location or utilisation of climatic conditions.

Energy performance of buildings is highly dependent on the characteristics of the climate zone in which the buildings are located. Considering their position, climate differences between the zones of Republic of Croatia are significant, and that exerts an impact on the energy performance of buildings. The paper has brought froth an analysis of energy performance models of the reference residential buildings (family houses and apartment buildings) which are located in two cities with exceptionally different climate features – Gospić and Split. The analysis entailed calculations and comparisons of values of the annual thermal energy demand for heating, cooling and DHW, specific annual primary energy and specific annual amount of delivered energy in relation to different heating systems.

Considering the heating season, the values of the annual thermal energy demand for the two family houses in two cities show a difference that is five times greater and between the apartment buildings in the cities a difference being more than six times greater. If buildings with an installed cooling system are taken into consideration, the values of the annual thermal energy demand for heating and cooling in the cases of the two houses are 2 times different and the two apartment buildings 1.5 times different.

The comparison between the annual primary energy for different heating, cooling and DHW systems point to the fact that the nZEBs in entire Croatia will predominantly use fuels from renewable sources and high efficient heating systems. These include heat pumps, wood-pellet boilers, solar PV and DHW panels, while systems running on fossil fuels such as coal, heating oil and the like, could only serve as auxiliary systems.

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References

[1] Nearly Zero Energy Buildings Definitions across Europe, Factsheet, Buildings Performance Institute Europe (BPIE), Brussels, April 2014.

[2] Energy Strategy of the Republic of Croatia, Ministry of Economy, Labour And Entrepreneurship, The Republic of Croatia, Zagreb, June 2009.

[3] Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama (NN 128/2015) / Technical regulation on energy economy and heat retention in buildings (OG 128/2015)

[4] Meteorološki podaci, Ministarstvo graditeljstva i prostornog uređenja, RH, siječanj 2016. / Meteorological data, Ministry of construction and physical planning, Republic of Croatia, January 2016. http://www.mgipu.hr/default.aspx?id=34363 [December 2017]

[5] Državni hidrometeorološki zavod: Klima: Glavne meteorološke postaje / Meteorological and Hydrological Service: Climate: Main meteorological stations http://prognoza.hr/karte_postaja.php?id=glavne [December 2017]

[6] Z. Veršić, Određivanje modela referentnih zgrada javne namjene iz različitih razdoblja izgradnje u Hrvatskoj u svrhu energetske analize i obnove na gotovo nula-energetsku razinu (nZEB / Determining a model of reference public buildings from different periods of construction in Croatia for the purpose of energy analysis refurbishment into nearly zero-energy buildings (nZEB), scientific project, Faculty of Architecture, Zagreb, 2017.

[7] Z. Veršić, I. Muraj, M. Binički, "Model ugrađene najamne zgrade zagrebačkog donjogradskog bloka. Analiza u svrhu poboljšanja energetske učinkovitosti." / "A Model of Attached Apartment Building in Zagreb's Lower Town Blocks Analysis Aimed at Energy Efficiency Improvement.", Prostor, vol. 23, no. 2(50): Zagreb, pp. 236-249, 2015.

[8] HRN U.J5.600 Toplinska tehnika u građevinarstvu, Tehnički uvjeti za projektiranje i građenje zgrada / Thermal Technologies in Construction, Technical Requirements for Building Design and Construction, 1987.

[9] Faktori primarne energije i emisije CO_2, Ministarstvo graditeljstva i prostornog uređenja, RH / Primary Energy and Carbon Emission Factors, Ministry of Construction and Physical Planning, Republic of Croatia, http://www.mgipu.hr/ [December 2017]

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Masonry columns behaviour analyses due to a different mode of confinement with GFRP straps

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Abstract

The paper describes the experimental research of masonry columns behavior under the load of vertical compression. A total of thirty-four specimens were tested: three unconfined specimens and thirty-one specimens confined with GFRP straps. In addition to the load-bearing efficiency analysis of confined columns in relation to the number of the confinement layers, the intention of these tests was to determine the efficiency of spiral confinement in relation to conventional confinement. The impact of the existing compressive stress in a column during confinement to the final increased load-bearing capacity of the confined column was also studied.. The test results have shown that all of the confined specimens have a greater load-bearing capacity and ductility than the unconfined specimens. The results of spiral confinement were almost identical to the results of conventional confinement, which is vital considering that spiral confinement is easier to perform. The results of the test lead to the conclusion that the presence of compressive stress in a column during confinement does not significantly reduce confinement efficiency. This makes it possible to effectively increase the bearing capacity of masonry columns without the need to previously unload the structure, while the structure is in service. The paper also provides expressions for the estimated increase in the compressive strength of confined columns that well correspond to the testing results.

Keywords: *tests, masonry columns, strengthening, glass fibre reinforced polymer straps, GFRP, results*

Notation

E_f modulus of elasticity of GFRP straps;

E_M modulus of elasticity of wall;

E_{M1-3} secant modulus of elasticity of wall determined for the compressive stress of 1,0 to 3,0 MPa;

F compressive force in masonry column during testing;

f_f tensile strength of glass fibre fabric (GFRP);

f_M compressive strength of unconfined masonry column;

f_{Mc} compressive strength of confined masonry column;

f'_l effective lateral stress in column during confinement;

ε_{fu} ultimate strain of glass fibre strap;

ε_M longitudinal strain of column;

ε_{Mu} longitudinal strain of masonry column at failure;

ε_{Mc} longitudinal strain of masonry column for $\sigma_M = f_{Mc}$;

ε_l lateral strain of column;

σ_M compressive stress of column;

1. Introduction

Due to the growing need for reconstruction and rehabilitation of the existing masonry, new methods and technology of strengthening the existing load-bearing elements of masonry structures are being investigated today. The greatest number of investigations is focused on increasing the load-bearing capacity of masonry structural elements by applying fibre reinforced polymer (FRP) [1]. This type of strengthening has more advantages than the traditional methods. The most important benefits of such a type of strengthening are in the fact that the existing bearing structure of the building is not undermined; that it is fast and simple to perform, and that it does not violate the aesthetic requirements of the building and its functionality during the strengthening process. Although FRP is not a ductile material, it could be used for strengthening masonry structures as the collapse is mainly achieved through masonry. Over the past few years extensive experimental, analytical and numerical investigations of masonry wall [2], as well as masonry columns being strengthened with glass fibre reinforced polymer straps (GFRP) have been conducted. The purpose of these investigations was to research and describe in the most helpful way the behaviour of masonry walls subjected to horizontal in-plane load strengthened with glass fibre straps as well as the behaviour of masonry columns under compressive load that are confined with glass fibre straps.

The paper shows a part of the investigation relevant to the behaviour of masonry columns under variable axial compressive load until failure. Experimental testing of confined and unconfined masonry columns were conducted, which is only a continuation of similar investigations in the world [3], [4], [5]. The experimental research was aimed at determining the impact of the method and volume of confinement with glass fibre straps on increasing the compressive strength of masonry columns. Considering that in practice it is difficult to obtain full load release of a column during confinement, the compressive strength of a column during confinement on the increase n load-bearing capacity was analysed within the conducted investigations. The aim was also to obtain good working diagrams of the confined columns behaviour, as well as the relations between longitudinal and lateral strains with the load change for further numerical and analytical analysis. The paper shows the results of the completed experimental investigations and proposes analytical expressions for the estimate of the total bearing capacity of confined columns.

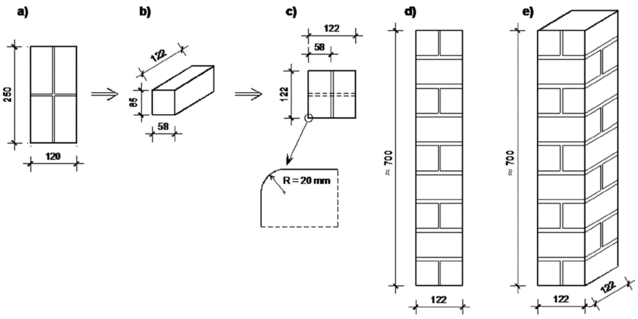

Fig. 1. Tested sample of masonry column

2. Experimental program

a. Test specimens and material properties

Testing was conducted on small masonry column specimens with dimensions *a*/*b*/*h* = 122/122/700 mm (Figure 1). All specimens were made with masonry elements of solid brick of width/height/length = 58/65/122 mm, made by cutting brick of standard dimensions w/h/l = 120/65/250 mm into 4 identical parts. The mean values of tensile strength and compressive strength of bricks were 3.98 MPa and 23.33 MPa, respectively. The mortar used in making specimens was cement-lime mortar of the same volume content (cement/lime/sand = 1/3/9). The mean value of compressive strength of mortar was 5.70 MPa, tensile strength of mortar was 1.74 MPa. Straps and glass fibre fabrics were used for confinement of masonry columns, along with the epoxy adherent and levelling mortar. The description of the testing procedure was given in Soric et.al. [6]. The tensile strength of FRP composite (glass strap embedded in epoxy resin) was 890.1 MPa; strain at failure: $\varepsilon_{f,max}$ = 19.3 ‰; modulus of elasticity was 46169 MPa. The properties of levelling paste declared by the manufacturer were: compressive strength > 80 MPa; tensile strength > 30 MPa; strain at failure 12 ‰; modulus of elasticity 3000 MPa. The specimens had curves R = 20 mm on vertical edges to avoid sharp edges and possible damaging of strengthening straps at the bending location of vertical edges.

Twenty-six masonry columns were tested to determine the impact of the method and volume of confinement with glass fibre straps on the increase in compressive strength of masonry columns: three unconfined column specimens (type A) and twenty-three confined specimens. Confined masonry columns were strengthened in eight different ways (Figure 2). Seven series had three specimens, and one had two specimens. All confined specimens were confined with the same GFRP straps (Mapewrap G UNI-AX 900/60, Mapei); with the only difference being the method of confinement (horizontal, spiral), the number of strap layers and their width.

Specimens of type B, C and D were confined with horizontal confinement (conventionally confined specimens) over the entire surface. Confinement was made with two 300 mm wide straps, and one 100 mm wide strap (2×300+100=700 mm = height of specimen). The strap length depends on the number of confinement layers (1-3 layers). The strap overlap of these specimen types was 100 mm. The neighbouring straps were set to each other without overlapping.

Specimens of type E, F, G have spiral confinement with 100 mm wide straps. The confinement was made with a vertical overlap. The value of overlap varies from the type of specimen. E type specimens have vertical overlapping of 5 mm and represent specimens with one layer of spiral straps. F and G type specimens have an overlap of 50 and 70 mm respectively and represent specimens with two or three layers of spiral straps. The percentage of confinement which corresponds to one, two or three layers of glass fibre strap is made by a smaller or larger spiral pitch. Specimens of type H and I have a spiral confinement with 50 mm wide straps, but the unconfined space between two straps is also 50 mm. H type specimens have one layer of strap while I type specimens have two layers. This type of confinement is used to determine strengthening efficiency without covering the entire specimen surface.

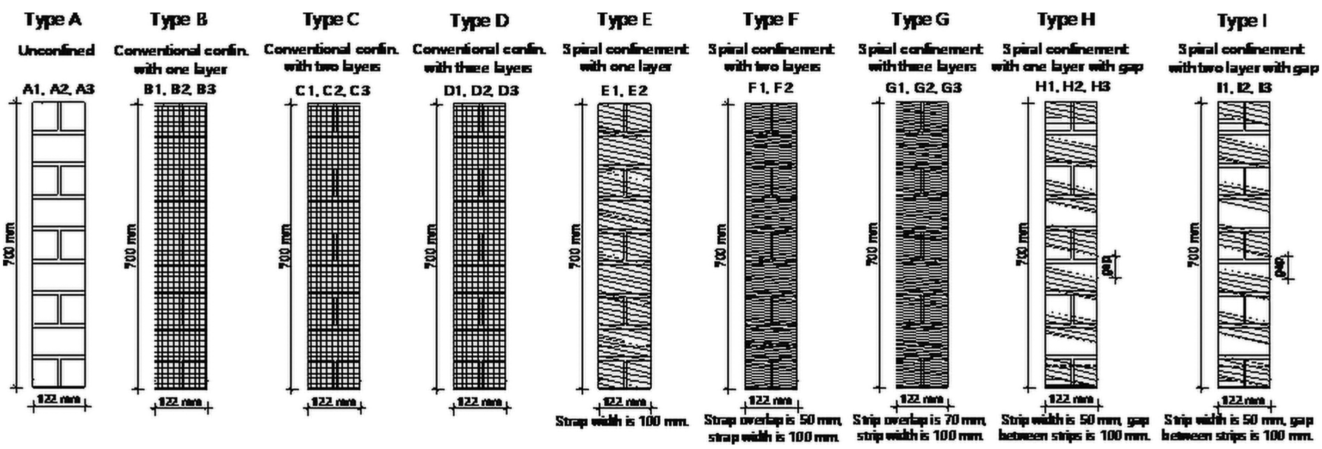

Fig. 2. Specimen type of confined masonry columns

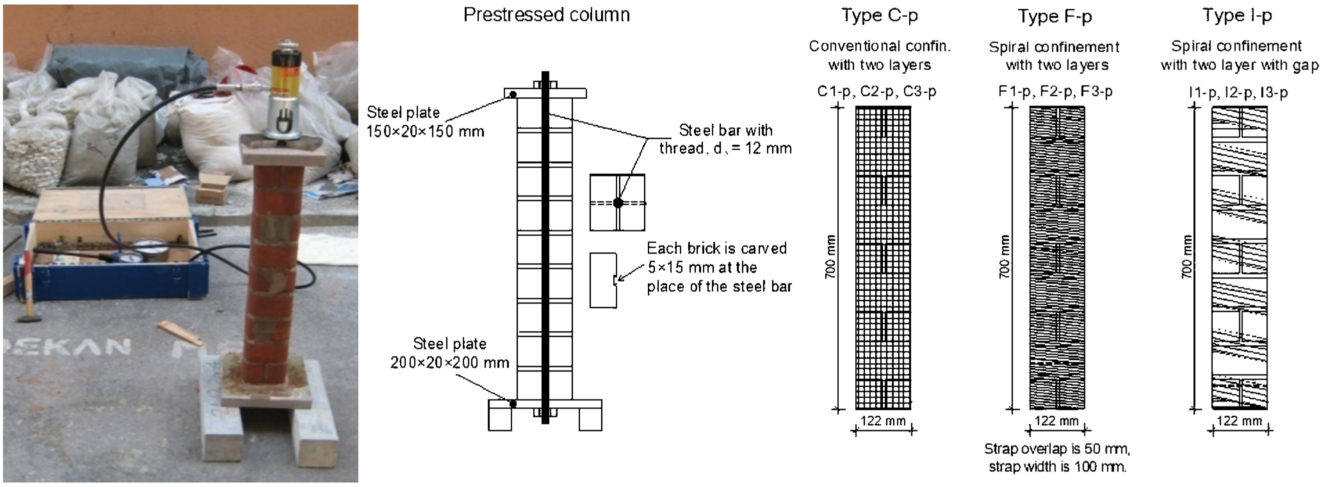

Fig. 3. Specimens which were exposed to compressive load (prestressing) during confinement

All specimens were made on 15 mm thick steel plates. Before confinement with GFRP straps, masonry surfaces of the specimens were well brushed, coated with primer, and then levelled with levelling paste. After the column surfaces had been levelled, glass fibre straps were glued on surfaces using epoxy resin.

Additionally nine masonry columns were tested to determine the impact of compressive stress in column during confinement on the increase in bearing capacity of the confined masonry column.

All nine specimens were confined and their method of confinement matched the strengthening types C, F and I shown in Figure 2 except for their exposure to compressive load during confinement. Compressive load was achieved by prestressing with a steel bar d_b = 12 mm placed at the centre of the cross section. Compressive stress during confinement was σ_M = 2,0 MPa which corresponds to 21.5% of bearing strength of unconfined masonry column. The compressive stress value was determined based on the fact that compressive stress in masonry columns under the dead load of the structure (after load release during removal of floor layers, facade and useful load) was 20-25% of the wall strength. That way the real situation was simulated in practice of applying FRP strengthening. Prestressed specimens are shown in Figure 3.

b. Testing procedure

The main objective of testing was to record the axial stress-strain curve and the failure mode of all masonry specimens that were subjected to axial load applied monotonically under the displacement control mode in a compression testing machine. The testing machine was Zwick Z600E with a 600 kN capacity. Before the beginning of the main testing every specimen had been "trained" , i.e. loaded twice up to force F = 30.0 kN (corresponding to stress σ = 2.0 MPa) and unloaded to 0 kN. In the specimens that were prestressed immediate-

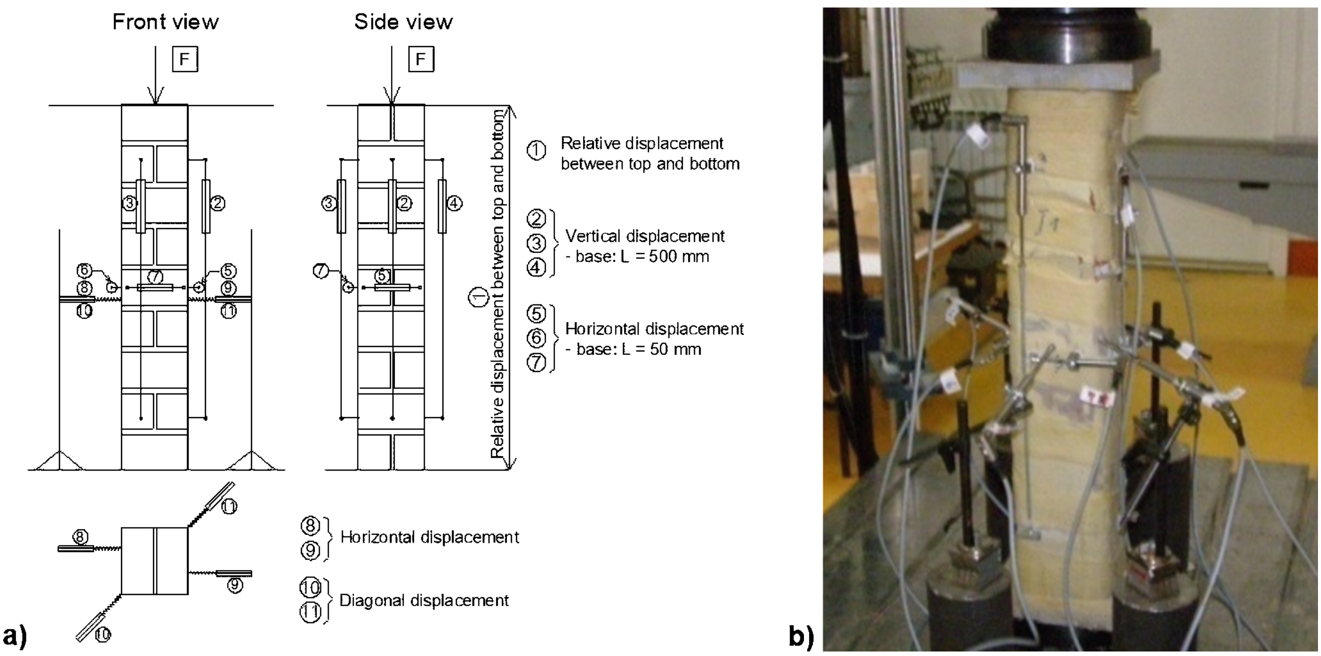

Fig. 4. a) Scheme of loading and LVDT setup and b) Specimen during testing

ly before testing, the specimens were unloaded by releasing prestressing force and removing the bar in the middle of the section. Specimens were tested using displacement control, at a displacement speed of 0.2 mm/s. The loading scheme and LVDT setup is shown in Figure 4. During testing the value of vertical compression force (F) was measured as well as the vertical displacement of the hydraulic jack (1). Also, vertical deformations were measured in three places (2, 3, 4) as well as horizontal deformations in the middle of the specimen height (5, 6, 7). Horizontal displacements (8, 9, 10, 11) in the middle of the specimen were also measured.

3. Experimental results and discussion

Table 1 shows the mean values of test results for each series of column specimens. The following values are shown: F_{max} = maximum compression force; f_{Mc} = compressive strength of confined masonry specimen; ε_{Mu} = sample failure (ultimate) strain; $E_{M1\text{-}3}$ = starting modulus of elasticity (secant modulus of elasticity for the stress level from σ_M = 1.00 to 3.00 MPa); E_M = secant modulus of elasticity for the stress level $\sigma_M = 0.3\times f_{Mc}$.

a. Description of the behaviour of particular specimen types

Unconfined columns (Type A) – For a comparison with other specimens, three unconfined (reference) specimens were tested. The first visible (vertical) cracks appeared at approximately 90% of compressive strength. Just before the brittle failure of the specimen, they spread and developed at the full height of the specimen. The results of testing and the appearance of the specimen are shown in Figure 5.

Conventionally confined columns (Types B, C, D) – Until the compressive force F = 230 to 250 kN (σ_M = 14.68 to 15.83 MPa) for the specimens type B, the force F = 275 kN (σ_M = 17.36 MPa) for the specimens type C, and the force F = 320 kN (σ_M = 19.65 MPa) for the specimens type D, there was no visible damage of specimens. Specimens acted as a single monolithic structure which is confirmed by the diagram "σ_M-ε_M" up to these stress

Table 1. Test results for column specimens (mean values)

Type of specimens	F_{max} (kN)	f_{Mc} (MPa)	ε_{Mu} (‰)	$E_{M1\text{-}3}$ (MPa)	E_M (MPa)
A	140.1	9.45	2.45	7078.3	7078.3
B	287.2	18.20	20.46	7283.7	6370.8
C	349.1	22.04	24.12	7257.7	5648.6
D	456.7	28.04	40.92	7348.0	5049.5
E	294.1	18.78	17.15	7320.0	6619.3
F	361.6	23.73	25.76	7269.8	6082.2
G	429.5	26.57	31.24	7252.1	5646.6
H	252.4	15.74	7.46	7125.5	6379.2
I	252.4	16.27	7.36	7160.3	6283.9
C-p	327.0	20.67	24.49	7074.0	5859.9
F-p	323.0	20.39	20.03	7177.5	6283.6
I-p	254.6	16.28	7.66	7074.5	6359.1

values. Up to the previously stated values of compressive load the serviceability of specimens was not impaired. After that the first visible damage followed by a cracking sound begins to appear. There are no visible vertical or horizontal cracks, but the fabric confinement at the place of horizontal joints begins to fold (Figure 6). This folding increased with an increase in compression and deformation. The reason for that is crushing of mortar in joints between two bricks, which leads to greater longitudinal masonry deformation at these places.

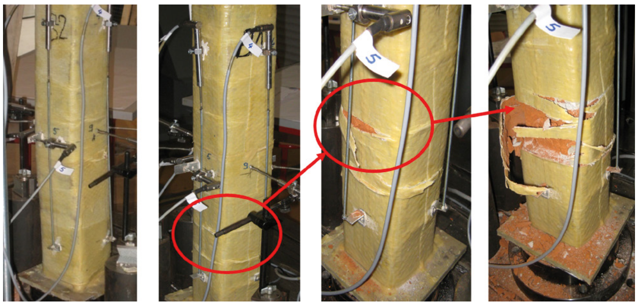

Fig. 6. Development of specimen damaging during testing until failure (B2 specimen)

After the first visible damage had appeared, the increase in the deformation increment at the same load increment was significantly higher than before the damage. This could be seen in the diagram "σ_M-ε_M", which has an approximately horizontal branch (Figure 7a). That "yielding" pattern is the result of mortar and bricks crushing where the confinement straps do not allow its decompo-

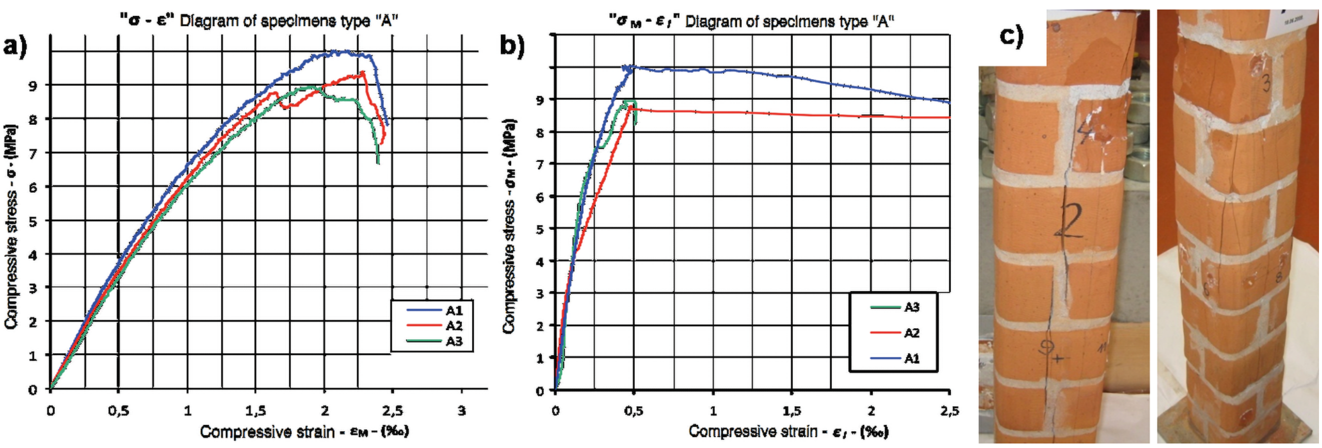

Fig. 5. Test results of unconfined specimens: a) "$\sigma_M - \varepsilon_M$" diagrams; b) "$\sigma_M - \varepsilon_l$" diagrams; c) appearance of specimen failure

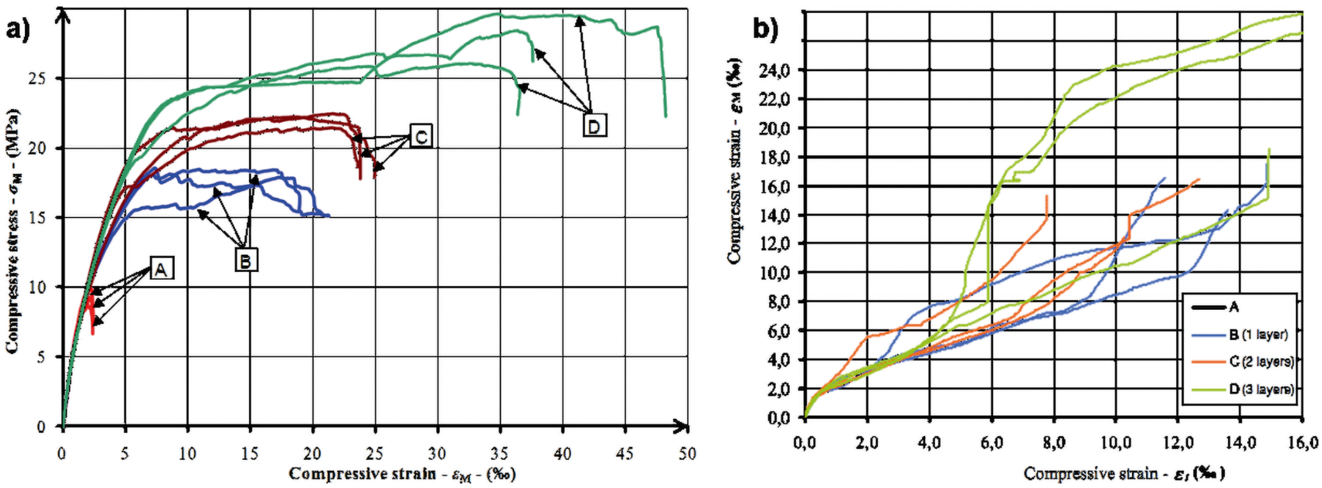

Fig. 7. Comparison diagrams of specimens A, B, C and D: a) "$\sigma_M - \varepsilon_M$" diagrams; b) "$\varepsilon_M - \varepsilon_l$" diagrams

sition (the effect of sand in a bag). Furthermore, "yielding" is the result of specimen bending where bending is not solely the result of physical stability loss. Bending is also the result of material homogeneity lack where the damage is localized in one part of the specimen, resulting in larger deformations in the area which causes buckling. This occurrence should be taken into consideration in the case of slender columns since it affects the stability and bearing capacity of columns. With the number of fabric layers increasing, the strength and deformability of specimen increased too. The specimen failure occurred when local deformations caused confinement failure at one specimen edge. The straps were damaged due to folding and inclining little brick pieces into the strap. The tearing of straps occurred in one of the places where confinement was significantly folded and where masonry was completely squashed and almost turned into dust. Conventionally confined specimens had significantly greater load bearing capacity than unconfined specimens. They also had much greater ductility, i.e. there was no brittle failure at the point where maximum stress was reached. The failure of the specimen was ductile with large longitudinal and transversal deformations (Figure 7a). Specimens of type D with three layers of confinement had the greatest ductility, while the specimens of type B with one layer, the lowest. The confinement increased the specimen compressive strength up to three times in case of confinement with three layers of straps, while the increase in the ultimate strain was as much as seventeen times. An increase in the load bearing capacity and the ultimate strain depended on the number of confinement layers. The greatest step of load bearing capacity and ductility growth was achieved with one layer of confinement in comparison with the unconfined specimen. An additional strap layer increased the load bearing capacity and specimen deformation, but for a smaller step than in case of one confinement layer.

The modulus of elasticity of the unconfined specimen was increased by approximately 5% by specimen confinement. This increase was more a result of primer and epoxy usage than of the confinement itself. The first part of "σ_M-ε_M" diagram is similar for both the unconfined and confined specimens.

After failure stress, the confined specimens showed further resistance followed by large deformation and stiffness reduction due to cracking. It is important to notice that modulus of elasticity of the confined specimens

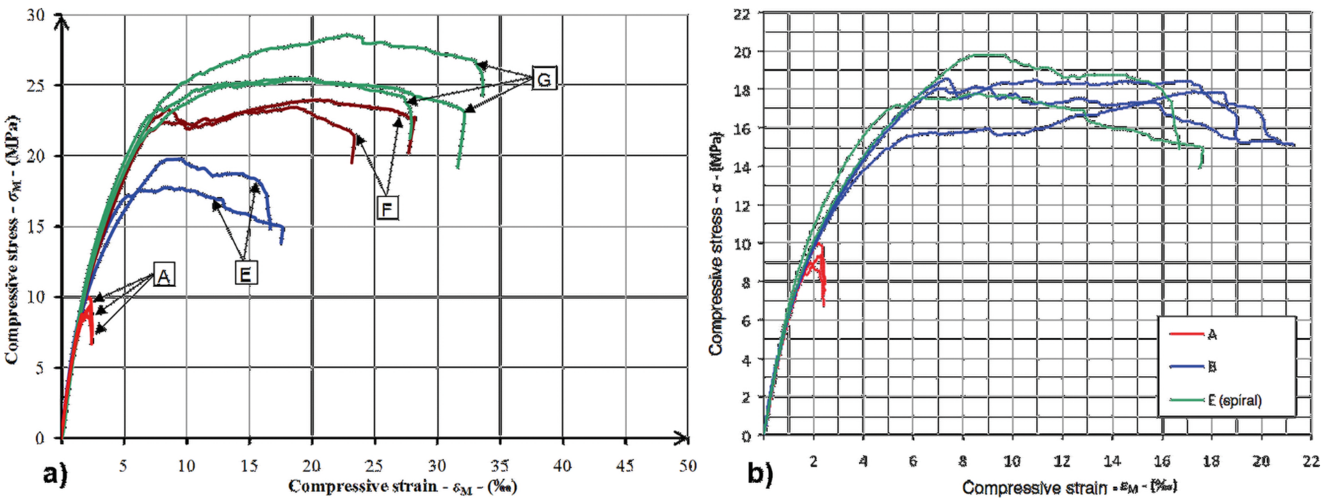

Fig. 8. a) "$\sigma_M - \varepsilon_M$" diagram of spiral confined columns; b) Comparison "$\sigma_M - \varepsilon_M$" diagram for conventional and spiral confinement with one layer of GFRP straps

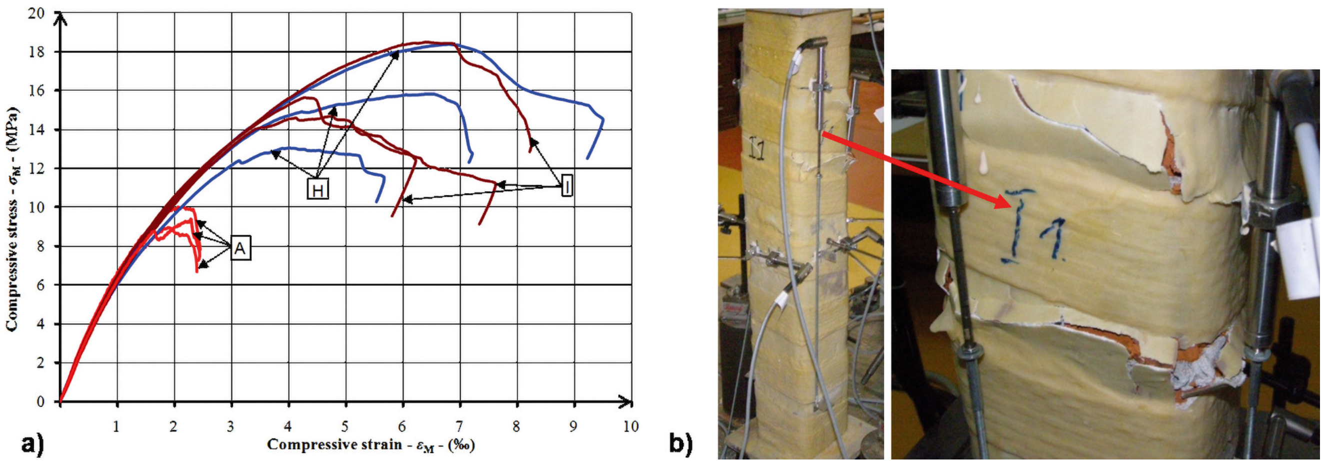

Fig. 9. a) Comparison "$\sigma_M - \varepsilon_M$" diagram of specimens A, H i I; b) failure of specimen I

wasn't proportional to their compressive strength (as it is proposed by codes, for instance $E_M \approx 1000\, f_M$). This should be considered in some numerical models.

Spirally confined columns (Types E, F, G) – The only difference between specimen types E, F and G from types B, C and D was the spiral type of confinement. The straps were wrapped spirally because of easier confinement process, especially if there were two or three confinement layers. The behaviour of spirally confined specimens is identical to the one in conventional confinement. Compressive strength of spirally confined specimens was almost identical as in the case of conventional confinement while ductility was somewhat reduced. The specimens still had high ductility and strength, and the reason for reduced ductility in relation to the conventionally confined specimen was that the spirally confined strap could easily be damaged because of the specimen longitudinal deformation which could cause tearing of straps. Figure 8a shows "σ_M-ε_M" diagrams for specimen type A, E, G and F, and Figure 8b gives a comparison of spiral and conventional confinement in case of confinement with one layer of fibre glass strap.

Spirally confined columns with gap between straps (Types H and I) – The failure of both H and I specimen types occurred due to a damage at the area of specimen without straps i.e. between straps. The specimens did not show substantial ductility and considerable deformations. However, the specimens had an increase in bearing capacity compared to unconfined specimens because the straps prevented the development of vertical cracks and splitting of specimens. Figure 9a shows comparative diagrams for specimens A, H and I. These diagrams show an increase in bearing capacity of 80%. However, the increase in bearing capacity was much smaller than in fully confined specimens because the specimen failed in the area between spiral straps (Figure 9b). Increasing the number of confinement layers did not increase the bearing capacity. The reason for that was that the failure occurred in the area without confinement between spiral straps.

Specimens subjected to compressive load during confinement (Types C-p, F-p and I-p) – Behaviour of masonry columns subjected to compressive load during confinement was identical to the behaviour of the same specimens that were not subjected to compressive load during confinement (specimens types C, F and I). In columns with full confinement an increase in compressive strength was smaller by 6.2% compared to the same col-

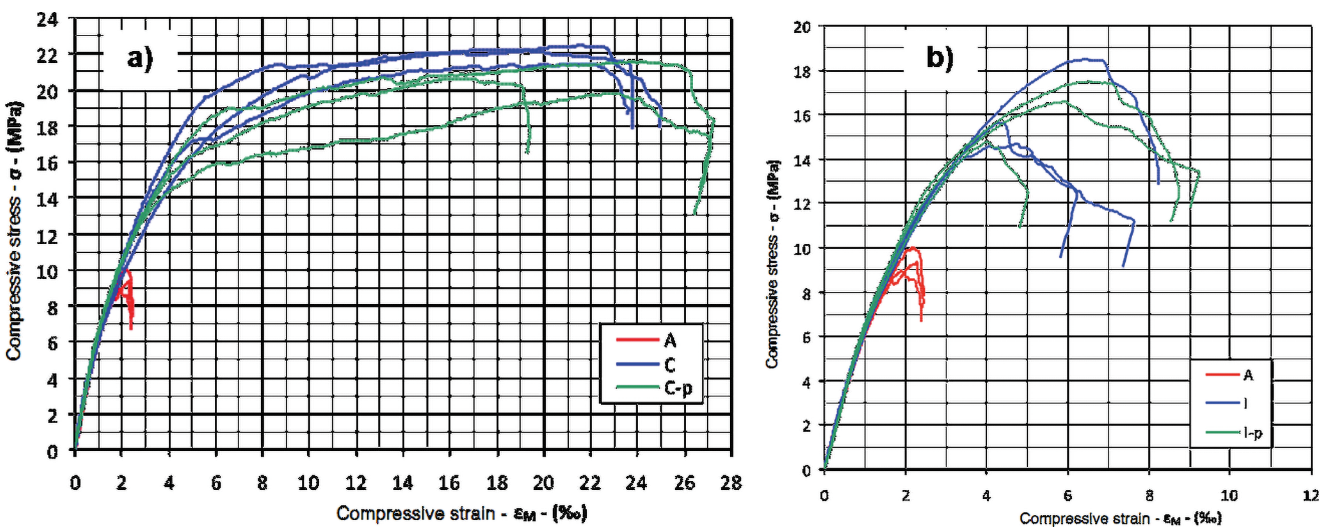

Fig. 10. a) Comparison "$\sigma_M - \varepsilon_M$" diagram of A, C and C-p; b) Comparison "$\sigma_M - \varepsilon_M$" diagram of A, I and I-p

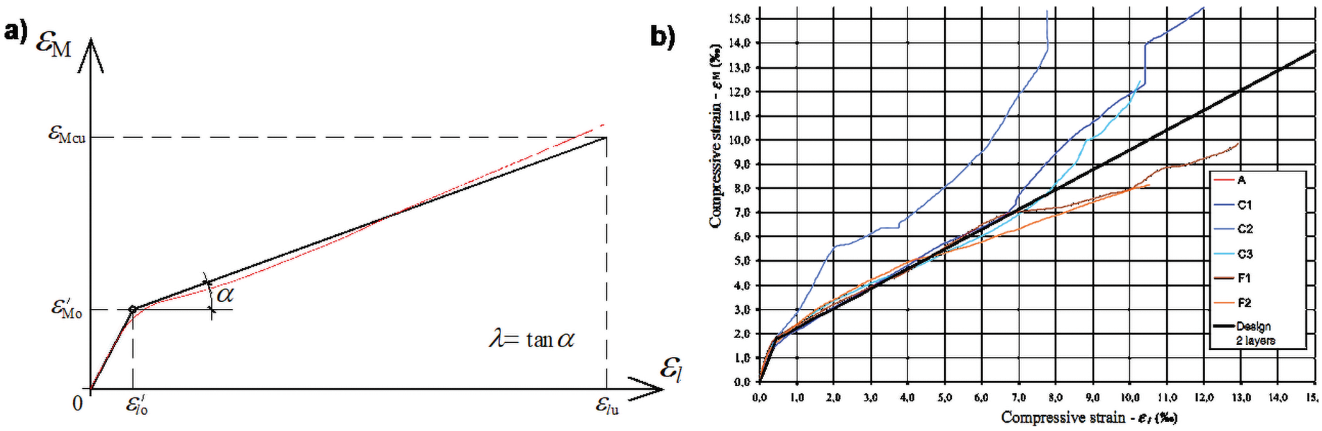

Fig. 11. a) Bilinear "$\varepsilon_M - \varepsilon_l$" diagram; b) Bilinear "$\varepsilon_M - \varepsilon_l$" diagram of confined columns with two layers

umns that were not subjected to compressive load during confinement (Figure 10), while the modulus of elasticity was somewhat higher (3.7%). Although the efficiency of confinement in these specimens is somewhat lower, a further increase in bearing capacity due to confinement is significant compared to unconfined columns (an increase by 118% for confinement in two layers). A slightly higher modulus of elasticity that was achieved is the result of compressive stress during curing of specimen which ensured a better consolidation of the column than in the case of the specimens that were "trained" during testing. In spirally confined specimens with a gap between straps almost identical results were obtained as in specimens that were not subjected to compressive stress. The results of testing are shown in Figure 10.

b. The relation between longitudinal and lateral strain

In addition to diagram "$\sigma_M - \varepsilon_M$" during testing the diagrams of the relation between longitudinal and lateral strain were analysed i.e. "$\varepsilon_M - \varepsilon_l$". Although the working diagram "$\varepsilon_M - \varepsilon_l$" has three areas described by the design model for confined concrete by researchers Saenz and Pantelides [8], for practical application the relation "$\varepsilon_M - \varepsilon_l$" can be approximated by a bilinear diagram (Figure 11a) and expressions (1).

For $0 \le \varepsilon_l(f_l') \le \varepsilon_{lo}' \rightarrow \varepsilon_M(\varepsilon_l, f_l') = \dfrac{\varepsilon_{Mo}'}{\varepsilon_{lo}'} \cdot \varepsilon_l(f_l')$

for $\varepsilon_{lo}' \le \varepsilon_l(f_l') \le \varepsilon_{lu} \rightarrow$ (1)

$$\varepsilon_M(\varepsilon_l, f_l') = \varepsilon_{Mo}' + \lambda \cdot (\varepsilon_l(f_l') - \varepsilon_{lo}')$$

Where: $\varepsilon_{Mo}', \varepsilon_{lo}'$ = longitudinal and lateral strain that determine the point of failure of diagram "$\varepsilon_M - \varepsilon_l$"; λ = line gradient of the other area of diagram in Figure 11a ($\lambda = \tan\alpha$). A good congruence with the test results was obtained for values: $\varepsilon_{Mo}' = 1{,}74$ ‰, $\varepsilon_{lo}' = 0{,}44$ ‰, λ = 0,71; 0,83; 0,96 (for confinement with one, two and three layers of strap) which can be seen in Figure 11b. For strain values that determine the point of failure of diagram "$\varepsilon_M - \varepsilon_l$" it can be assumed that it is $\varepsilon_{Mo}' \cong 0{,}82 \cdot \varepsilon_{Mo} = 0{,}82 \cdot 2{,}13 = 1{,}74$ ‰ and $\varepsilon_{lo}' \cong 0{,}25 \cdot \varepsilon_{Mo}' = 0{,}44$ ‰. Bilinear diagrams for individual cases of confinement

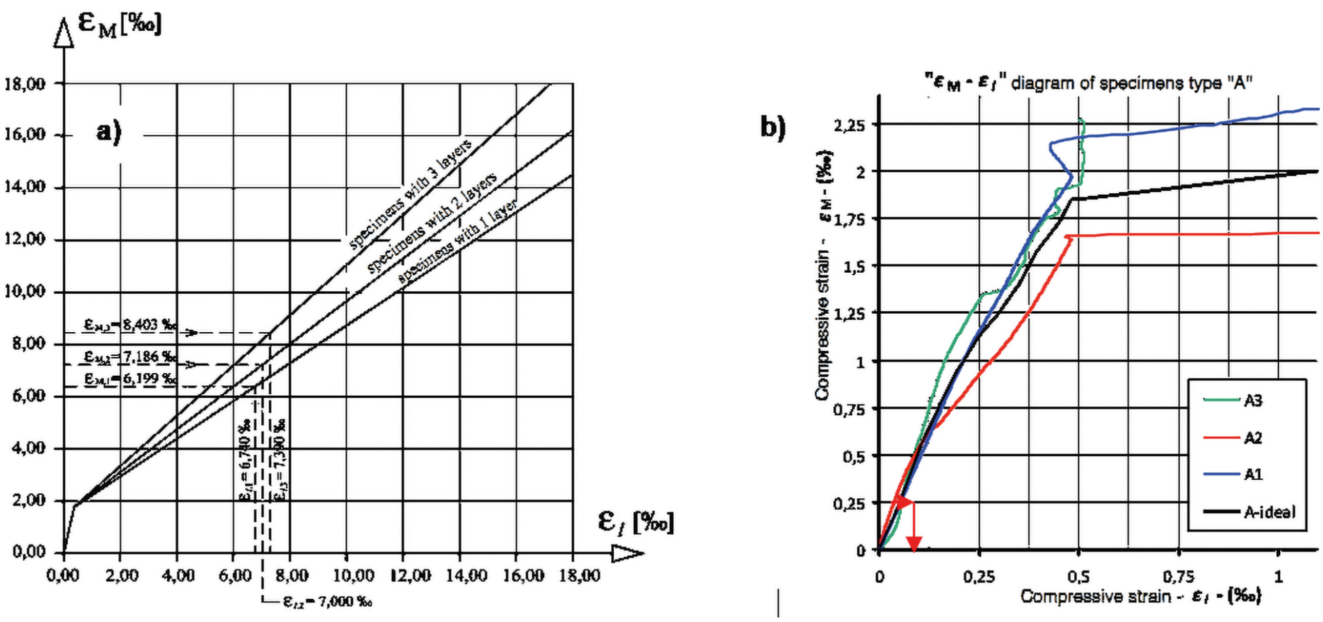

Fig. 12. a) Bilinear "$\varepsilon_M - \varepsilon_l$" diagram for different number of confinement layers; b) "$\varepsilon_M - \varepsilon_l$" diagram of unconfined columns

with strain that is congruent with the compressive strength of columns are shown in Figure 12a. In line with the testing and graph shown in Figure 12a lateral strain and effective strain in FRP that is congruent with the compressive strength of the confined column is $\varepsilon_l = \varepsilon_{fe} = 7{,}04$ ‰.

Accordingly, stressing in FRP that is congruent with the compressive strength of the confined column is $f_{fe} = E_f \cdot \varepsilon_{fe} = 46169 \cdot 0.00704 = 325.16$ MPa. With that stress value an analysis was conducted in Chapter 4.

4. Estimate of compressive strength of confined masonry column

Based on the testing results the calibration of general expression (2) was made to determine the increase indec compressive strength of confined column as well as the modification of the expression (3) proposed by Mander [9] in 1988, for the estimate of an increase in compressive strength of concrete columns due to the lateral stress.

$$\frac{f_{Mc}}{f_M} = 1 + k_1\left(\frac{f_l'}{f_M}\right)^{\alpha} \qquad (2)$$

Where: α, k_1 = constants determined by calibration of the testing results; f_l' = effective lateral stress in column during confinement taking into account geometric characteristics of cross section in line with [4].

$$\frac{f_{Mc}}{f_M} = 2,254\sqrt{1+7,94\cdot k\cdot\left(\frac{f_l'}{f_M}\right)} - 2\cdot k\cdot\left(\frac{f_l'}{f_M}\right) - 1,254 \qquad (3)$$

Where: k = correction coefficient with which the existing expression for confined concrete proposed by Mander [8] is adjusted for the design of masonry columns that are subjected to triaxial load.

Expression (2) taking into account that lateral strain of the confined column at maximum bearing capacity $\varepsilon_l = \varepsilon_{fe} = 7.04$ ‰ best matches the testing results for values $\alpha = 0{,}68$ and $k_1 = 2{,}3$ i.e. as presented in expression (4).

$$\frac{f_{Mc}}{f_M} = 1,0 + 2,3\left(\frac{f_l'}{f_M}\right)^{0,68} \qquad (4)$$

Columns that were subjected to compressive load during confinement had compressive prestressing $\sigma_M = 2.0$ MPa in which longitudinal strain was $\varepsilon_M = 0.28$ ‰ and lateral strain $\varepsilon_l = 0.05$ ‰ (see Figures 5a and 12b). In the columns that were subjected to compressive load during confinement, the effective strain of FRP that matches the compressive strength of the confined column and amounts to $\varepsilon_{fe} = 7.04 - 0.05 = 6.99$ ‰ was decreased by that exact value of lateral strain.

Taking into consideration a decrease in effective strain of FRP due to the already incurred lateral deformation of the column in prestressing according to expression (5) the obtained value of design compressive strength in expression was $f_{Mc} = 20.45$ MPa. Comparing the design

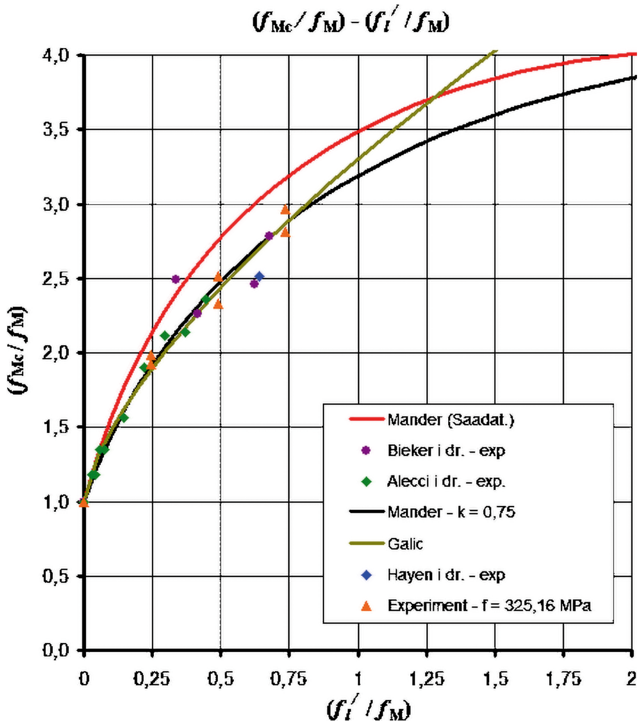

Fig. 13. Comparison of experimental results with theoretical expressions (4) and (5)

compressive strength determined for specimens that were not prestressed before confinement, $f_{Mc} = 21.58$ MPa, and the design compressive strength determined for specimens that were subjected to compressive strength before confinement, $f_{Mc} = 20.45$ MPa, the obtained decrease in comp. strength $\eta = (21{,}58 - 20{,}45)/21{,}58 = 0{,}053$ i.e. 5,3%. A decrease in bearing capacity of prestressed specimens from the previous analysis (5.3%) approximately matches the bearing capacity decrease from experimental testing (6,2% for C-p type specimens). This also explains why the presence of the usual level of compressive stress in masonry columns in practice during the time of confinement has no significant impact on an increase in compressive strength and bearing capacity. In practice it allows the application of confinement of masonry column with compressive load without a need to implement full unloading of columns.

5. Conclusion

Full confinement of masonry columns significantly added to increased bearing capacity. An increase in bearing capacity approximately linearly depends on the number of layers in which the greatest increment of increase in bearing capacity is achieved with one layer of confinement, whereas for several layers the increment of growth is somewhat lower. Full spiral confinement yields results almost identical to full conventional confinement which is important considering that spiral confinement is easier to perform. The use of spiral confinement with a gap between straps increases the bearing capacity, though it is lesser than in the case of full confinement since the failure of column takes place in the area between straps. An increase in bearing capacity in columns with a gap among straps does not depend on the number of layers in confinement; it is almost equal for one, two or three layers. The presence of moderate compressive stress (≈ 0.21 f_M) during column confinement insignificantly decreases the bearing capacity of the confined column compared to columns without compressive prestressing. In practice that permits implementation of confinement in masonry columns with compressive load without necessity for full unloading.

For the practical application, the relation of longitudinal and transversal strain can be described with a bilinear relation diagram. The paper also provides expressions for the estimate of compressive strength of confined columns that correspond with the testing results presented in this paper as well as with the results published by certain researchers [3], [5] and [9].

References

[1] Motavalli, M. & Czaderski, C., FRP Composites for Retrofitting of Existing Civil Structures in Europe: State-of-the-Art Review, In: *Proc. of the Composites & Polycon, ACMA 2007 Conference,* Tampa, USA, October 17-19, 2007. p.10.

[2] Galic, J., Kisicek, T. & Galic, M., Strengthening Masonry Walls with GFRP Straps – Testing and Application. *Advanced Materials Research*, 688, 230-236 (2013).

[3] Bieker, C., Seim, W. & Sturz, J., Post-strengthening of Masonry Columns by Use of Fiber-reinforced Polymers, Presented at *3rd International Conference of Composites in Infrastructure*, San Francisco, CA, USA, 2002.

[4] Krevaikas, D. T. & Triantafillou, C. T., Masonry Confinement with Fiber-Reinforced Polymers. *Journal of Composites for Construction*, ASCE, 9(2), 128-135 (2005).

[5] Alecci, V., Bati, S. B., Ranocchiai, G. Study of Brick Masonry Columns Confined with CFRP Composite, *Journal of Composites for Construction*, ASCE, 13(3), 179-187 (2009).

[6] Soric, Z., Galic, J. & Rukavina T., Determination of Tensile Strength of Glass Fiber Straps, *Journal Materials and Structures*, 41, 879-890 (2008).

[7] Saenz, N. & Pantelides, C. P. Strain-Based Design Model for FRP-Confined Concrete Columns, ACI Special Publication, SP230: 7th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures (2005), Paper SP230-57, 1011-1028.

[8] Mander, J.B., Priestley, M.J.N. & Park, R. Theoretical stress-strain model for confined concrete, *Journal of Structural Engineering*, ASCE, 114(8), 1804-1826 (1988).

[9] Hayen, R., Schueremans, L., Van Balen, K. & Van Gemert, D. Triaxial Testing of Historic Masonry, Test Set-up and First Results, *Proceedings of Historical buildings VII*, WIT Press, Southampton, pp. 151-160, Bologna (2001).

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