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Research of the collapsibility of the European loess – review

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Abstract: Foundation of the buildings on the loessial soil is often associated only with difficulties resulting from the possibility of the collapse of the ground. For these reason, loess is too often unfairly disqualified as the construction subsoil in spite of its good strength and strain parameters. Thanks to continuous development of research and publications of the results, reliable data regarding loess are spread and, as a consequence, loess becomes more and more common soil used in the geotechnical engineering.

Loess collapsibility has been studied since the middle of the 20th century, nevertheless, only the computer techniques and specialist laboratory and microstructural tests, that have been developed from the end of last century, helped us to find an answer to the important questions regarding the occurrence of this phenomenon. Detailed mechanisms that cause sudden loess volumetric reduction due to humidity and load, and the elements that affects the collapsibility are still studied. Furthermore, varied technics are researched, including in-situ tests, which allow estimating the risk of collapse, as well as the methods of its elimination.

The aim of this paper is to systematize the directions of current studies of European loess collapsibility and to indicate their most significant results. The review was made on the basis of the scientific publications published in the Polish and international journals as well as the Journal Citation Reports (JCR) Web of Science database.

Keywords: loess, collapsibility, soil structure, in-situ test, laboratory test

1. Introduction

Loessial soil occurs in many areas, in each of them being soils of special importance. Because of their unique properties, they constitute an important domain of global research in various branches of science. Paleopedology, geomorphology, geology, as well as geotechnics are the examples of fields, where the research on the subject of the loess is still not exhausted. In spite of the intensive development of this scientific domain, the majority of easily accessible papers do not discuss the subject of the loess profoundly enough.

The genesis of the loess has been widely discussed over the past few decades in the circles of notable geologists around the world [1]–[6]. It aroused disagreements among supporters of various monogenetic concepts [7]–[17], until in the sixties and seventies of the twentieth century, the research, which was an attempt to reconstruct the conditions for the accumulation of the loessial soils, allowed to confirm the polygenetic concept [18]. The complexity of processes, which affect the shaping of these soils, makes it very difficult to define them unequivocally. The principle of granulometric composition, frequently used because of its simplicity, results in the erroneous inclusion in the definition of „loess" the soils with a completely different origin. In the cited monographs [19]–[22], the authors presented a consistent view on the need to classify loess on the basis of the origin of the soil. One of the most accurate is the definition of the loess as a Pleistocene extraglacial work, which was transported and sedimentated in the syngenetic stage mainly via the aeolian pathway.

The specific genesis of the loess, affecting the size, shape and arrangement of its particles, as well as the mineralogical composition translate into its well-known sensitivity to water. The rapid changes in volume observed in a part of soils of this type, which are the result of dampness and even a small load, were called the collapse subsidence and were mentioned as the one of the main properties, which, next to the adoption of appropriate geotechnical parameters, should be taken into account when designing foundation structures on the loess soil. It is known, however, that the collapsibility does not apply to all loess [23], [24]. Meanwhile, even in the areas where its occurrence is very common, loess is often disqualified as a stable substrate that can be used for foundation designed for various buildings, only because of the possible collapsibility. Laboratory and field tests indicate, in many cases, good and very good strength and strain parameters of loess [25], [26]; therefore, omitting it when choosing a foundation may result in the adoption of uneconomi-cal construction solutions. Only after supplementary research it is possible to determine the risk of collapsibility in the given area. The results of laboratory and field tests provide the basis for reliable static and strength analysis of the setting. Determining of the sensitivity of the loess to water does not, however, compromise its suitability for the foundation of a building, but indicates the need for dewatering in the immediate vicinity of a designed foundation. If the preventive measures are undertaken and the entry of technological or atmospheric water to the foundation level is forefended, the risk of collapsibility will be eliminated, which will allow full construction use of the loessial substrate. It is important to recognize the loessial soil at the place of the investment both in terms of its geotechnical parameters and sensitivity to water, and then to conduct a thorough analysis of the obtained results.

Scientific research enables to increasingly better understand the mechanism and causes of collapsibility, and papers presenting extensive analyses of this phenomenon spread reliable information. Thanks to this, engineers and geologists have more and more knowledge of the loess behaviour. This paper presents the main directions of research on European loess collapsibility. The analysis of scientific publications was carried out on the basis of national and international journals from the Journal of Citation Reports (JCR) database of the Web of Science.

2. Research of collapsibility of European loess

There are various directions adopted by the authors of the scientific papers devoted to the collapsibility of the European loess. One of them is the study of the loess microstruc-ture, which is sought to be the cause of sensitivity to water. The scanning electron micro-scope SEM is widely used in this type of research. In case of a set of works dedicated to find the influence of the loess microstructure on the water retention curve and changes in the volume of loess due to changes in humidity, the SEM test served to confirm the theses along with the mercury intrusion porosimetry test carried out in parallel [27]. The authors of the paper have identified a range of stress in which intact loess and reconsolidated loess show a greater hysteresis of the water retention curve. On the basis of the conducted tests, hysteresis was found in the entire examined stress range, i.e. 0–400 kPa and 4–140 MPa, however, to the level of stress of 20kPa it was more pronounced for loess of an intact structure, and in the case of the levels of stress exceeding 30 kPa – more significant for reconsolidated loess (Fig. 1).

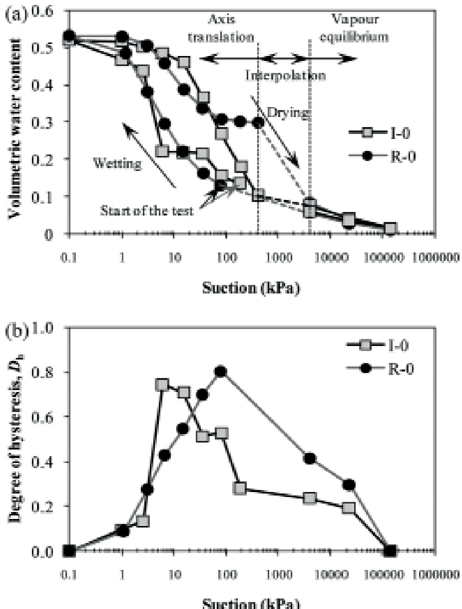

Fig. 1 Comparison of water retention curves (a) and hysteresis level (b) for intact loess and reconsolidated loess.

As a result of the study, the authors created a conceptual model combining the water retention curve with the corresponding function of the density and pore size of the loessial soil.

Loughborough University, where English engineers have identified geometric models of four types of pores, six main types of structures and three processes related to the loess collapsibility [32]. The results of computer-generated geometry models were correlated by the authors with the results of oedometer tests carried out on loess samples reproduced under laboratory conditions. It was found that laboratory soil samples (prepared on the basis of accepted accumulation techniques) correspond to the obtained geometric models and, more importantly, to the natural loess. Moreover, based on the computer-generated geometric model of loess accumulation, it was observed that the pores resulting from the random collapse of model particles often gain a vertical shape, reaching even 80% of the sample height. It is emphasized that it is possible that this type of pores, typical for loess, occurs as a result of genetic processes, and not vegetation, as commonly believed.

The procedure of the preparation of loess samples under laboratory conditions was also developed by Arya Assadi Langroudi [33]. In his work, the author included information on current knowledge regarding collapse subsidence and methods applied to prevent it. In his considerations, he raised the issue of micromechanisms causing rapid change in the volume of soil under the action of water and load, and optimization of practices to strengthen this type of ground. The research was carried out on samples of loess prepared under laboratory conditions, according to a strictly established procedure, specific granulometric composition and percentage of minerals (kaolinite and carbonates). Due to this approach, tested soil samples were identical, and the determined strength of dust particles, dust bonds and intermolecular forces in different humidity and stress conditions were meaningful. In his paper, the author separated 11 major types and 40 subtypes of loess, for which he determined the risk of collapsibility, and using the edometric test he verified the effectiveness of the loess consolidation with the use of selected methods.

Arya Assadi Langroudi and Ian Jefferson [34] point out in their paper regarding loess subjected to water, stress and drying due to the exploitation of a building that the geological past of the loess (in terms of its humidity and loads acting on it) has a great influence on the arrangement of particles. The considerations were carried out on the basis of the results of the research concerning microstructure, particle size and arrangement, as well as loess pores subjected to gradual load increase. Tested samples were prepared in a laboratory according to the procedure which facilitated obtaining uniform samples, some of which were subjected to a selected stress pathway in the dry state, some in the humid state, and the rest in the saturated state. Based on the results of the research, conclusions have been drawn regarding dampness of the loess samples under any load, as a factor affecting the reduction of collapsibility after drying. Initial stress of 25 kPa prior to hydration of the sample was considered to be the cause of the largest increase in its density. At the same time, the content of particles with dimensions of 5 – 20 μm was assessed as defining the permanent retention properties of the loess after the cycle of its watering and drying. As a result of the conducted research, the authors found the possibility of strengthening loess hydrotechnical buildings with a controlled cycle of loading and watering.

Apart from the microstructure and external factors, the behaviour of the loess is also determined by its physical properties, mainly related to the natural moisture of the soil residing in the substrate and its porosity. The studies of the impact of these properties on collapsibility were carried out on loess samples in a direct shear apparatus [35]. It should be emphasized that the tests were carried out both on samples characterized with natural moisture, and after their full saturation with water. As a result of the research, the conclusion was drawn that the humidity and porosity are the main factors determining the structure of the soil in terms of its susceptibility to moisture. Moreover, it was found that these factors manifest themselves simultaneously and are interdependent.

The results of the oedometer tests of samples of Belgrade loess of intact structure taken from exploratory boreholes were compared with the results of parallel in-situ tests using a dilatometer (SDMT) [36]. Obtained sizes of edometric module Eoed for samples characterized with natural humidity were found to be highly consistent with the values of MDMT modules from the in-situ test. On the basis of the performed studies, two possible methods of defining the collapse potential of the loess were determined with the use of the results of the dilatometric test. One of them consists in determination of the ratio of the strain modulus to the edometry module G0/MDMT and its interpretation, the second one – the indication and interpretation of intermediate parameters, such as ID and KD. Clear and coherent conclusions allow us to attempt to apply the criteria of collapsibility indicated in Serbia for the loess from other areas.

Serb loess was also subjected to oedometric test regarding the collapsibility. Meanwhile, observations of subsidence of the existing complex of agricultural buildings were performed [37]. The complex located near Feketić included a mill, an outhouse and an accompanying grain silos. Due to the temporary storage of grains, the stresses transmitted to the loess bed were variable over time, with the maximum stress level of 190 kPa for the silo (including 48% of its own weight) and 155 kPa (59% of its own weight) for the mill. In order to identify the ground, 8 test drillings to a depth of 14.0 m and two cone penetration tests CPT were made. The samples of an intact structure from a test excavation and from the depth with a use of a thin-walled Shelby tube were taken for the laboratory tests. Field and laboratory tests allowed the determination of the geotechnical conditions occurring in the ground. The dominant substrate was loess with a thickness of about 12m, occurring directly above the layer of fine-grained medium-thickened and compacted sands. A double oedometer test helped to qualify the loess as unquestionably collapsible. Subsidence calculations were made for loess with natural dampness, which was assumed, because it was obviously not possible to allow the ground to get moist or to allow water to infiltrate the level of foundation. The calculations were made using the numerical method (elastic foundation) using strain parameters, loads and the foundation level, obtaining the result of 136 mm of subsidence for the silo and 97 mm for the mill. Based on geodetic measurements conducted with the installed points of the geodetic network with an accuracy up to 0.5 mm, it was found that the real subsidence of the mill reached the value of 109 ± 33 mm, and the silo – 175 ± 38 mm. Actual subsidence was measured over 45 months. On the basis of precise analysis, it was found that the difference between the calculated and actual subsidence values resulted from the partial collapsibility, which the ground underwent due to increased precipitation and infiltration of rainwater, with the simultaneous exposure to a significant load. Due to the lack of relevant tests, the increase of the dampness content in the loess forming the ground was estimated on the basis of the amount of rainfall, the filtration factor of the soil and its retention properties. Renewed numerical analyses made for a group of buildings, taking into account the moisture of the ground, allowed the determination of a potential subsidence of 183 mm. The obtained result was classified as large, but not excluding future safe use of the facilities provided that specific recommendations on geodetic control measurements are observed and the drainage in the foundation level is improved.

The in-situ and laboratory tests were also conducted in southern England (near Kent) in order to determine the loess' collapsibility. The scope of field tests included testing the collapsibility on a large-size soil sample treated with water until full saturation and then surface-loaded (with the stress of 210 kPa) for a period of 10 days. Weakening of intermolecular forces during subsidence was documented with the use of various geophysical and geotechnical instruments. The field test of the collapsibility eliminates the problems related to the intake of the intact soil sample and a small scale of the study. The results of laboratory tests (edometric determining of collapsibility) and in-situ tests were matched in order to compare the soil behaviour under the same load, but under two different test conditions [38].

The oedometer tests were also used by Hungarian researchers to determine the collapsibility of the loess [39]. Several dozen performed tests allowed the determination of the dependence of rapid subsidence on the natural humidity of the soil. In the subsidence curves, which present the results of the tests, 3 zones were separated - before a sudden change of the height of the test sample, during collapse subsidence, and after its completion (Figure 2).

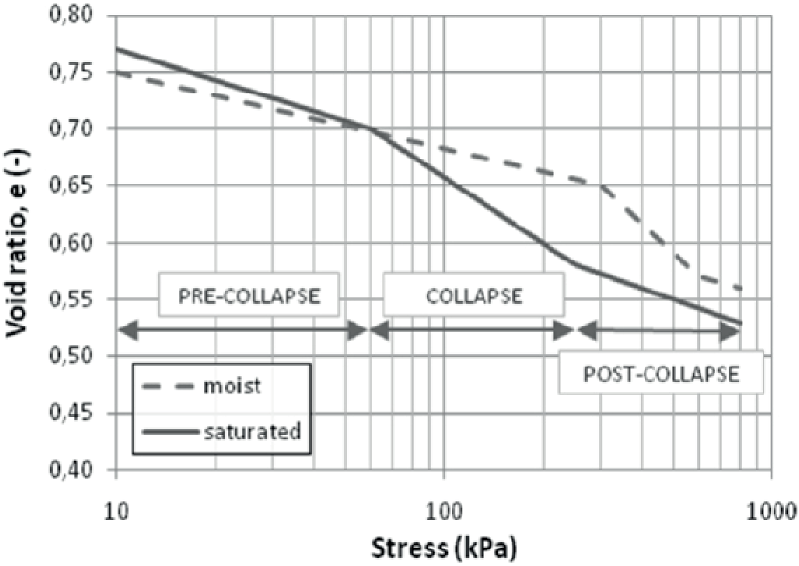

Fig. 2 Typical result of an oedometer test.

Moreover, it was found that in case of soil samples with higher natural humidity, water saturation at higher stress values results in less collapsibility.

Another aspect of the collapsibility of loess was covered by Bulgarian and English researchers: namely, the impact of subsidence on construction, on the example of loess in Western Europe, particularly in Bulgaria [40]. In their work, they focused on estimating the effectiveness of strengthening the loess soil, on the example of the methods used in Bulgaria. In order to determine the safest and most economical solutions applied, the works were undertaken aiming at the analysis of the foundations designs on loessial soil, measurement of the change in soil volume, and determination of the effectiveness of the applied reinforcement method on the basis of the results of tests conducted after reinforcement.

The effectiveness of reinforcement of the substrate with the use of a chosen method was also studied by Alan Lutenegger, Ph.D. [41]. The analysis was carried out with in-situ tests (dynamic probe and dilatometer) and laboratory density tests, determining the loessial soil before and after applying the dynamic load. The load was applied by dropping a concrete compactor of 15 tons from a height of 5 -10 m from the surface. As a result of the conducted research, the influence of dynamic loess substrate density on the potential collapsibility was also determined. Similar research was carried out in Romania to indicate the effectiveness of reinforcement of the loessial soil using the dynamic method [42] and estimating the range of the active zone of the surface load [43]. Estimation of the active zone was associated both with the observation of real structures, mounted on the loess ground and with detailed laboratory tests with the use of an oedometer and a triaxial apparatus.

In the considerations regarding the reinforcement of the loess substrate, one cannot omit the work of the geologist Evstatiev, who describes eight types of techniques tested on loess soils from many areas [44]. There are two main types and four subclasses of the loess depending on their thickness and on the demonstrated collapsibility. Reinforcement techniques can be divided into densification (in a dynamic way, by dampness, vibrations, etc.), change in granulometric composition by adding thicker fractions, surface or volume stabilization with chemical additives or binders, with the use of jet grouting, introduction of elements resistant to stretching into loess, geomembranes, particle drying (electroosmosis, drainage or hygroscopic materials), and finally appropriate shaping of the loess slopes.

A new method of reinforcement of loess with the use of nano-particles of clay was examined by an international group of scientists [45]. Laboratory and in-situ tests were carried out on loess on which the dam in Gonbad in Iran is built. The nano-particles of clay were added to the representative samples of loess in weight proportion ranging from 0.2% – 3%. For such prepared samples, Atteberg's boundaries were determined, as well as Proctor density, compressive strength, collapsibility, and a triaxial compression test was performed without runoff. Moreover, field tests have been carried out in a dedicated research area of loess modified with nano-particles of clay. As a result of the conducted tests, it was found that the addition of nano-particles impacts the change of plasticity, compressive strength, stiffness and collapsibility of loess. The results of laboratory and field tests were considered to be convergent, and the addition of nano-clay particles in the proportion of 2% to the weight of the loess was assessed as the cause of its distinct reinforcement.

The analysis of the change of the plasticity level as a result of many years of floods was conducted in the loess areas in the Volga basin in the European part of Russia [46]. The mentioned paper describes the loess dust in terms of its geotechnical properties, as well as its geological origin. Significant deterioration of the state of the soil was determined, which due to the action of the long-term increased water level changed its consistency from compact to plastic.

Despite the risk due to collapsibility of loess, which is described, among others, on the example of the loess areas of Hungary [47] or Moldova [48], these substrates are often used for construction. The reason of this is mainly that for the most part they occur in a compact, semi-dense or hardplastic consistency, and that is why they have good strength and strain characteristics [26].

3. Summary

The analysis of the papers regarding the subject of collapsibility allows us to ascertain that studies of European loess collapsibility are conducted in many various ways. This extremely important feature is determined with various methods, using both in-situ, laboratory and computer tests. There are many threads mentioned in the papers, which are known to geotechnics for decades, as well as completely innovative approaches to this topic.

The leading examples of research trends regarding European loess collapsibility are the analysis of microstructure, studies of external factors affecting the soil, physical aspects, such as two main characteristics of the loess – porosity and natural humidity, analysis of applied methods of reinforcement of collapsible grounds and the study of the possibility of applying in-situ tests to determine the collapse potential of the loess.

It's important to develop continuously the research and further enlarge of the data set, which in the future may help us to use the existing knowledge to create new standards and guidelines facilitating the research and design process for buildings located on subsidence substrates. The analysis presented in this paper was mainly based on international papers published in the Journal of Citation Reports (JCR) list of the Web of Science database. It means that it's possible and even certain that the important results of local tests regarding loess collapsibility are still not reported to the international news. Therefore, it is necessary to update the global state of knowledge on this subject.

References

[1] Tungsheng L., Loess and the Environment, Beijing: China Ocean Press, p. 1–481, 1985.

[2] Dylik J., Zagadnienie genezy lessu w Polsce, Biuletyn Peryglacjalny, vol. 1, p. 19–30, 125–131, 1954.

[3] Smalley I. J., „In-situ" theories of loess formation and the significance of the calcium-carbonate content of loess, Earth Science Reviews, vol. 7, no. 2, p. 67–85, 1971. DOI:10.1016/0012-8252(71)90082-1

[4] Pye K., Aeolian dust and dust deposits. 1987.

[5] Grabowska-Olszewska B., Wiązania strukturalne w lessach i ich wpływ na osiadanie zapadowe, p. 65–69.

[6] Jahn A., Less , jego pochodzenie i związek z klimatem epoki lodowej, vol. 1, 1919.

[7] Kriger N. J., Less, jego swojstwa i swiaz' s gieograficzieskoj sriedoj. 1965.

[8] Różycki S. Z., Pyłowe utwory typu lessowego na świecie ich występowanie i geneza, Studia Geol. Polonica, vol. LXXXV, p. 193, 1986.

[9] Lysenko M., V. V. Dokuchayev i lessovaya problema, Pochvovedemye, vol. 7, p. 59–67, 1956.

[10] Obruchev V. Λ., Loess as a particular kind of soil, its genesis and the tasks of its investigation, Byulleten' Kommissii po Izucfteniyit Chetverlichnogo Periods, vol. 12, p. 5–17, 1948.

[11] Łoziński W., „Die periglaziale Fazics der mechanischen Verwitterung", [in:] Compte Rendu de la XI :e Session du Congrès Géologique Internationale, 1912, p. 1039–1053.

[12] Geikie J., The tundras and steppes of prehistoric Europe, Scottish Geographical Magazine, vol. 14, no. 6, p. 281–294, 1898.

[13] Berg L. S., Loess as a product of weathering and soil formation. 1960.

[14] Gansen R., Die Entstehung und Herkunft des Löss. 1922.

[15] Richthofen F., China. 1877.

[16] Hoobs W. H., The glacial anticyclones and the European continental glacier, American Journal of Science, vol. 241, no. 4, p. 333–336, 1943.

[17] Soergel W., Lösse, Eiszeiten und paläolitische Kulturen. 1919.

[18] Maruszczak H., Definicja i klasyfikacja lessów oraz utworów lessopodobnych, Przeglad Geologiczny, vol. 48, no. 7, p. 580–586, 2000.

[19] Tutkowskyj P., K voprosu o sposobe obrazovaniy a lessa, Zemlevedeniye, vol. 6, no. 1–2, p. 213–311, 1899.

[20] Grahmann R., Der Löss in Europa. 1931.

[21] Pécsi M., Lösse und lössartige Sedimente im Karpatenbecken und ihre litostratigraphische Gliederung, Ptermanss Geographische Mitteilungen, vol. 110, p. 176-189; 241-252, 1966.

[22] Malinowski J., Badania geologiczno-inżynierskie lessów, 1971.

[23] Grabowska-Olszewska B., Osiadanie zapadowe lessów in: Przegląd Geologiczny, vol. 31, no. 3, p. 162–165, 1983.

[24] Stróżyk J., Charakterystyka ściśliwości gruntu pylastego, na przykładzie lessu z rejonu Wrocławia, Górnictwo i Geoinżynieria, vol. 1, p. 575–582, 2009.

[25] Nepelski K., Rudko M., Identyfikacja parametrów geotechnicznych lessów lubelskich na podstawie sondowań statycznych CPT, Przegląd Naukowy Inżynieria i Kształtowanie Środowiska, vol. 27,

no. 2, p. 186–198, 2018.

[26] Nepelski K., Lal A., Franus M., Analiza wyznaczania konsystencji lessów lubelskich na podstawie wyników sondowań statycznych CPT, Budownictwo i Architektura, vol. 15, no. 4, p. 183–194, 2016, DOI:10.24358/Bud-Arch_16_154_18

[27] Charles Wang Wai Ng, Hamed Sadeghi, S.K. Belal Hossen, C.F. Chiu, Eduardo E. Alonso S. B., Water retention and volumetric characteristics of intact and re-compacted loess, Canadian Geotechnical Journal, vol. 53, no. 8, p. 1258–1269, 2016, https://doi.org/10.1139/cgj-2015-0364.

[28] Delage P., Cui Y. J., Antoine P., Geotechnical problems related with loess deposits in Northern France, Proceedings of International Conference on Problematic Soils, no. May, p. 517–540, 2005.

[29] Delage P., Geotechnical Problems Due To The Collapse Of Unsaturated Soils: The Case Of Loess From Northern France, Journal of Applied Engineering Science & Technology, vol. 1, no. 1, p. 17–22, 2014.

[30] Cui Y.-J., Terpereau J.-M., Marcial D., Delage P., Antoine P., Marchadier G., Ye W.-M., A geological and geotechnical characterisation of the loess of Northern France, Skempton Memorial Conference, 2004, p. 417–428.

[31] Knight K., The origin and occurrence of collapsing soils, Reg. African CSMFE (1), 1963, p. 127–130.

[32] Assallay A. M., Rogers C. D. F., Smalley I. J., Formation and collapse of metastable particle packings and open structures in loess deposits, Engineering Geology, vol. 48, no. 1–2, p. 101–115, 1997.

[33] Langroudi A. A., Micromechanics of collapse in loess, no. August, 2014.

[34] Langroudi A. A., Jefferson I., Collapsibility in calcareous clayey loess, International Journal of GEOMATE, vol. 5, no. 1, p. 620–627, 2013.

[35] Dobrescu C. F., Calarasu E. A., Ungureanu V. V, Engineering approach on stability assessment of loess soil structures considering basic geotechnical characteristics, Bulletin of the Transilvania University of Braşov, vol. 9, no. 58, 2016.

[36] Dušan B., Zoran B., Čebašek V., Šušić N., Characterisation of collapsing loess by seismic dilatometer, Engineering Geology, vol. 181, p. 180–189, 2014.

[37] Santrač P., Bajić Ž., Grković S., Kukaras D., Hegediš I., Analysis of calculated and observed settlements of the silo on loess, Tehnicki vjesnik - Technical Gazette, vol. 22, no. 2, p. 539–545, 2015.

[38] Zourmpakis A., Boardman D. I., Rogers C. D. F., Jefferson I., Gunn D. A., Jackson P. D., Northmore K. J., Entwisle D. C., Nelder L. M., Dixon N., Case study of a loess collapse field trial in Kent, SE England, Quarterly Journal of Engineering Geology and Hydrogeology, vol. 39, no. 2, p. 131–150, May, 2006.

[39] Mahler A., Turi D., Vonza C., Evaluation of the collapsibility risk of loess based on oedometer test results, no. 1963, p. 135–139, 2011.

[40] Jefferson I., Rogers C., Evstatiev D., Karastanev D., Treatment of metastable loess soils: Lessons from Eastern Europe, Elsevier Geo-Engineering Book Series, vol. 3, no. C. p. 723–762, 2005.

[41] Lutenegger A. J., Dynamic Compaction in Friable Loess, Journal of Geotechnical Engineering, vol. 112, no. 6. p. 663–667, 1986.

[42] Dumitru M., Geotechnical Testing for Certification of Loess Improvement By Dynamic Compaction, 5th International Young Geotechnical Engineers' Conference, 2013.

[43] Bally J. R., Some specific problems of wetted loessial soils in civil engineering, Engineering Geology, vol. 25, no. 2–4. p. 303–324, 1988.

[44] Evstatiev D., Loess improvement methods, Engineering Geology, vol. 25, no. 2, p. 341–366, 1988.

[45] Tabarsa A., Latifi N., Meehan C. L., Manahiloh K. N., Laboratory investigation and field

evaluation of loess improvement using nanoclay – A sustainable material for construction, Construction and Building Materials, vol. 158, p. 454–463, 2018, https://doi.org/10.1016/j.conbuildmat.2017.09.096.

[46] Baranova M., Maltsev A., Vasilyeva D., Environmental construction safety on loess soils in the coastal zone of reservoirs, vol. 02015, 2017.

[47] Fodor P., Kleb B., Engineering geological problems in loess regions of hungary, Quaternary Intenational, vol. 24, no. C, p. 25–30, 1994.

[48] Olyansky Y. I., Kuzmenko I. Y., Shchekochikhina E. V., Features of Construction Buildings on the Loessial Soil of Central Moldova, Procedia Engineering, vol. 150, p. 2208–2212, 2016, https://doi.org/10.1016/j.proeng.2016.07.265.

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The concept of light and color as a key element of experiencing 'feeling architecture'

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Abstract: This article investigates the role of light in the perception of contemporary architecture. Light is an essential element that creates and reveals the beauty of architecture, emphasizes its aesthetic values, and allows us to feel the unlimited space „with one's whole self". Since time immemorial, light in combination with colour has played an important role at the design stage and later in its reception. Nowadays, technological and civilization progress has contributed to the increase in the role of light and color, enabling their application already at the moment of design. Increasing expectations towards architects have led to an intensification of the phenomenon, which is increasingly expressed in projects filled with light and colour.

Keywords: architecture, light in architecture, feeling of architecture

1. Introduction

Since the beginning of the centuries, light has inspired people as a gift of nature, sustaining life on Earth. It constitutes an active element of life, being in the past as well as now, a source of energy. It is one of the key elements of expression, without which it would be impossible to perceive the architectural space and the elements that it is composed of.

Light is considered to be one of the most important factors defining architecture - it is a „play of solids in light", as Le Corbusier [1] wrote. Since the earliest times, it has been used in the creation of plastic shapes of buildings and interiors. In ancient times, buildings which worshipped light as the main source of life were erected. Nowadays, it inspires architects, becoming a material and an independent element of composition, serving to express ideas, philosophy and current trends of the century.

Currently, thanks to the widely developed technology in construction, light allows to create both architectural and urban spaces. Thanks to its versatility and proximity to the human perception senses, it gives a unique character to the objects. It is more than just making the building more visible, it is a creation of the environment, atmosphere, monumentality, intimacy and tranquility, which strongly influence the feelings and emotions of a person. It builds a three-dimensional space, emphasizing the atmosphere and aesthetic values of the building.

Today, the concepts of „light" and „colour" have been characterized as physical or psychological-physical phenomena in which colour is considered to be a kind of light radiation. Le Corbusier, in his work "Polychromie architecturale", defining the interdependencies between light and colour, called „colour, daughter of light", so for modernists colour had the

Postmodern concepts in architecture reduced its essence to the idea of space in which they became a source and field of activity [3]. Architecture is created, recognized, understood, „felt", and remembered primarily as compositions of three-dimensional forms placed in light and colour. Architectural perception is achieved by synthesizing the interdependencies among the individual elements of buildings that co-create them, constituting an excellent source of colour emission. The concepts of light and colour have undergone various transformations over the years, but their strength and power of meaning have not diminished to this day, playing a key role in the process of feeling architecture.

The aim of this work is to show the meaning of light and colour in the perception, or in other words, the „feeling" of contemporary architecture. The importance of these two elements was presented on the example of residential and public buildings.

2. Light in architecture

The phenomenon of architecture consists in engaging all the most important senses of humans: sight, touch, hearing, and sense of smell at the moment of its reception, which allows to „feel" the beauty with the whole of oneself. The basic elements that make up the visual image of architecture are light and colour, without which it loses its monolithic character and ceases to exist.

The notion of „light" was shaped as a result of long-term research, during which it was characterized as a physicochemical or physiological-psychological phenomenon. It is considered to be an electromagnetic wave that propagates at a huge speed in various transparent material media [4]. The phenomenon of light made it possible to decipher not only its physical nature, but above all its internal structure of matter and the role it plays in the process of „feeling" - the perception of architecture. Colloquially, light is the visible part of the electromagnetic radiation received by the retina of the human eye, which includes visible, ultraviolet, and infrared rays of light.

For many centuries scientists have been asking themselves the same question: what is light? Greeks are considered to be precursors of the phenomenon of light reflection and the discovery of a straight line of light rays. They claimed that light from heavenly bodies has a different character than other types of radiation. According to Greek theory, the source of light is therefore the human eye, which sends out an invisible kind of sensors - i.e. light, and informs people about the shape, size and location of objects [5].

Already in the 6th century B.C., Pythagoras was the first to notice that light comes from the sun and stars and that it is emitted by every luminescent celestial body. By splashing on the objects encountered, it bounces off them, accidentally hitting the eye and causing them to be seen. The turn of the 5th/4th century B.C. saw Plato's theory that light is three separate streams of light from the eyes, the object visible, and the light source that interact with each other [6, 7].

Euclid was the next one to study geometric optics, and it was he who formulated the principle of the rectilinear propagation of light and the law of reflection. He noticed that light falls straight and reflects. Newton, however, claimed that the propagation of light is based on the straight motion of tiny molecules passing from a given source to the human eye, producing an impression of light. This theory was called the „corpuscular theory of light". Further research in the 19th century by Young and Fresnel led to the discovery of diffraction and light interference, confirming its wavy nature [8].

The above theories are the basic source of knowledge concerning the laws governing the

same meaning as the material from which architecture was built at that time [2].
propagation and reflection of light. Their discovery is an important basis used in the design process, because thanks to the knowledge of these rules, architecture becomes predictable and shows the intention of the creator.

3. Colour in architecture

Man's vision of colours is due to the sense of sight, which is an essential tool in the perception of the outside world. It provides important information about its colours, shapes and phenomena occurring in it. The process of receiving elements of the external environment consists of complex psychological, physiological and physical processes. A person receives about 80% of the information visually from the environment, while the hearing organ has a complementary function and its share in obtaining information is relatively small. The process of seeing light and colour by humans plays a key role in the perception and feeling of architecture, positively influencing their well-being [9]. Colour contrast plays an important role in the process of colour vision, which contributes to colour change as a result of other stimuli acting simultaneously on the retina of the eye [10]. Therefore, light is one of the most important factors co-creating architecture, because without it, the form, texture and colour do not exist.

Colour in architecture for many years has been considered to be an insignificant factor, mainly used by interior designers. It was not until the 90's of the 20th century that its interest and wide application in architecture came back. Today, the use of colour and light in the design process is connected with changing global trends. Colour is used to emphasize and give a specific character to a given space, according to the intentions of the architect and investors. The designers have at their disposal a wide range of different coloured building materials, which correspond to the current trends. The rapid development of technology and the emergence of new multicoloured materials used in construction, caused that the imagination of architects has no limits, which is visible in the newly designed buildings.

Designers and architects use their knowledge of colours when designing public and residential buildings. In addition to psychological effects, colour also has a therapeutic function, which is also often used at the design stage. Its skillful application allows the designers to warm up, cool down, lift or lower the room, and properly let in daylight, which enables the recipient to have a better insight into the depths of a given architecture.

By observing buildings from a certain distance, they may seem flat, because the human sense of perception is not able to separate the solids from the surroundings. The visible outline does not allow to distinguish its architectural depth and convex forms are perceived as undefined space. Colour in architecture, unlike in painting, plays a complementary role. It serves mainly to emphasize and highlight certain details, giving the building a unique character.

Primitive people used natural-coloured materials, which were an integral part of the landscape of the time, to build their homes. Later, when man discovered the way colours could be produced, it was possible to obtain a variety of, but still limited number of colours. When the colour of building materials began to depend on man, it began to be used on an increasing scale. For most people, colour has only symbolic meanings, and so in Sweden, for example, houses are often painted in deep red, imitating more permanent, old manor houses that used to be built of red brick.

Colour in architecture is used to emphasize the character of the building, accentuate its form, and show the most interesting elements or hide imperfections. It is not the most important element in the design process, as is the case in painting. Without colour, a work of art ceases to exist, while architecture gives an individual character by breaking up the monotony of a solid and giving it a new function.

Sometimes colours add lightness, or optically enlarge or reduce the space. The facility, designed for children and fun games, will have a multitude of colors, while the monumental and heavy architecture will be filled with subdued and soft colors. Colour in interiors serves the function of accentuating the form and architectural divisions. After choosing the right colour, it is possible to optically enlarge or reduce the size of the room, as well as shorten or extend it. Colour is a powerful means of expression for the architects, because thanks to it, they can not only emphasize the structure of the building, but also allow to create a unique architectural composition. It is therefore obvious that there is an unexplainable relationship among material, light, and colour.

It can be said that color is only a subjective feeling of every person, because when there is no light, also color disappears. Colour has a special impact on the psyche of a person, and colour in an individualized form influences emotional states.

Le Corbusier wrote: „architecture is a wise, thoughtful play of solids in the light", so the art is to create a building with appropriately selected colours, which will have a positive impact on the viewer. When Corbusier designed the houses in Pessac, he created the impression of a colourful composition floating in the air through the appropriate use of colour on the buildings. The introduction of lightweight reinforced concrete construction and the addition of colour, reduced the weight and monotony of the residential buildings of the time. In this way he created „artistic sketches in colour", a collage of overlapping, semi-transparent buildings intermingling in an unbelievable way.

Not long ago, colour was treated as not important and was only an addition to the architecture, little attention being paid to it. Over the years, its power has been appreciated and it has been used on an increasing scale to decorate buildings. In many towns and cities, the prefabricated housing estates were repainted using a rich palette of colours, which not only pleases the eye, but also helps to build the identity of the local community.

The designer of a residential estate at Smyczkowa Street in Lublin has created a high residential development with an internal street and courtyard. The density is high, so people often look into each other's windows and their balconies almost touch each other to make contacts. The architecture of residential buildings is a simple box shape, but what gives them the hallmarks of uniqueness, is a well-thought-out colour concept. In this housing estate, the focus was put on painting wall planes in some kind of patterns, interwoven with subdued colors. Some of them are dominated by shades of green, interspersed with yellow and red, while others have warm colors of oranges and greens. Graduation of colour intensity occurs when colours are exposed to the sun or the shade, and where twilight prevails, the colours get stronger. (Fig. 1 and 2) The presented residential complex is an example of an interesting social development, which improves living conditions not only through its shape or infrastructure, but in particular, creates a friendly atmosphere through the use of appropriately subdued colors.

The colour tradition is not a static phenomenon. Let us take Turin as an example, where for many years the yellow colour has been perceived as characteristic for this city, and in the 1960s more than 1,000 facades were repainted to this colour [10].

Therefore, colour on the one hand creates buildings, space and architecture as an indispensable element of human life and functioning. (Fig.3.) On the other hand, its inappropriate use may disfigure a given architecture, having a destructive effect on the image of a given place. (Fig.4.) The building of the Lublin Oncology Centre located in Lublin can be used as an example of improperly applied colour in architecture.

The body of the building with its colourful, loud orange-yellow façade dominates the view over a part of the city, and in a rather blatant way blends in with the panorama of the city. The nine-storey building located at Jaczewskiego Street is clearly visible from many parts of the city and this is due to the inappropriate use of bright and „biting” colours on the façade. The location of the building on the elevation in an additional way exposes the nightmarish mass, exposing its imperfections. In the original plan, the façade was to be completely different, where instead of bright colours topped with a brown stripe, glass interlaced with light aluminium panels was to be used. Financial considerations forced investors to introduce changes to the façade, which would have been more economical but, as it turned out, destructive from a visual point of view. The use of bright, intense yellow and orange colours complemented by a dark shade of brown has contributed to the visual disfiguration not only of the building but of the entire area.

From a psychological point of view, it is well known that optimistic and vivid colours influence people in a positive way, adding energy and willingness to act. This is particularly important for the sick, as they often awaken in them the will to fight the disease, increasing their willingness to live. However, this type of argument does not justify the colour scheme used in the COZL. The therapeutic-therapeutic effect on the patient fulfils its purpose if it is used inside the room where the patient is staying. On the other hand, if colour is used on the external façade of the building, it loses its therapeutic effect and has a purely decorative or, as in this case, „destructive” function. The bright yellow-orange colour scheme of the building is criticised by tourists, residents and architects, who call it „a nightmare”, „gargamela” and „cancer”. The building also took second place in the „Macabryła 2015” competition for the biggest architectural fail of the year.

Fig. 1, 2. A residential block of flats on Smyczkowa street, 2018, author’s photo.

Fig. 3. Residential buildings renovated in colorful tones, Ajaccio, Corsica in France, 2016, author's photo.

Fig. 4. Center of Oncology in Lublin, 2018, author's photo.

4. The role of light in architecture

Contemporary architecture finds many followers and continuators of the creative use of light. A good example is the Osaka Light Church (1989) of the Tadao Ando project, in which light naturally plays an independent role. The architect's concept of simplicity and legible geometry, with excellent precision, introduced sunlight in a controlled manner, which emphasized the individual elements and shapes of the architecture.

The Kimbell Art Museum in Forh Worth, designed by L. Kahn, is also an important example that perfectly emphasises the importance of light in architecture. The architect created a space of metaphysical significance, which was shown by means of light. The objective was achieved through the use of uniformity of materials, space, and appropriately introduced daylight [11].

Light has been explored and used in art, architecture and painting for centuries. Ancient Greeks are considered to be the precursors, who learned about phenomenon of light in depth. At that time this knowledge exerted a huge influence on the process of formation of numerous buildings, i.e. Roman Pantheon, Egyptian temples, Hagia Sophia or Greek cathedrals, recognizing light as a source of life [5].

One of the best examples of light from a fully enclosed interior illuminated from above is the Pantheon. Entering the interior, the greatest impression is made by the huge space, in which there is harmony and tranquillity. The whole structure is dark. As we reach the rotunda, we can see a gentle light coming in through a high hole in the ceiling, which is a metaphor for the connection between the buildings of the outside world and the heavenly vault. The evenly distributed light in the interior perfectly illuminates the beautiful marble floor, which reflects them to the sides and the rest of the room, giving softness and plasticity to the forms found there.

Hagia Sophia, the largest building in Istanbul, is another excellent example of the use of daylight in the „feeling” of the architectural interior. The palace church built by Emperor Justinian in 532-537 is the most perfect example of a dome basilica with a central layout. The three-nave building with 107 columns, covered with a dome, is filled with windows on all sides. The light entering through them provides amazing light effects that give the impression of a huge dome floating above the ground, becoming a lightweight, like an openwork vault. The rays of light falling into the interior give incredible plasticity and lightness, additionally illuminating beautiful interiors covered with mosaic patterns. A well-designed building, thanks to the appropriately introduced light, gives special attention to those elements that are most important in the church, giving them a majestic character.

Light in architecture is one of the tools that give an expressive form to a solid, without which space and its co-creating elements would have no raison d’être. It is not possible to control the intensity or colour of natural light, as it varies according to the time of day or year. Light allows us to look at architecture from a different perspective, it is a carrier of information, which not only allows us to look at it, but also to „feel it”. More and more often the creation of space takes place thanks to the use of modern technological solutions, i.e. artificial lighting, which from a better perspective allows for the reception of a given object. Light, through its diversity, allows one to recognize the true plasticity of an architectural work and „feel” it with all of oneself.

Light, which is a basic element necessary for the proper functioning of the human body, plays a very important role in the creation of architectural space. It makes it possible to present the building from a completely different perspective, creates new forms, emphasizing elements of architecture that deserve more attention of the audience. It allows to emphasize or blur borders, and weaken or enhance contrasts using the phenomenon of reflection and light penetration. Suggestive perception of space is possible thanks to the intensity of light and colour, which are used for creative presentation of a given interior and architectural objects contained therein. Modern technologies in the construction industry allow to combine the external and internal worlds, creating surprising visual effects. On the one hand, light can emphasise the shape of the building, and on the other hand, it creates the appearance of the perceived shapes, or partially masks them. Sufficient amount of daylight let into buildings allows the proper functioning of a person inside. Poorly lit buildings cause rapid fatigue, sluggishness, or depression due to the lack of sufficient daylight. That is why it is so important to skillfully introduce daylight already at the architectural design stage.

More or less concentrated light falling in the same direction best exposes form and texture, providing a sense of security and „being” together in a given space [12]. It is one of the important factors shaping architecture, where, apart from plans, sections and elevations, it is an important element of usability for man. Architecture not only serves the purpose of admiring from outside, but also creates a space that satisfies the inner needs of man [12].

Many art theorists believe that light is one of the most important factors defining architecture. Modern engineers are often inspired by both natural and artificial light. More and more often used daylight, combined with innovative technology and various building materials, allows to design unique architectural objects that impress the viewer.

Contemporary architecture comprises of wonderful buildings, which surprise the viewers with unprecedented solutions both in terms of the selection of material and the use of light. The Scientific Information Centre and Academic Library in Katowice are good examples in which light naturally plays an important role. In the project, the authors used various materials such as concrete, steel, glass, brick or coloured mosaic in order to obtain interesting visual effects. The library building consists of two intersecting cubes with two glazed entrances. It is a compact monolithic mass covered with large sandstone slabs, which are separated by narrow windows. The stone covering the façade of the building was consciously selected by the architects because „its split texture and arrangement make the façade look different in the sun and different at dusk, different dry and different after rain, different in summer and winter, different from a close up and far away" [13]. The dense arrangement of the windows causes that after dark, they give the building the plasticity and mysteriousness, at the same time emphasizing its texture. The architecture is simple and legible in its geometry, dominated by concrete and steel. The intention was to use a large number of windows so that they would provide enough light for the reader's needs. The incoming light is controlled by the stream or reflection of the sun's rays. An important role is played here by the introduced aspect of „silence", which is achieved by controlled introduction of light and the materials used. The design of the library, both inside and outside, uses simple and minimalist means of expression characteristic of contemporary architecture. The rhythmic layout of walls, bookshelves, and tables is complemented by wooden elements of balustrades and wooden floors, giving the interior a „warm" and cosy character. (Fig. 5,6,7)

An equally interesting public facility designed by Bolesław Stelmah is the Meeting of Cultures Centre in Lublin. Both inside and outside the building, we can observe the play of light scattered on various textures and structures. Glass, combined with raw concrete and steel elements, creates an unusual building, which is a marker of modern architecture. The building was designed with many glass surfaces so that sunlight could freely penetrate into the interior, to emphasize and exhibit the works of art presented there. The glass used, thanks to its excellent transparency, ensures greater permeability of daylight while illuminating the interior of the building. A glass exit to the roof and spatial glazed structures on the roof are an innovative approach to traditional building materials used in the project. The unique texture of glass on the façade of the building is characterized by a unique and uniform surface, which provides adequate illumination, creating an impression of privacy. The architect perfectly met the requirements set for him and designed a unique building, which perfectly fitted into the structure and character of the city. (Figures 8, 9, 10 and 11)

Bolesław Stelmach describes his building as connecting the past with the future. The sloping hills in front of the building symbolise the burial mounds associated with the past, while the glass multimedia facades reflect the present and the green roof is the near future of architecture [14].

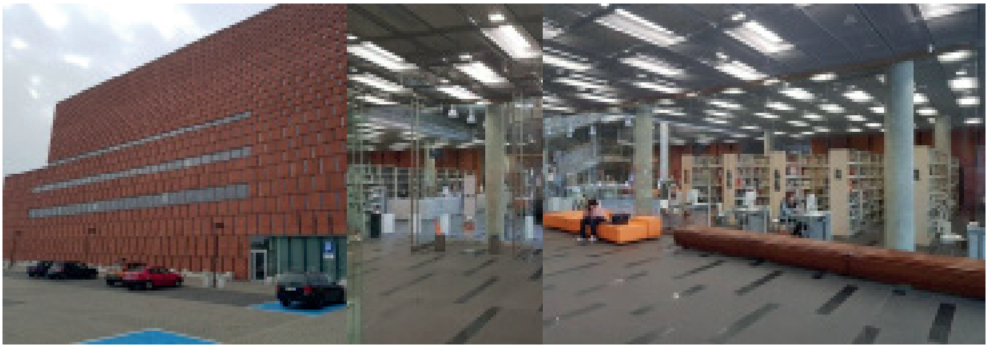

Fig. 5, 6, 7. Center of Scientific Information and Academic Library in Katowice, 2008, photog. Jacek Małyszek

Ryc. 8, 9, 10, 11. The Cultures meeting center in Lublin, 2017, author's photo

Contemporary architectural trend, in search of originality, uses the influence of light combined with raw materials and modern technology. Light is used as a key element necessary to maintain communication with the outside world. Light and colour complement each other, making it possible to better understand and „feel" architecture as a composition of three-dimensional and spatial solids.

5. Conclusions

Architecture, light, and colour have cooperated and complemented each other for centuries. Both colour and light intensity play an important role in architecture, as they are an essential tool for the creative presentation of architecture. Modern technology makes it possible to connect the outside world with the interior of the building, where the use of appropriate building materials allows an even better and more effective presentation of the building body, creating a unique visual effect. Light and shadow, on the one hand, shape and expose the silhouette, and on the other hand, can hide what is not very attractive. Regardless of the epoch or style in which it was created, light has always given architecture its own value and ensured also economic benefits that are important already at the stage of sustainable design. Multilateral use of light is possible thanks to a greater awareness of designers and huge technological possibilities. Regardless of current trends or fashion, the use of light in architecture has a timeless dimension. It reveals the aesthetic aspects of the buildings, showing their shape, texture or colours. It is an excellent material that can be formed. Thanks to its properties, it enables designers to create magnificent architecture in which materiality ceases to matter when it is not visible to the naked eye.

The basic function of light in architecture is to expose the building, its details and co-creating elements. More and more frequently, it also plays an entertaining, decorative and aesthetic role in a given space. Adequate light intensity in relation to a specific surface determines the perception of a given solid in urban space. The resulting light phenomena deepen the effect of seeing architectural forms, which allow an in-depth and profound „feeling" of architecture.

The architecture of light is a „magical" field, upholding the heritage of the whole essence of humanity. Design, classical architecture, interior design, and photography intersect there. Light makes architecture one of the most complex, and at the same time, important art forms among other design and artistic specialties.

The beauty of today's architecture is, on the one hand, to build simple cubic solids with the appropriate use of modern materials. On the other hand, it is the „art" of selecting individual elements, colour and light of the designed buildings. Contemporary architecture is, above all, a large amount of glass, brick, concrete and steel, and it is the „architecture of light", which gives lightness, transparency, and illusory character to the building. It is an excavation of beauty by emphasizing ceilings or facades and giving an individual architectural context to the solid.

Literature

[1] Martyniuk – Pęczak J., Światła miasta, Wydawnictwo MARINA, Wrocław 2014.

[2] Gage J., Kolor i kultura. Teoria i znaczenie koloru od antyku do abstrakcji, tłum. J. Holzman, Kraków 2008.

[3] Rabiej J., Architektura: sztuka transfiguracji, Gliwice 2013.

[4] Marcinkowski R. [red.], Słownik Języka Polskiego, tom 3, Wydawnictwo Naukowe PWN, Warszawa 1981.

[5] Płochoccy E. i Z., Światło odwieczna zagadka, Wydawnictwa Normalizacyjne Alfa, Warszawa 1988.

[6] Krokiewicz A., Zarys filozofii Greckiej, Aletheia 1995.

[7] Verdenius W.J., Parmenidesa koncepcja światła, Przegląd Filozoficzny 2/54 (1992) 281.

[8] Nawrot A., Karolczak D., Jaworska J., Encyklopedia fizyki z astronomią, Wydawnictwo GREG, 2011.

[9] Konarski S., Światło i barwa, Instytut Wydawniczy Zawiązków Zawodowych, Warszawa 1982.

[10] Linton H., Color on Architecture. Design Methods for Buildings, Interiors and Urban Spaces, New York 1999.

[11] Ando T., Fehn S., Wolf G., Fehn T., Wolf S., Ando G., The Secret of the Shadow: Light and Shadow in Architecture, Wasmuth 2002.

[12] Rosmussen S. E., Odczuwanie architektury. Wydawca Karater, Kraków 2015.

[13] Wywiad dla tygodnika „Polityka" Piotr Śmierzewski z HS99. http://www.ciniba.edu.pl/ [dostęp: 17.07.2016].

[14] http://www.architektura.info/index.php/architektura/polska_i_swiat/centrum_spotkania_kultur_w_lublinie [dostęp: 16.09.2016].

Światło i kolor jako kluczowy element ‘odczuwania architektury’

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Streszczenie: Niniejszy artykuł w szczególny sposób zwraca uwagę, na rolę jaką pełni światło w odbiorze współczesnej architektury. Światło stanowi zasadniczy element kreujący i uwidaczniający piękno architektury, podkreśla jej walory estetyczne i pozwala odczuwać nieograniczoną przestrzeń „całym sobą”. Od zarania dziejów światło w połączeniu z kolorem odgrywało istotną rolę już na etapie projektomania a później jej odbioru. Współcześnie postęp technologiczny i cywilizacyjny przyczynił się do zwiększenia roli światła i koloru umożliwiając zastosowania ich już momentu projektowania. Wzrastające oczekiwania wobec architektów spowodowały intensyfikację zjawiska, która coraz częściej wyrażana jest realizacjami przepełnionymi światłem i kolorem.

Słowa kluczowe: architektura, światło w architekturze, odczuwanie architektury

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Increasing The Energy Efficiency of Dwelling Houses: Case Study of Residentia; Quarter in Upper Silesia, Poland

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Abstract: The paper assesses thermomodernisation measures aimed at improving energy efficiency of dwelling houses in a city quarter in Upper Silesia, Poland. The area was encompassed by the city council's program of emission restriction that promoted energy saving activities. The assessment was carried out by means of thermographic examination. It confirmed the fact that the thermomodernisation measures taken so far provided considerable improvement, but did not solved all issues. Further works should be undertaken on the basis of thorough examination of the current condition of the buildings.

Keywords: energy efficiency, residential buildings, insulation, thermography

1 Introduction

Thermography is used worldwide in the construction industry for the research and quantity analyses [1, 2, 4, 7, 9, 15, 20] as well as quality analyses [5, 10, 17, 21]. Balance-sheets are made of the demand for energy [3, 10, 11, 16], as well as their analyses and then on their basis – the attempts at modelling the use of heat energy in order to obtain the optimum solutions [6, 12, 19].

In the currently analysed case of the Polish quarter of the Upper Silesia the program aimed at increasing the energetic quality of the dwelling houses was carried out in a positive manner thanks to the cooperation of the tenants, the self-government and the managers. The effect of those activities is limiting the emission of CO2 resulting mainly from the change of the source of heat used for heating the flats as well as obtaining warm water and the improvement of the thermal parameters of the walls and ceilings. In each of the modernized buildings the same range of thermomodernisation activities was carried out. The author estimated them in the aspect of insulation quality and the issues concerning heat escape from the building made visible after insulation.

2 Case study on the basis of a program accepted for the Upper Silesia in Poland

The program of limiting the emission of CO2 for the Polish quarter under analysis was established in 2007 [18]. The time of accomplishment of the program comprised the years 2008 – 2010. Financing the modernization activities made it possible for the final recipients to obtain funds for the actions they were taking up. Every owner of a flat in the analyzed quarter could take advantage of it.

2.1 The accomplished range of activities

The accepted investment tasks concerning dwelling houses according to the approved plan [17] consisted in: isolating the walls and ceilings (of the basement and the top floor), renovation of the flues and their exchange for combustion ones, exchange of most of the door woodwork and part of the window woodwork as well as the exchange of the heating system for the double-function gas stoves. The program comprised 610 flats in 39 dwelling houses owned by the city.

2.2 The effects of the activities within the limits of the modernization program of the quarter from 2008 to 2010 [19]

The accomplishment of the program of thermomodernisation activities made it possible to achieve 100% of the intended ecological effects in November 2010. Apart from the decrease of heat energy demand of the buildings it resulted in a substantial restriction of harmful chemical compounds emission to the atmosphere. At the same time it also restricted the generation of solid waste i.e. containing the harmful substances gathered in table 1.

Table 1. The obtained ecological effects [17]

No.	The ecological effect of the thermomodernisation investment
1	dust – 10.674 kg/a
2	SO2 - 5.977 kg/a
3	NOx - 532 kg/a
4	CO - 37.045 kg/a
5	CO2 - 802.895 kg/a
6	b-a-p - 8,07 kg/a
7	decrease of heat energy demand by about 5.934 GJ/a

The undertaken activities improved the living comfort of the inhabitants of the quarter under analysis and reduced the environment degradation, they also made the quarter more attractive as a dwelling place. The range of complex thermomodernisation of the houses connected with the modernization of the existing heating systems and their exchange into ecological ones included about 55% of all inhabitants of the quarter.

Due to the activities taken up in the quarter and accomplished in the years 2008 – 2010 on the basis of the accepted program of improvements. The heating demand in the quarter has been reduced by more than 72%.

3 Estimation of the state of dwelling houses after thermomodernisation carried out in the years 2008-2010

The estimation of energy absorption of the building structures was carried out by means of thermovisual examination. The author is convinced that the best non-destructive method for the houses after thermomodernisation is using the thermographic method. This is the way to obtain information concerning the technical-energetic state of the analyzed buildings. The author made the first research in 2006 together with W. Adamczewski an expert as far as thermographic research is concerned. The source of the research and the analysis was described in a dissertation [14]. Later on the author carried out cyclic research by means of a thermovisual camera and presented the analysis during the years 2011-2012. Thus her opinion concerning the estimation of the energetic quality of the buildings is mainly based upon her own research carried out cyclically since 2006 in the region of south-eastern Poland. The conviction is also confirmed by long-term research made among others by H. Nowak [6], as well as Wł. Adamczewski [1], Al. Wróbel et al. [13, 20] and T. Kisielewicz [7]. Quantitative analyses carried out by E. Grinzato [2] with his team for detecting defects in the dynamic state seem better that those made in the static state, which means that the infra-red examination should be carried out during the heating period, at low temperatures. The author made use of the method in the quantitative analysis of her own thermographic research. Information obtained by means of modern thermographic diagnostics is not only useful while managing separate buildings but also a housing estate and a quarter. In the author's opinion this is the non-invasive way to obtain large-scale trustworthy data concerning the thermomodernised Silesian buildings under analysis and their elements characterized by the excessive emission of heat energy. That is why in February 2012 the author carried out thermographic research in a chosen quarter in order to estimate the state of traditional buildings after the accomplished process of the earlier invented and accepted by the inhabitants thermomodernisation. The analysis confirmed the generally good quality of the investment accomplishment which resulted in a considerable decrease of heating demand and testified to the sensibleness and effectiveness of the undertaken activities. The quality estimation of the accomplished insulations was carried out by means of thermovisual camera, at night. The thermographic research was made in February 2012. The measurement was made with the FLIR B350 appliance. The analysis of thermograms was done by means of analytic instruments from the program: FLIR Reporter 8,5 and 9,0 where the following parameters were used: temperature field, the line on the thermogram also described the minimum and maximum temperature) and the colour palette InvertedGrey. The obtained thermic profiles of the external divisions were analysed and provided with comment under each figure. Also the environment conditions and the established rules of accomplishment were taken into account. During the cyclic thermographic research the following details were observed from the ground level: ground courses, walls, portfenetres, door and window woodwork as well as roofs and chimneys. It was important to make sure that the temperature of the air outside should slowly fall from -5°C to -10°C for 4 hours before examination and during the research it should be stable and stay at about -10°C. The research was made at night. Attention was paid to the rule that no sunlit walls should be examined before 6-8 hours [1] after research. The wind was to be weak or very weak, south-western and faster than 2m/s. The temperature inside was about 20°C and it was not regulated for 4 hours before the research.

The analysis of the selected result of thermographic research was restricted to the characteristic cases recurrent in many buildings in the quarter, which was presented by means of thermograms accompanying diagrams that presented line profiles of particular thermal sections. Under the figures there were descriptions of elements, junction points or certain points of the elevation specified on the basis of the accomplished result analysis as emitting most heat on the level minimum 3K with reference to the other elements of a buildings or neighbourhood (e.g. a tree).

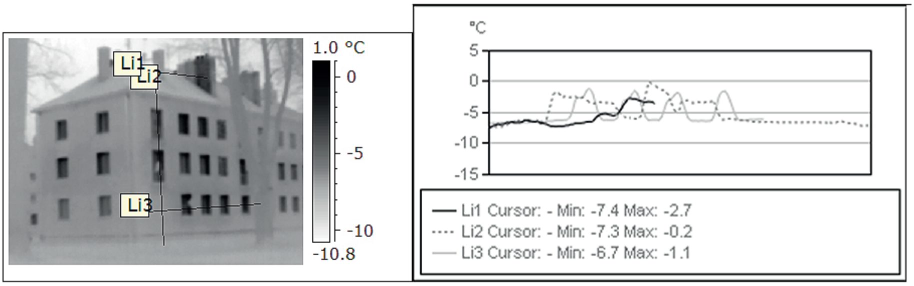

Fig. 1. Southern Poland 2012, a traditional technology after insulation. Thermogram and the analysis of the particular elements of the elevation (grand course, walls, doors, windows, chimneys)- description in the text

The thermogram analysis (fig. 1) testified to heat escape through chimneys (vents), where the temperature difference is 5K. Heat also escapes through the non-insulated casings of the door and window woodwork (temperature difference 6K) and the junction point of the insulation of basement walls and the ground floor walls (temperature difference up to 3K).

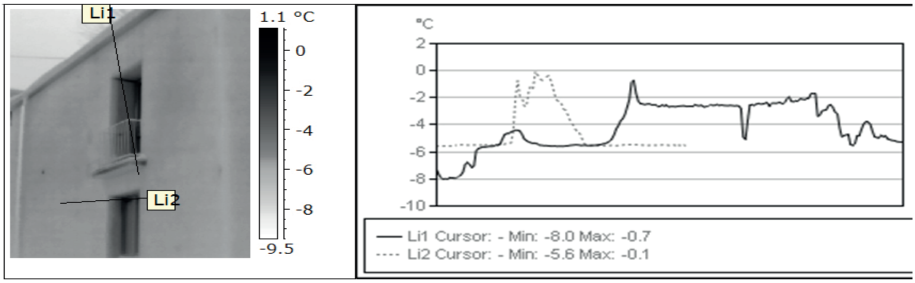

Fig 2. Southern Poland 2012, a building made in the traditional technology after insulation. Thermogram and the analysis of a fragment of the gamble wall with a portfenetre – description in the text

The accomplished analysis of the thermogram (fig. 2) testified to the escape of heat through the responds (horizontal and vertical) where the temperature difference on both thermal profiles is 5,5 K.

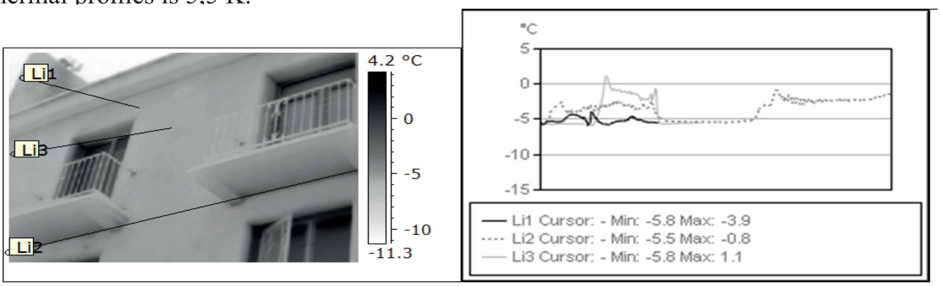

Fig. 3. Southern Poland 2012 a building made in the traditional technology, after insulation. Thermogram and the analysis of a fragment of the longitudinal wall with balconies – description in the text

The accomplished analysis of thermogram (fig. 3) testified to the escape of heat through the door responds where the temperature difference on both thermal profiles is 6K. Heat also escapes through the non-insulated balcony slabs (temperature difference 4,5 K).

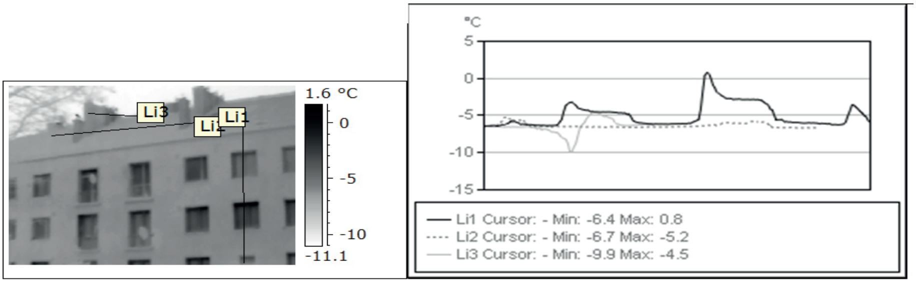

Fig. 4. Southern Poland 2012, a building made in the traditional technology after insulation. Thermogram and the analysis of a fragment of longitudinal elevation (window, woodwork, chimneys) – description in the text

The thermogram analysis (fig. 4) testified to the escape of heat through the non-insulated responds of the window woodwork (temperature difference 7K). Heat also escapes through chimneys (flues) where the temperature difference is 5K.

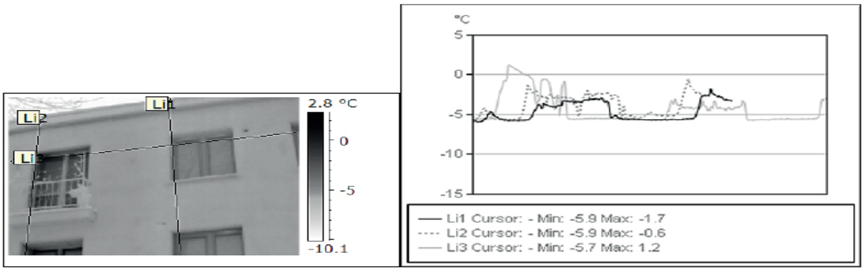

Fig. 5. Southern Poland 2012, a building made in the traditional technology after insulation. Thermogram and the analysis of door and window woodwork and the portfenetres description in the text

The accomplished analysis of the thermogram (fig. 5) testified to the escape of heat through the non-insulated responds of the door woodwork (temperature difference 7K) as well as window woodwork (temperature difference even 5,5K). Heat escapes through the portfenetres, where temperature difference between them and the wall is even 5K.

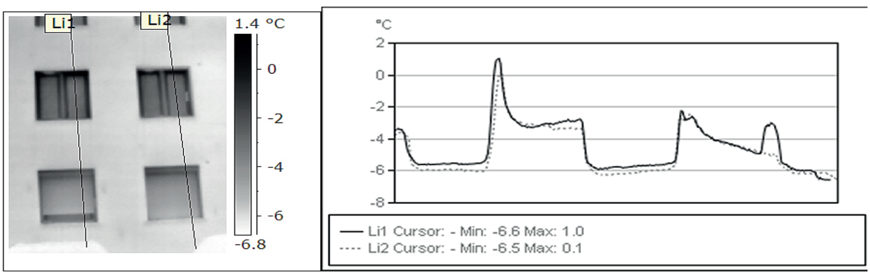

Fig. 6. Southern Poland 2012, a building made in the traditional technology after insulation. Thermogram and the analysis of window woodwork in a longitudinal wall-description in the text’

Analysis of the thermogram (fig. 6) testified to the escape of heat through the non-insulated responds of window woodwork (temperature difference 5,5K). External roller blinds were fitted in the ground floor windows that reduced the temperature difference between the window and the wall to 2K.

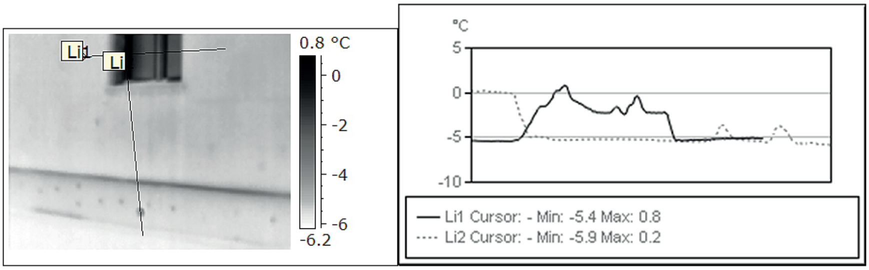

Fig. 7. Southern Poland 2012 a building made in a traditional technology after insulation. Thermogram and the analysis of a window in a gable wall and the area of the ground course – description in the text.

The analysis of the thermogram (fig. 7.) testified to the heat escape through the non-insulated responds of the window woodwork (temperature difference 6K). Heat also escapes through the junction point of the insulated ground course with the ground floor wall and the wallplugs (the temperature difference is from 1,5 to 2K) but the escape is negligible.

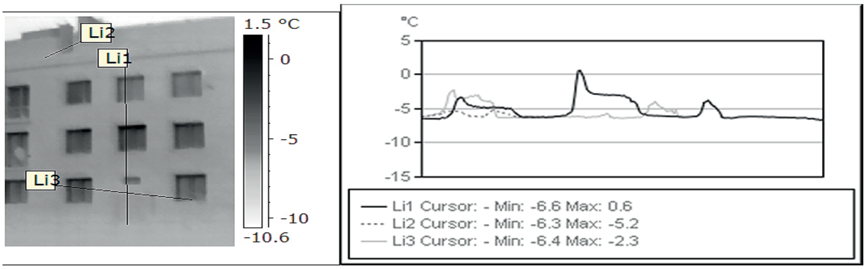

Fig. 8. Southern Poland 2012, a building made in the traditional technology after insulation. The thermogram and the analysis of the particular elements of elevation (the grand course, the wall, windows, the entrance door, the chimney) – description in the text

The analysis of the thermogram (fig. 8) testified to the escape of heat through the window responds (temperature difference from 3 to 6,5K). The temperature on the wooden entrance door is similar to the temperature of an insulated wall.

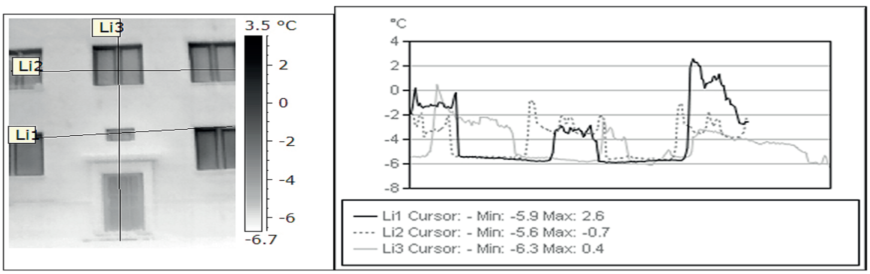

Fig. 9. Southern Poland 2012, a building made in the traditional technology after insulation. Thermogram and the analysis of the particular elements of the elevation (the wall, windows, the entrance door) –

description in the text

The accomplished analysis of the thermogram (fig. 9) testified to heat escape through the window responds (temperature difference from 4 to 8,5K). Temperature at the entrance door (exchanged) is not similar to the temperature of an insulated wall as it is with wooden (old type, not exchanged) door; in this case the temperature difference is 3K.

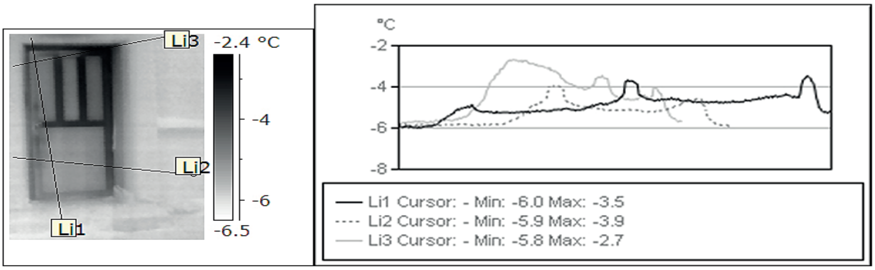

Fig. 10. Southern Poland 2012, a building made in the traditional technology after insulation. Thermogram and an analysis of the entrance door – description in the text

The analysis of the thermogram (fig. 10) testified to heat escape through the responds and casings of the exchange entrance door (temperature difference to 3,5K). Temperature at the aluminium entrance door, insulated and with a thermal glass pane is not similar to the temperature of the insulated wall and is 2,5K an average. During the analysis of the results of thermographic activities carried out in a Silesian district in southern Poland it was stated that, in spite of the insulations made during the period of 2008-2010 in 39 buildings, there are still some activities left to be accomplished during the process of complex thermomodernization.

4 Discussing the research results

The analysis of the effect of thermomodernization of the buildings confirmed the fact that not all elements were insulated in a complex manner, which has been presented in table 2.

Table 2. A specification of results of thermographic research on the basis of an insulated multi-family building, made in the traditional technology

No.	Problem	Estimation expressed by the average temperature of the heat escape through a given element	The percentage of mistakes against the number of analysed buildings	Recommendation
1	Chimneys – combustion flues	5,00K	95,00%	Heat should be regained from the combustion flues.

No.	Problem	Estimation expressed by the average temperature of the heat escape through a given element	The percentage of mistakes against the number of analysed buildings	Recommendation
2	Door and windows external woodwork in flats and the responds (external reveals)	5,95K	63,00%	Roller blinds should be fitted and the responds should be insulated.
3	Portfeneters or balconies	4,75K	99,00%	They should be insulated.
4	The woodwork of the entrance door	3,00K	57,00%	Casing profiles should be insulated and the thermal quality of the door woodwork after exchange should be improved (the frame profiles).
5	Discontinuities of insulation (cornices the junction point of grand floor wall insulation with the basement wall, the wallplugs, etc.)	1,75K	92,00%	Cornices may be insulated, and the insulation of the ground course can be extended.

The accomplished analysis of the research shows that the door and window external woodwork and the non-insulated responds constitute the biggest problem and present the worst state as far as the average temperature of heat escape is concerned, as they are varied thermally as well as in the aspect of the material (5,95K). The next items are chimneys (5K) and the French windows or balconies (4,75K). The average heat escape through the entrance door is not substantially smaller (3K). Heat escape through the discontinuities of insulation – both the linear ones and the punctual are negligible in the overall heat balance of a building and of the quarter, as they are 1,75K on average.

It was also stated that the highest percentage of mistakes is connected with the shortcomings in the insulation of French windows or balconies (99%), not much lower as far the chimneys are concerned (95%) and the insulation discontinuities (92%). There are also mistakes in the choice of quality of the exchanged door and window woodwork in the flats

(63%) and the entrance door (57%).

In the author's opinion the further improvement works should be connected, first of all with the insulation of French windows and balconies, then with the regain of heat from the chimneys, as well as fitting the roller-blinds and reveals insulation. Moreover, in the exchanged woodwork of the entrance door it is necessary to insulate the frames and tightening of the casings. The above elements specified in the order of urgency of the improvement activities influence directly the energetic quality of the buildings in the heat balance of a dwelling house and the whole quarter. The activities are accepted by the inhabitants which, is also confirmed by the social research carried out by the author since 2004, in Poland.

5 Recapitulation and conclusions

Multifamily houses built in the 50s or the 60s of the previous century in Poland demand the finishing of the modernization process. Typical thermomodernisation activities in the houses made in the traditional technology reduce their cost of maintenance and improve the quality of living of the inhabitants. They also increase the cost of the living space at the property market and the attractiveness of living in a given quarter.

The accomplishment of the discussed range of activities is connected with the cost paid by the final recipient. Taking advantage of the system of subsidies gave some relative gains in the further exploitation of the buildings.

The analysis of the example of the Silesian quarter in southern Poland confirmed the fact that the accomplishment of the properly designed program of modernization subsidized from the external sources gives really good results and constitutes an immense potential of energetic effectiveness in the energetic balance of the quarter. In the above analysed case the savings of 70% of energy on the scale of the whole quarter have been obtained. In view of the complexity of the thermomodernisation process there are still certain works to be done that can increase the effectiveness of the hitherto accomplished activities, which was presented in detail in p. 4. The author is convinced that the possibilities of new solutions should be taken into account which, were discussed in the following publications [8, 12, 11, 13, 14, 15].

Literature

[1] Adamczewski Wł.: Thermographic research outside. in: Badania termograficzne w budownictwie. No 3, 2008, pp. 96-100. 1

[2] Grinzato E., Vavilov V., Kauppinen T.: Quantitative infrared thermography in buildings. Energy and Buildings, 29 (1998), pp.1-9. 2

[3] Kisielewicz T.: The influence of insulating, dynamic and spectralproperties of partitions upon the heat balance of energy saving buildings. Monograph 364, Seria Inżynieria Lądowa, Politechnika Krakowska, Cracow 2008. 11

[4] Nowak H., Kucypera M.: Using active thermography for non-destructive research of partitions. Energia i Budynek, Nr 7, 2011, 13-18. 3

[5] Nowak H.: Heat protection of the construction objects in the aspect of energy saving in the building trade worldwide – the new measurment opportunities by means of a thermovisual apparatus. in: Optimalization of the industrialized construction systems. Toruń, May 21-22 1979, IV Toruńska Konferencja Problemowa, pp. 205-217. 7

[6] Nowak H.: Modelling of the longwave radiation incident upon a building. Archives of Civil Engineering, 2001 Vol. 47, Issue 2, 243-267. 14

[7] Nowak H.: The employment of thermovisual research in construction. Oficyna Wydawnicza Politechniki Wrocławskiej. Wrocław 2012, pp. 1-332, 290-296. 4

[8] Nowak Ł., Nowak H.: The advanced systems of glazing of the energy-saving buildings elevations. Energia i Budynek. 2011, Annual 5, No 1, pp. 18-24. 19

[9] Ostańska A., Taracha K.: The analysis of the opportunities of improvement activities for energy saving on the basis of a staircase building. Przegląd Budowlany 2/2012,

a monthly magazine PZiTB, pp.17-22. 5

[10] Ostańska A., Taracha K.: The energetic municipal audit for Lublin. Przegląd Budowlany 12/2011, a monthly magazine PZiTB, pp. 38-45. 8

[11] Ostańska A., Taracha K.: The energetic municipal audit, using the template MDN/R+E as an instrument of planning the effective energy saving in a city. Budownictwo i Architektura, 2011, Vol. 9, pp. 141-159. 12

[12] Ostańska A.: A Model of an Energetic Municipal Audit as an instrument of the effective energy saving in a city on the basis of Lublin. Oficyna Wydawnicza Politechniki Wrocławskiej – the typescript put into print in 2012. 15

[13] Ostańska A.: Estimation of the hitherto accomplished thermomodernizations of multifamily prefabricated buildings and the suggestion of improvement of the energetic condition in a housing quarter. Przegląd Budowlany 9/2011, a monthly magazine PZiTB, pp. 68-74. 20

[14] Ostańska A.: The problems of modernization and revitalization of the complexes of prefabricated dwelling houses on the basis of the Stanisław Moniuszko memorial quarter in Lublin, Politechnika Wrocławska, doctoral thesis written under the direction of Ass. Prof. Eng. Arch. Dr Wandy Kononowicz, Wrocław 2008, pp. 1-164. 18

[15] Ostańska A.: Thermal imaging for detection of defects in envelopes of buildings in use: qualitative and quantitative analysis of building energy performance. Periodica Polytechnica-Civil Engineering - 2018, s. 1-8

[16] Staniec M., Nowak H: Analysis of the earth-sheltered buildings' heating and cooling energy demand depending on type of soil. Archives of Civil and Mechanical Engineering. 2011, Vol. 11, Nr 1, pp. 221-235. 13

[17] Taracha K., Ostańska A., Nowak S.: Estimation of the energy-saving activities in multifamily buildings on the basis of the quarter and housing estate Dźbów in a monograph: Energy-saving and Ecological Materials, Installations and Technologies in Construction, Wydawnictwo PSW JPII, Biała Podlaska 2012, s. 41-54. 9

[18] The Resolution of Częstochowa Town Council No 169/XVI/2007 of September 24, 2007. 17

[19] Włodarczyk D., Nowak H: Statistical analysis of solar radiation models onto inclined planes for climatic conditions of Lower Silesia in Poland. Archives of Civil and Mechanical Engineering. 2009, Vol. 9, Nr 2, 127-144. 16

[20] Wróbel Al., Wróbel A., Kiesielewicz T., Ortyl Ł., Kwartalnik-Pruc A., Szafarczyk A., Owerko T., Rakoczy A., Nowak K.: The quantitative qualification of the heat properties of construction partitions using the thermographic technology. Wydawnictwa AGH, Krakow. 6

[21] Wróbel Al.: Thermography in the stock-taking measurements of construction objects. Wydawnictwa AGH, Seria: Rozprawy, Monografie [Series: Papers, Monographs] No 2009, Kraków 2010. 10

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Stigmergic behaviour and nodal places in residential areas: Case of post-socialist city Kharkiv in Ukraine

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Abstract: The study of urban development and regeneration of residential areas in the cities are mainly focused on the separate infrastructural systems and less how networks of infrastructural systems and their elements, as nodal places, interact with the existing living environment and its urban tissue. The central goal of the paper is to examine contemporary residential areas of low liveability with nodal places of logistics and services infrastructural networks, with an eye on existing urban policies and application of transdisciplinary concept of stigmergy in contemporary urban environment. Research objectives: (a) conceptualisation of stigmergic process in urban planning; (b) overview of socialist and post-socialist urban policies for residential areas; (c) stigmergic behaviour in the development of nodal places in residential areas. Methodology: Use of Earth Time Observation Systems for identification of urban changes of nodal places under the stigmergic behaviour in the case study residential area in post-socialist city in Ukraine; contextualization of the case study with the categories: Ideology, Institutional level, Politics, Economics, Mobile Infrastructures. Discussion and conclusion: (a) as concept, stigmergic behaviours are efficient, but work as a self-organization form; (b) urban policies should, under the stigmergic behaviours, contextualize changes, continue or prevent the process.

Keywords: nodal places; urban policies; post-socialist city; residential areas; stigmergy; stigmergic behaviour

1. Introduction

The research of urban development and regeneration of residential areas in the cities are mainly focused on the separate infrastructure systems [1, 2] and less how networks of infrastructure systems and their elements, as nodal places, interact with the existing living environment and its urban tissue. A nodal place, a node, is a morphological element of a network, a “concentrations of activities” [3], “concentrations of land uses in a geographical area” [4], an integral component [5] or sub-centre, the focus of specific concentrations [4], a vertex in the theory of networks [6]. The nodes are connected in the network by means of “diverse links”, “space of flows” [5]. The nature of networks received diverse meanings in various fields, natural and artificial (built) sense, material and non-tangible areas. The diversity of the networks challenges the developing of ways, in which these formal and informal networks are coupled, layered to one another, the way processes spread and diffuse over the links [6, 7]. The social networks, their behaviours, memory of the place, and other informal networks are present in the society and its environment of space, living and urban place; hence envisage the use of applied transdisciplinary concepts of networks development.

Urban planning mutually comprises the built networks, infrastructures, which serve to create liveable urban environment for citizens. Networks of infrastructure systems are a "subsystem of urban structure, which supports production and development of the city" [5], and its living environment in the residential areas. The meaning of development and regeneration of residential areas in the cities involves the development of elements of infrastructures as nodal places, which cumulate and integrate the activities to the urban environment. This process demands research-based steps to understand the changes in the society, which lead to the development of the activities, need of functions and facilities in urban environment. Hence, the support with urban policies for effective urban development becomes an integral question for the contemporary city, which will cumulate knowledge of networks integration, economic changes, societal influences and needs, and in particular networks' structural elements.

The experience of development and implementation of urban policies for territories in the cities received challenges in the approaches in various countries. The environment in the European cities, in particular the residential areas, during the stages of the development, faced challenges in the processes of urban policies during the last decades. For instance, the Netherlands that had been much concerned on social housing questions among other Western European countries, as well as on urban renewal and regeneration faced that in the 1980s "the policies of different ministries as regards objectives, available resources and even the designation of problem areas, moved further and further away from one another, creating a real patchwork of urban policies and problems" [8]. A decade ago "the Dutch national urbanisation policy […] is often said to be inadequate and not a timely answer to societal changes" [4]. Cheng et al. [4] states that, "any policy-making must be based on the proper understanding of the network", development of infrastructural system in the cities.

The contemporary city faces the changes in the societies, thus should aim the development in the framework of up-to-date visions and strategies. It is New Urban Agenda by United Nations Conference on Housing and Sustainable Urban Development (Habitat III) [9] that stresses the attention on "readdressing the way cities and human settlements are planned, designed, financed, developed". This deep declaration actualizes the questing of understanding of the urban processes, its networks and societal influences. Michael Batty in his The New Science of Cities [7] expresses the statement „there is now considerable momentum in developing formal ideas about how cities are ordered and structured. A new paradigm is emerging". This opens the possibility to involve contemporary transdisciplinary approaches to understanding of needs, influences and challenges in the cities today. There are attempts in transdisciplinary urban researches with other disciplines (computation, biology, other) to apply and built the stigmergic approaches in understanding of: cities' system elements as urban street networks [10]; generating of street networks in urban context based on minimum spanning trees computation [11]; urban activity patterns from positioning data in crowds urban dynamics [12]; urban processes of self-organization and emergence [13]. Nevertheless, the concept of stigmergy is not widely used in urban planning theory by now, new transdisciplinary applications continue emerging with increasing number of application domains. Heylighen underlines that "as yet under investigated application of stigmergy to human affairs opens the way to a virtually limitless expansion across the various scientific, technological and social disciplines that study society, cognition, and behaviour" [14, 15].

Hence, stigmergy opens broader possibilities for analysis of the development of the city, its networks and processes.

In this paper, we are addressing to the transdisciplinary concept of stigmergy to examine contemporary urban environment of residential areas and its nodal places at the time of changing economies, policies and societal influences. This paper thus focuses on understanding of application of transdisciplinary concept of stigmergy and conceptualisation of stigmergic process in urban planning. It is considered to examine the stigmergic approach in the developing environments, such as post-socialist cities, as they face much deep challenges in their liveability then urban environments in developed societies. The special interest is put on residential areas of low liveability with nodal places of logistics and services infrastructural networks, with an eye on changes, challenges and urban policies. We refer the living environment of low liveability in residential areas in the cities as the residential areas of prefabricated housing estates with living environment of low quality in the post-socialist city. This typology of residential environment draws our attention because is based on the socialist ideology in the state planning system approach as 'administrative planning design' in a socialist city during the time of existing of the USSR. Today these residential areas receive non-systematic changes in functioning around and in their nodal places. The study is guided by the conjecture that define the research hypothesis: the application of the transdisciplinary concept of stigmergy and stigmergic behaviours in urban planning envisage contextualization of changes by urban policies.

The article is structured as follows. The „Stigmergic concept and behaviors, related work and general approach" subsection of Introduction describes concept of stigmergy as a self-organization form and stigmergic behaviour both in general and transdisciplinary approach. The "Contextualization of the research" subsection of Introduction goes to the overview and justification of the context of the research to post-socialist living environment looking on: (a) socialist and post-socialist residential areas transformations under the stigmergic behaviour; (b) informal non-systemic urban development leads to functional changes. The section "Research objectives and methodology" defines and explains the content of the objectives, hypothesis and methodology of the study, which form the research design structure. The following section "Case study analysis: stigmergic behaviour and nodal places in residential area Saltivka District (Kharkiv)" aims to analyze the justified case study in post-socialist city addressing functional transformations in residential area as a stigmergic behaviour during the 1980s to 2017 under the cross-related stigmergic contexts (ideology, politics, economics, other) and categories (Actors, Time, Place, Actions). The "Discussion and conclusions" section summarizes the key findings about urban policies and stigmergic behaviour in urban planning, opens the floor for further research.

1.1. Stigmergic concept and behaviors, related work and general approach

The concept of stigmergy comes from entomology, a biology specialty devoted to the study of insects in all its aspects, as well as their relationships with man, plants and animals, and the environment [16]. The concept was first developed by Pierre–Paul Grassé in his study of the termite of 1959, applying it to his behavior. These behaviors differed according to the point of observation, being that: (a) as a group, the termites cooperate for the construction of their nests; and (b) as individuals, termites seem to work without any involvement in any collective work. Termites, as well as different sets of social insects, interact stigmergically, that is, their communication is characterized by reactions to changes in the environment and not by direct transmission of signals [17].

The concept of stigmergy, although it has already crystallized definitions of its meaning, is still to be explored in different disciplinary areas [18]. It is assumed that stigmergy is a model where a collective of agents exhibits the ability to face complex problems in self-organization, as are the examples found in social insects, contributing to the development of the disciplinary areas of Collective Intelligence, Swarm Intelligence or Emergent Behavior [19]. This capacity for self-organization, without benefits of central control or direct communication between different actors, is determined by the agents' reaction to continuous environmental changes [17].

As a computational programming language, the concept of stigmergy is used in synthesis, considering that the action of an agent in an environment stimulates a reaction, established by predetermined rules, in other agents that, in turn, the leads to intervene and modify this same environment. For example, ants detecting a certain degree of pheromone concentration, left by other ants in a path, are encouraged to intensify it. Conversely, the evaporation of the same pheromone in a course, promoted by the absence of ants, leads to its abandonment by other ants. Through the replication of this model it is possible to identify and analyze patterns of urban activities, observing their spatial and temporal dynamics [12].

In the Artistic area, the stigmergy concept finds relevance in approaches motivated by Artificial Intelligence, where the examples of Swarm Painting up to Artsbot, from the Robot Art collection of the Portuguese artist Leonel Moura, reveal the application of algorithms of artificial intelligence for the development of Artificial Creativity, in models of self-organization without control or hierarchy [20]. As Leonel Moura affirms, it is understood that the concept of stigmergy can be applied to mechanisms of cooperation between animals, as well as to urban, social, cultural or political phenomena [21]. Indeed, the very idea of Leonel Moura's city, in a wider context and analyzed in the light of the concept of stigmergy, indicates that these are no more than „(...) true social pheromone peaks (stimuli), capable of attracting everything and everyone around them" [21].

However, in a deeper approach, the same author differentiates levels of stimulus that characterize the processes of self-organization and stigmergy in the construction of the city, resulting from a permanent confrontation of interests and expectations, identifying: a) the construction and destruction as „(...) the product of individual action and conjunctural collective agreements."; and b) the planning and resulting political decision „(...) of the activity of multiple agents (...)" [21].

1.2. Contextualization of the research

Justification of the context of the research to post-socialist living environment. This subsection justifies the context for examination of stigmergy in urban environment. We suggest addressing stigmergic approach in the developing environment of post-socialist cities, which receive challenges in liveability of urban environment, and residential areas in particular, which are much more significant than in the developed societies. At the same time, the residential areas in the post-socialist cities face non-systematic transformations and changes, informal interventions after the collapse of the USSR in 1991. This applied research is contextualized within the environment of residential areas of low quality in the post-socialist city in the post USSR territory with the case of Ukraine.

Regarding the features and quality of the residential areas in post-socialist city, where the non-systematic transformations and informal interventions with trade function were and are situated, it is important to clarify the ideological principles of socialism, integrated to the development of the residential areas. The planning typology of residential areas in post-socialist city was strictly organized according to the socialist ideology implemented in the 'administrative planning design' during the USSR. The planning design of residential areas during the Soviet era embraced the next principles of socialist ideology: (a) administrative totally centralized urban planning and design mechanism, which had been performed only through state design institutes; (b) the residential areas were designed according the 'free planning' system and micro district division of its territory and public facilities; (c) the most economic prefabricated housing typical (series) projects of prefabricated housing, which were constructed in the cities on the whole territory of the Soviet Union; (d) common facilities (kitchens, canteens, bath etc.) in the 'communes' during the early Soviet period; (e) housing policies declared the minimum of living space for each family member in the small apartment; (f) no private housing for the citizens – the state was the only owner, which led to citizens' dependence from their place of work. These socialist principles crucially influenced on the quality of the living estates of prefabricated housing from 1954, time of beginning of prefabricated housing constructions in the USSR, till 1991, which was the time of its collapse. The quality of this living environment was low enough from the moment of construction of the housing.

The predominant typology for housing in the socialist cities during 1954–1980s was prefabricated multi-family housing block. The quantity of constructed dwelling according to the typical projects in the USSR had been rising from year to year, for instance, in 1958 – 77 %; 1960 – 88 %, 1965 – 95 % [22]. Hence, three quarters of citizen lived in the prefabricated housing by 1991, and today we receive the similar statistics: 63,8% of typical housing among all housing in the city in Kiev, 81,8% – in Donetsk [23]; 85,2% – in Kharkiv [24].

The scale of residential areas in the socialist city was planned according to the state norms and differed during the time. The planning unit for the urban development of residential area was a micro district. The planned quantity of population for such a micro district was defined in the state norms taking into consideration the size of the city (small, medium, huge, etc.). For instance, according to the state norms [25], the micro district in a city with total population from 500 to 1000 thousands citizens had to be planned for 12000–20000 inhabitants, with the density of 170 – 220 persons/ha. The open free spaces between the housing blocks served to fulfil the norms of natural insolation of dwellings, but functionally were not fully occupied and caused appearance of big empty spaces.

Informal urban developments – functional changes. The functioning of the contemporary living environment, therefore networks and nodes, in residential areas embraced the informal self-organising processes (informal retail trade places, self-parking places, etc.) during the last 25 years of post-socialist time. The informal sector in retail trade in post-socialist city resulted "from a lack of trading space, the need of convenience and flexibility in retail locations, an absence of seed capital and week state regulations" [26]. The main urban spaces in the post-soviet cities, which had been influenced by informal retail trade, were open-air markets, sports stadia, sites around bus and rail stations, or metro stations. Partially, these informal trade sites appeared in the residential areas near sites around bus and metro stations, "informal trade on the streets and rail stations" [26], or chaotically expanding open-air markets in the form of self-organising processes and the features of stigmergic behaviour of retail trade participants. The informal sites of concentration of retail trade as self-organizing process were mostly situated in and around nodes in residential areas of large-scale post-socialist housing estates in the cities after 1991. This kind of trade function in the informal trade sites received the transformation of its form during the last 25 years from the "trade on 'a portable table', later to "kiosk as relatively stable feature of the post-Soviet urban space", and finally functional transformations of apartments on the ground floor of residential blocks from residence to commerce or services from 2000. This last form of functional transformations of apartments on the ground floors of prefabricated housing blocks from residential to commercial facility will be discussed in the case study analysis at section 3 of this paper, addressing to the concept of stigmergic behaviour. Together with the concentrated informal retail trade sites around metro stations, the process of non-systematic transformation of apartments on the ground level from residential function to commercial results as self-organising process of stigmergic behaviour of the actors (residents, retail trade participants, authorities) in the urban environment of the nodes.

However, today the state and the cities' authorities do not possess the clear strategies for: the urban regeneration of post-socialist residential areas; the redevelopment of nodes in residential areas; the ongoing functional transformations of ground floor residencies to commerce here, in particular.

2. Research objectives and methodology

2.1. Research objectives:

The central goal of the paper is to examine contemporary residential areas of low liveability with nodal places of logistics and services infrastructural networks, with an eye on existing urban policies and application of transdisciplinary concept of stigmergy in contemporary urban environment. This goal sets the next research objectives: (a) conceptualisation of stigmergic process in urban planning; (b) overview of socialist and post-socialist urban policies for residential areas; (c) stigmergic behaviour in the development of nodal places in residential areas.

Conceptualisation of stigmergic process in urban planning. Stigmergy anticipates the process of "indirect communication between actors in the shared environment" [27]. In case of urban planning and city development, it becomes important to understand that the process of development occupies certain time, is produced by different institutions as continuous process. On this basis, we suggest to look on the stigmergic process in urban planning during time and define the types of shared environments as contexts in the urban system networks. Urban planning as a complex process embraces the design procedures fulfilled by design institutions, which continue the ongoing development of the settlements. We may trace the indirect communication during the urban planning process between different actors or participants (human: architects, citizens; non-tangible: ideology, needs, other) in the shared environments with various contexts (duration of time; urban area as place; functional actions, etc.). Hence, this kind of indirect continuous process of development in the content of urban planning in its different levels (institutional level; design level; economics conditions) of actions is carried out in the frames of features and meaning of stigmergy transferred to human practises as transdisciplinary approach. The process as actions done by actors of the environment and are using indirect communications to continue the previously finished action conclude the stigmergic behaviour. Thus, we suggest to define the categories of environments and contexts for conceptualization of stigmergic process in urban planning as follows: (a) contexts/ environments: Actors, Time, Place, Actions; (b) levels: Economics, Institutional, and Design.

Overview of socialist and post-socialist urban policies for residential areas. The research is contextualized within the environment of post-socialist residential areas in Ukraine. The aim of this objective for the research is to look on the category of Time and conditions of design in the framework of the concept of stigmergy. The category of Time crucially divides the conditions of design process in the post-socialist country to socialist and post-socialist eras as following: (a) the socialist ideology is always inside the design process as administrative centralized design process fulfilled by state institutions during socialist era; (b) design process is carrying out by restructured state design institutions and new private design entities during post-socialist time. Here the Institutional and Design levels are connected between each other by certain time. The organizational changes of forms of owner of design institutions result on the scale of design processes, implementation or lack of urban planning strategies in the urban networks and nodes. Especially, we may trace the changes in urban environment of post-socialist cities, which possess chaotic interventions in urban tissue, especially in the post-socialist residential areas. The non-systematic changes in urban environment as residential areas and nodal places were and are appearing mostly as self-organized process have been done by actors (citizens, private owners, entrepreneurs). These non-systematic changes have been taking place with the nature of stigmergic behaviour: the process as actions (change n) done by actors (citizens, etc.) of the shared environment (residential area) and are using indirect communications (demand, needs, result of the done action) to continue the previously finished action (change n-1). Hence, a self-organizing process with non-systematic changes appears, because of lack of urban policies. This reason underlines the meaning of urban policies as conditions for efficient stigmergic behaviours.

The urban policies for residential areas during socialist and post-socialist time in Ukraine embraced accordingly opposite ideological approaches. However, the contemporary urban policies for residential function are the reworked version of old rules and do not comprise the direct needs of living conditions. The development of urban policies, norms and rules we may follow in the next stages: (a) socialist era – in 1930, 1954, 1958, 1962, 1971, 1985, 1989; (b) post-socialist time – in 2003, 2005, 2011, 2015. These stages declared a very slow increase of quantity of living area per person in the residential buildings, principal structures of the housing and their typology, normative social services in the residential areas and their density.

Stigmergic behaviour in the development of nodal places in residential areas. Stigmergic behaviours take place under indirect communication in the environment. The process is influenced and triggered by environments and contexts: Actors, Time, Place, Actions; Economics, Institutional, Design (Tab. 1).

Table 1. Contexts of stigmergic behaviours.

Contexts/ Environments	**Actors**	**Time**	**Place**	**Actions**	**Reactions**
Economics	State planning	1917–1991	City	State trade, State property	
	Needs and demands	1991<2017	Residential areas	Ground Floor Changes: Commerce and Services	Create nodal places with commerce, market

Contexts/ Environments	Actors	Time	Place	Actions	Reactions
Institutional	Ideology and politics	1950–1991	Urban territories	State Design Institutes/ Directive planning	Centralisation
	Democracy	1991<2017	-//-	Private Design Institutions/ Market	
Design	State Design Institutes	1950–1991	-//-	Administrative centralized urban planning	
	Architects	1991<2017	-//-	Individual projects	

2.2. Methodology

We used a case study approach to investigate the concept of stigmergy and stigmergic behaviour in urban planning. Consistent with the research focus and, hence, the research hypothesis, which is defined in the Introduction, the case study approach aims to identify the environments and contexts in urban areas, which stimuli stigmergic behaviours. The transdisciplinary theoretical framework opens application of the stigmergic concept in urban environment, and we draw attention to the developing urban societies, in particular to their residential areas and nodes. Stigmergic behaviour is defined as process of actions fulfilled by actors within the environment (contexts) under indirect communications (result of the action), which continue the previously finished action. Heylighen is defining "stigmergy as a mechanism of indirect coordination in which the trace left by an action in a medium stimulates subsequent actions" [18]. Thus, the process may continue unless there are changes in the context (time, economy).

Case study approach envisages the justification of the residential area, which includes actions done by actors in the environment during certain time. Research methods include the use of: (a) Earth Time Observation Systems (Google Earth Engine, Google Earth Pro) for identification of large-scale changes in the case study residential area during 1991–2017; (b) the micro-scale changes obtained by observation on the case study area. The large-scale changes in the case study residential area are the informal developments of retail trade and open-air markets around metro stations as nodes during 1991–2017. Google Earth Engine allows tracing these changes on the territory around the node during 1984–2016. The micro-scale changes in the case study residential area are the non-systematic functional transformations on the ground floors of residential blocks around nodes in post-socialist prefabricated housing estate built during the 1970–80s in Kharkiv, Ukraine. These functional transformations change residence apartments to commerce and services mostly not under urban policies. The data of micro-scale changes are obtained by on-site observations, since the data at Area (regional) Council authorities are not open as well as at the Department of statistics of Kharkiv.

The aim to identify the environments and contexts in urban areas, which stimuli stigmergic behaviours and work as trigger under the stigmergic concept. The physical environments and non-tangible contexts, where the actions are fulfilled by the actors in a continuous process, and take place during certain time form the frame of categories: place, time, economics, ideology, politics, infrastructures. The application of the transdisciplinary concept of stigmergy and stigmergic behaviours in urban planning envisage contextualization of changes (contexts and categories) and opens the field for improvement of urban policies, which could effectively continue or prevent the process.

3. Case study: stigmergic behaviour and nodal places in residential area Saltivka District (Kharkiv)

3.1. Case study context

Among the biggest cities of Ukraine is Kharkiv with the population of 1,45 m citizens (2016) [28]. This city received the prefabricated housing estates in 1950–80s. The scale of large post-socialist residential areas differed accordingly to the scale of the city. Thus, the biggest prefabricated residential area in Kharkiv is Saltivka with the population 385 000 residents (2010) [29] and built during the 1970–80s.

Large-scale housing estate Saltivka is the biggest living area in Kharkiv, with large-panel multi-storeyed housing, developed during the 1970–80s, in the northeastern part of the city. The territory of living area Saltivka (Saltivka) occupies more than 700 hectares. The growth of population showed in 1977 – 250 000 residents [30], 2010 – 385 000 residents [29]. The construction of Saltivka was performed according to the phases of micro districts' plan development until late 1980s, and enabled its rapid growth. Few new living blocks were built during last 15 years on the empty territories of Saltivka. Being the largest socialist housing estate in Ukraine, it comprises 22 micro districts. Each micro district was developed for 17 500 residents on average. The typology of prefabricated buildings in Saltivka is based on the typical projects: large-panel 5-, 9-, 12-, 16-storeyed living blocks with linear, semi-linear and tower structure. The planning system of housing in the territory designed in the free (open) planning. The ideology of micro district planning includes social services, green areas few sport facilities.

The micro-scale changes in the residential area are the functional transformations of the apartments on the ground floors of residential buildings built during the 1970–80s from 2000. This process began rather as self-organizing actions, than the mechanism under the urban policies.

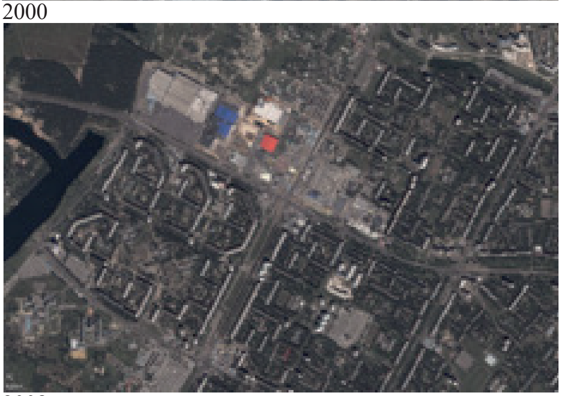
The large-scale changes in the case study area are two sites: (a) the area around the node, which include metro station Heroyiv Pratsi, development of shopping malls in its northern direction and market that, had been started from informal retail trade as open-air market place; (b) the area around the node near the south part of residential area Saltivka, which include metro station Barabashovo and a large market area Barabashovo that had expanded to the territory of 75 hectares during 1995–2017 (Fig. 2). The part of the territory, where the retail market Barabashovo is situated now, was reserved for the train parking area of metro infrastructure in the masterplan of Kharkiv.

3.2. Case study analysis: stigmergic behaviour and nodal places in residential area

The data for the case study analysis of large-scale changes were obtained using Earth Time Observation Systems (Google Earth Engine, Google Earth Pro). Google Earth Engine gives the opportunity to trace the changes in the planning of the nodes in two sites of the case study during the timelapse for 1984–2016.

The area around the node with metro station Heroyiv Pratsi started to grow with informal retail trade as open-air market place from the time of the USSR collapsed in 1991. The change of politics ideology in 1991 was the moment, when the context received the changes on the market from state ownership to private ownership in economics and business. The time period during 1991–2017 is the context of time for stigmergic behaviour in the place. Here under the stigmergic behaviour we understand the function of retail trade, fulfilled by the actors (inhabitants, informal traders, and small entrepreneurs). The persuaded retail trade had been taking place as an open-air market on the closest to the metro station free open area. The function was spreading almost chaotically without any planning development during this time, only in 2006 two shopping malls and two stores were built in the northern west direction from the metro station. At the same time, the open-air market with the retail trade received small transformations of retail places, but these changes did not rise the quality of the function and services in the node. The actions (retail trade) done by actors under indirect communication, which continue the previously finished action in the place and within the contexts (time, economics). Hence, the above process is the stigmergic behaviour in the case study residential area with large-scale changes, which are showed by the selected satellite images with the residential area around the node with metro station Heroyiv Pratsi (Saltivka, Kharkiv) in 2000, 2008, 2012, 2016 retrieved from Google Earth Pro in 2017 (Fig. 1).

2000



2008

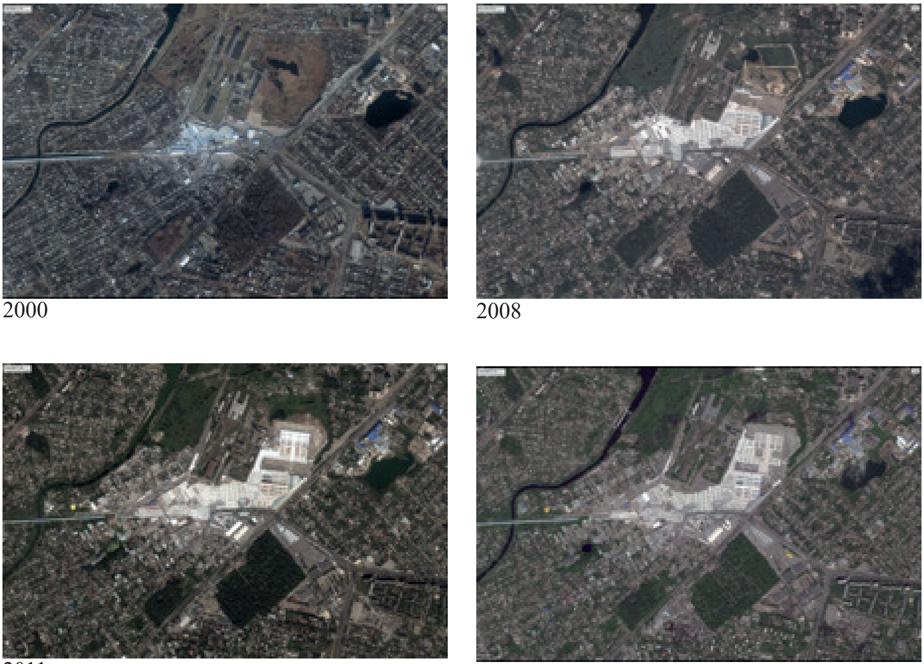
2012

2016

Fig. 1. The residential area around the node with metro station Heroyiv Pratsi, Saltivka, Kharkiv. 2000, 2008, 2012, 2016 [Google Earth Pro; retrieved in 2017].

The large-scale changes in the case study area around the node near the south part of residential area Saltivka include metro station Barabashovo and a large market area Barabashovo. The retail trade function started to develop in 1995 here as open-air market with containers for retail trade and trade rows. During the last 22 years it spreaded to the territory of 75 hectares and became one of the biggest retail markets in the Eastern Europe. The growth did not have any adopted or proved development plan and was directed by the group of directors of the market, which received the positive solutions from the authorities. The traders in the market area Barabashovo were informal dealers and small entrepreneurs. The chaotic structure of the market does not fulfil the norms and standards for planning and development of market areas, as: norms of emergency and evacuation, insolation, ventilations, sanitation, sewerage. For instance, these lead to the fact that one of the entrances to the metro station by Academic Barabashov is tightly surrounded by the trade rows and makes it difficult for the ordinary inhabitant to find easily the right direction where the entrance to the metro is situated.

Here we see the process of stigmergic behaviour in the nodal place that is similar to the above area of the case study, where the actions (informal function) are taking place in the environment (place) and contexts (economics, politics) during time. These large-scale changes of the market area Barabashovo around the node with metro station by Academic Barabashov (Saltivka, Kharkiv) are observed on the data of satellite images (2000–2016) retrieved from Google Earth Pro in 2017. The selected satellite images from 2000, 2008, 2011, 2016 are showed (Fig. 2).



2000 2008

2011 2016

Fig. 2. The market area Barabashovo around the node with metro station by Academic Barabashov, Saltivka, Kharkiv. 2000, 2008, 2011, 2016 [Google Earth Pro; retrieved in 2017] .

Functional transformations on ground floor of housing block in residential areas. The micro-scale changes in the case study residential area Saltivka are observed around the node with metro station Heroyiv Pratsi. The functional transformations of the apartments on the ground floors of residential buildings built during the 1970–80s started to take place from 2000. The process is not based under the strategic approach or any reconstruction program of the apartments. The mechanism of such functional transformation has the only formal step as official procedure of excluding of living square meters from housing function. This procedure is based on the apartment owner's application to the Area (regional) Council authorities and the final decision of these authorities. The urban policies define only the types of new excluded functions of services, which cannot be organised at the place, for instance (chemical storage, storage of recycled materials, etc.), and are not under any program or strategy of reconstruction. Thus, the owner of the property decides himself about a new function of commerce or services. The functional transformation causes as well the next reconstruction of the apartment as: construction of the individual entrance with the staircase to the facility from the street; reconstruction of the plan; construction of advertisement elements on the facade that belongs only to the facility; development of the entrance zone for the pedestrians and cars in the front of the facility; construction of the additional space of the facility in the front or at the backyard of the housing block (Fig. 3).

Fig. 3. Functional transformations on ground floor of housing block from residence to commerce and services in residential area Saltivka, Kharkiv [(c) Photos by O.Chabanyuk, 2017].

From residence to commerce and services as a stigmergic behaviour. The definition of stigmergic behaviour allows to understand functional transformations as actions fulfilled by residents or owners as actors in the process of functional transformations from residence to commerce within the environment (contexts) under indirect communications, which continue the previously finished action. Each action of transformation is a finished act, because the premises with the new function work successfully in the urban environment as a physical environment. The next place for the transformation is chosen by an owner of the residence himself, as well as the type of the function for the transformation. The only official step, which will allow this action is the application of the owner to the Area (regional) Council authorities and the obtaining of the official permission for the transformation, agreed design project. The commercial success of the services in the chosen location by the actor stimulates subsequent actions and plays the role of a trigger for another actor.

This example of the micro-scale changes in the urban environment in the case study allows to identify the cross-related stigmergic environments, which trigger the stigmergic behaviour. The stigmergic environments comprise physical (environment) and non-tangible spaces (context). This particular case study implicate the cross-related stigmergic environments: place, actions; and contexts as: time, economics, politics, ideology. Place as urban environment and urban tissue of the residential area is created under the politics and ideology (socialist state) of the 1970–80s. Contemporary time of 2017 starting from 1991 has changed the contexts of politics and ideology, but at the same time the urban environment of the residential area remains the same, hence the new rules of economics produce the context for stigmergic behaviour in the functional transformations in the residential areas in micro- and large-scale changes in the retail trade market.

4. Discussion and conclusions

Michael Batty (2013) expresses the vision about the contemporary urban environments that “it is high time we change our focus from locations to interactions, from thinking of cities as idealized morphologies to thinking of them as patterns of communications, interaction, trade and […] thinking of them as networks” [7]. We envisage that the understanding of implication of interdisciplinary conceptual approach, as stigmergic concept will allow working with interaction of actors in urban environment under the self-organizing process. The contextualization of interaction in self-organizing process as stigmergic behaviour in urban area specifies the environments and contexts. Stigmergic approach provides the lens for us to understand how the environments and contexts influence and trigger the actors’ actions. Stigmergic behaviour becomes a theoretical base for understanding the self-organizing process in urban space; describe emergent interactions of actors, reveals aim for equilibrium in urban planning. Stigmergy as a concept under the transdisciplinary application in urban planning provides capability to respond to shifting realities in the city development, its networks coordination.

Policy-making defines the frames for urban development, but not timely responds on the societal changes in the cities, which imply their own ways as self-organization process. However, it becomes the aim of urban policies to contextualize changes, which are under stigmergic behaviour, continue or prevent them, hence, direct to equilibrium in urban tissue. Stigmergic behaviours, as concept, are efficient, but work as a self-organization form.

Understanding that stigmergy can create efficiency without effectiveness, it's possible to assume and conclude that Urban Policies must seek and change the lack of effectiveness on stigmergic behaviours.

Urban policies must offer effectiveness to the stigmergic efficiency. Understanding emergent urban phenomenon as stigmergic behaviours can be translated to computational simulations in order to synchronize urban public demands to urban policies. Thus, urban policies must create effective policies.

With this preliminary understanding of transdisciplinary implication of stigmergic concept to urban planning, we envisage the general approach is still open in this domain for contributing to stigmergic capacity.

5. Literature

[1] Birk, R.H., Infrastructuring the social: Local community work, urban policy and marginalized residential areas in Denmark. . Environment & Planning A. , 2017. Vol. 49 (Issue 4): p. p767–783. 17p.

[2] Judyta, W., Urban Infrastructure Facilities as an Essential Public Investment for Sustainable Cities – Indispensable but Unwelcome Objects of Social Conflicts. Case Study of Warsaw, Poland. Transportation Research Procedia, 2016. 16: p. 553–565.

[3] Cheng, J., et al., Understanding urban networks: Comparing a node-, a density- and an accessibility-based view. Cities, 2013. 31: p. 165–176.

[4] Cheng, J., F.L. Clercq, and L. Bertolini, Understanding urban networks through accessibility. 2005, European Regional Science Association.

[5] Wdowiarz-Bilska, M., Concepts of the city in the AGE of knowledge-based economy. Czasopismo Techniczne; Architektura Zeszyt 12-A (27) 2015, 2016: p. 223–239.

[6] Newman, M.E.J., Networks : an introduction / M. E. J. Newman. 2010, Oxford: Oxford University Press.

[7] Batty, M., The New Science of Cities. 2013, Cambridge, Massachusetts: The MIT Press.

[8] Stouten, P.L.M., Changing Contexts in Urban Regeneration : 30 Years of Modernisation in Rotterdam. Design/Science/Planning. 2010, Amsterdam: Techne Press.

[9] New Urban Agenda. Draft outcome document of the United Nations Conference on Housing and Sustainable Urban Development (Habitat III), Quito, 17–20 October 2016. A/CONF.226/42016.

[10] Marsault, X., Can ants build urban street networks? 2009. p. 1706.

[11] Nickerson, J.V., Generating Networks. Design Computing and Cognition. Atlanta, 2008.

[12] Alfeo, A.L., et al., Stigmergy-based modeling to discover urban activity patterns from positioning data. 2017.

[13] Wohl, S., Considering how morphological traits of urban fabric create affordances for complex

adaptation and emergence. Progress in Human Geography, 2016. 40(1): p. 30–47.

[14] Heylighen, F., Stigmergy as a Universal Coordination Mechanism: components, varieties and applications. Human Stigmergy: Theoretical Developments and New Applications. Springer. Retrieved from http://pespmc1. vub. ac. be/papers/stigmergy-varieties. pdf, 2015.

[15] Heylighen, F., Why is Open Access Development so Successful? Stigmergic organization and the economics of information. arXiv preprint cs/0612071, 2006.

[16] Christensen, L.R. Practices of stigmergy in architectural work. in Proceedings of the 2007 international ACM conference on Supporting group work. 2007. ACM.

[17] Mason, Z. Programming with stigmergy: using swarms for construction. in ICAL 2003: Proceedings of the eighth international conference on Artificial life. 2003.

[18] Heylighen, F., Stigmergy as a universal coordination mechanism I: Definition and components. Cognitive Systems Research, 2016. 38: p. 4–13.

[19] Gordon, D., Collective intelligence in social insects. AI-depot essay, available online at: http://ai-depot. com/Essay/SocialInsects. html, 2004.

[20] Moura, L., Formigas, Vagabundos e Anarquia. LXXL Edições, 2003 (2009).

[21] Moura, L. Trails, Ants and Stigmergy 2017; Available from: http://www.leonelmoura.com/index.php/texts/trails-ants-and-stigmergy/.

[22] Zinchenko, M.Y., Zhylyshchnoe stroytelstvo v horodakh BSSR v seredyne 1950kh – 1960e hh. Pratsy histarychnaha fakulteta BDU, 2010(5): p. 39–47.

[23] Yaremenko, L.V., Arkhitekturno-planuvalna orhanizatsiia prydomovykh prostoriv v novykh zhytlovykh raionakh naiznachnishykh mist /na prykladi Kyieva. Avtoref. of Dissertation, kand. arkh.: 18.00.04. 1993, Kyiv. nats. un-t bud-va i arkhit.

[24] Kharkiv Masterplan 2026. 2004; Available from: http://gromada.kh.ua/upload/userfiles/1/genplan.pdf.

[25] DBN 360-92** Mistobuduvannya. Planuvannya i zabudova mis’kykh i sil’s’kykh poselen’ (zi zminamy stanom na 21.06.2011). 2011.

[26] Bradshaw, M.J. and A. Stenning, East Central Europe and the Former Soviet Union : The Post-Socialist States. DARG Regional Development Series. 2014, London: Routledge.

[27] Puusepp, R., Generating circulation diagrams for architecture and urban design using multi-agent systems. 2011, University of East London.

[28] State Statistics Service of Ukraine. [cited 2017; Available from: www.ukrstat.gov.ua

[29] Kharkiv City Council. [cited 2017; Available from: www.city.kharkov.ua.

[30] Ystoryia ulyts y ploshchadei Kharkova. Saltovskyi zhyloi massyv. Kharkiv
1977.

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Economical aspects concerning quality control of concrete

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Abstract: The paper deals with economical aspects concerning the quality control of concrete. About 70% of total concrete production is connected with the structural concrete, the subject of quality control and/or conformity. When checking the conformity criteria for a compressive strength of concrete for a small number of samples, qualification errors do not affect the formation of costs associated with losses on external deficiencies. In order to avoid costs related to qualification errors and losses on external deficiencies, the number of samples should be set larger than the minimum (included in contract's clauses). Furthermore, the designer recommendations should be indicated in the specification. In the paper the costs concerning quality control for concrete have been analyzed.

Keywords: compressive strength of concrete, codes of practice

1. Introduction

Concrete is currently most widely used building material in the world. European concrete industry produces about 537 million m3 of concrete per year and about 70% of the production is structural concrete, the subject of quality control and/or conformity. The global cost of quality control is very high and it inclines that producers shift some cost and risk on customers, i.e. investors and contractors of concrete buildings. According to the politics of leading organizations and groups of concrete producers, the appropriate and frequent changes of recommendations are introduced in codes, for instance different criteria for concrete quality have been applied in the following versions of standards for concrete specification, performance, production and conformity.

It should be emphasized that conformity testing due to recommended criteria are not always the statistical control. Such situation can take place when according to the European standard EN 206 [1] the conformity control is checked for a number of samples $n < 15$, especially when $n = 3$. The control is of the statistical character when the information obtained as result of the experimental trial leads to objective conclusions, consistent with the principles of mathematical statistics. A small sample can raise doubts about correctness of the characteristics estimation and of the proper qualification of a verified material batch. Arrangements of a statistical quality control result in a „strategic game" between producer and customer, and the standard conformity criteria can be treated as a result of a „specific" compromise between the requirements for quality, economy and safety [2,3]. The control of concrete production and a final inspection should be based on the assumption of producer's and consumer's risk being split between them and the verification whether delivered batches of concrete meet the conformity criteria. However, in practice, there are no statistical quality control methods that would be free of qualification errors.

2. Quality control of concrete compressive strength

Concrete should be subject to production control within responsibility of a producer according to EN 206 [1]. The inspection must include all steps and measures necessary to establish conformity properties of concrete with specified requirements as well as activities starting from the choice of materials, through a concrete mixture design, concrete production and testing, and finally analyzing test results. The final analysis should be performed on the basis of standard criteria [4, 5, 6].

Production control, conformity and identity are random and mostly statistical. Statistical nature of the control is determined by random sampling method, analysis of test results and conclusions are drown up based on the statistics principles. It does not matter whether the description of tested characteristics is quantitative (quantitative statistics) or qualitative (qualitative statistics) [7]. Conformity control of concrete compressive strength is carried out on concrete with specific class or on concrete families and it gives the basis for deciding about the quality of verified concrete.

European standard EN 206, as regards to concrete compressive strength, distinguishes initial production and continuous production for which the sampling plan and conformity criteria are different. Initial production covers the production until at least 15 test results within a period not exceeding 12 months [1] (Table 1).

Table 1. Conformity criteria for compressive strength according to EN 206.

Production	„n" number of test	Criterion 1	Criterion 2
		Mean from „n" results (f_{cm}) [N/mm^2]	Any single test result (f_{ci}) [N/mm^2]
Initial	< 15	≥ fck + 4	≥ fck – 4
Continuous	≥ 15	≥ fck + 1,48 σ	≥ fck – 4

For concrete quality assessment on the grounds of conformity criteria of compressive strength an off-line quality control method is used. Control procedure is used when the production of a batch of concrete is completed. Final inspection is carried out since manufacturing stage is completed, and as the aim is not to control them or influence on the process, but to protect the recipient from accepting concrete that does not meet quality standards (i.e. relevant conformity criteria formulated in [1]).

The compound criteria for initial production and number of samples n = 3 can have unfavorable effects to both - producer and customer. The most important defects of the criteria are following [8, 9, 10, 11]:

- Probability of concrete acceptance is not always compromise between risk of a producer and a customer. Accepted criteria may lead to excessive customer risk, especially in case of log-normal distribution of compressive strength.

- In case of the compliance compound criteria, a higher value of acceptance probability Pa corresponds to larger variability of concrete strength.
- For standard conformity criteria, probability of acceptance increases with the increase of standard deviation of concrete compressive strength.

Generally, the usefulness of statistical criteria for the small number of samples, expressed by the probability that a batch of concrete with defectiveness fraction can be accepted, is questioned. The relationship between concrete quality and defectiveness fraction can be described using the Average Outgoing Quality Curve [12,13]. When the Average Outgoing Quality Level is higher than 0.05, the concrete class is not reached (Fig. 1). This condition results from the definition of a standardized concrete class.

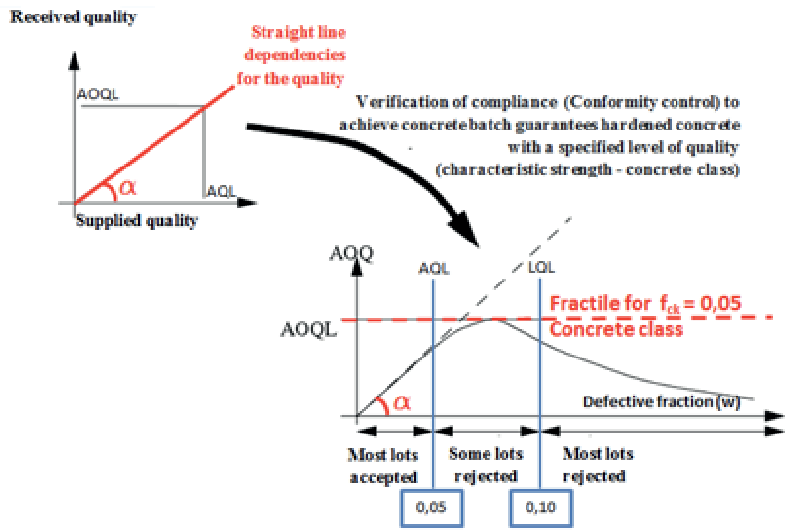

Fig. 1. Relationship between the quality of delivered lots to conformity control and the concrete class (outgoing quality).

Discriminatory power of statistic conformity criteria should be large enough to show evident diversity between the costs for the qualification with errors and the costs for the flawless qualification [14, 15]. It should be emphasized that in practice there is no statistic quality control methods that would be free of errors – errors of the first type (concrete batch of satisfactory quality will be rejected) and the second kind (concrete batch of lower quality will be accepted). It is easy to make a mistake in checking conformity criteria in case of number of a samples n = 3. Conformity criteria do not meet the requirements in terms of quality, hence the attempt to analyze these criteria in respect to economic requirements.

3. Quality control costs

Quality costs include all the costs related to conducting inspections in the company. They include costs associated with the performance or omission of control activities, costs of reparation and replacement of defective parts, costs resulting from customer loss and costs of decreasing company's position on the market. The classification of quality control costs covers: costs of prevention, costs of testing and evaluation, losses on internal deficiencies, losses on external deficiencies [16].

The cost of final inspection is a total of testing and evaluation costs and losses on internal and external deficiencies. Costs of testing depend on the cost of the control sample k_{pr} and the number of controlled samples n; expected control costs when using a single-stage plan are as follows:

$$K_{pr}(w) = P_a(w) \cdot n \cdot k_{pr} + \left(1 - P_a(w)\right) \cdot N \cdot k_{pr} \tag{1}$$

where: $P_a(w)$ – probability of acceptance of a concrete batch with a given defectiveness *w*

n – number of sample,

N – lot number defined as:

$$N = \frac{V_{prod}}{V_{sample}} \tag{2}$$

where: V_{prod} – volume of the concrete batch,

V_{sample} – volume of a test sample (cubic sample $V_{sample} = 3.375\ 10^{-3} m^3$).

Total expected cost of internal defectiveness K_{bw} in a testing plan according to the assessment is as follows:

$$K_{bw}(w) = P_a(w) \cdot n \cdot k_{bw} + \left(1 - P_a(w)\right) \cdot N_1 \cdot k_{bw} \tag{3}$$

where: k_{bw} – cost in case of non-compliant compressive strength of concrete not applied in structural member.

Losses on external deficiencies can be determined using the equation:

$$K_{bz}(w) = P_a(AOQL) \cdot n \cdot k_{bz} + \left(1 - P_a(AOQ)\right) \cdot N \cdot k_{bz} \tag{4}$$

where: k_{bz} – cost of repairing a structural member in case of non-compliant compressive strength of concrete,

$P_a(AOQ)$ - probability of average outgoing quality for a given concrete batch after tests.

Average outgoing quality is expressed as:

$$AOQ = P_a(w) \cdot w \tag{5}$$

AOQ - average outgoing quality of a concrete batch after conformity control.

In the performed analysis of quality control costs , the OC (Operating Characteristic) curve and the AOQ (Average Outgoing Quality) curve have been used.

4. Final inspection costs and qualification errors

In practice, there are no statistical quality control methods that are free from qualification errors. The probability of recognizing a sample as defective is therefore expressed by the formula

$$w^* = w\,(1-\beta) + (1-w)\,\alpha \tag{6}$$

where: w – defectiveness of a sample during inspection of a produced concrete,

β – probability of qualification error of recognizing a defective sample as a flawless one, recipient's risk,

α – probability of qualification error of recognizing a flawless sample as a defective one, producer's risk,

In case of qualification errors, the expected costs of research take the following form:

$$K^*_{pr}(w) = P_a^*(w^*) \cdot n \cdot k_{pr} + \left(1 - P_a^*(w^*)\right) \cdot N \cdot k_{pr} \tag{7}$$

$$K^*_{bw}(w) = P_a^*(w^*) \cdot n \cdot k_{bw} + \left(1 - P_a^*(w^*)\right) \cdot N_1 \cdot k_{bw} \tag{8}$$

$$K^*_{bz}(w) = P_a^*(AOQ^*) \cdot \cdot n \cdot k_{bz} + \left(1 - P_a^*(AOQ^*)\right) \cdot N \cdot k_{bz} \tag{9}$$

where: P_a*(...) – probability of accepting a material batch with presence of qualification errors.

In concrete production the good quality of concrete corresponds to the concrete class (the characteristic strength f_{ck} – the 0.05 fractile of the theoretical distribution of concrete strength). In practice, the fractile can be smaller or higher than 0.05. The defectiveness of a sample w in the case when the concrete strength is below fck is defined as:

$$P(f_c \leq f_{ck}) = w \tag{10}$$

where: f_c is the compressive strength, which is a random variable.

The operation characteristic curve of the conformity criterion (OC-curve or OC-line) is the function of $P_a(w)$, where P_a is the probability of acceptance, (Fig. 2). The rejection probability of a good quality batch $\alpha = 1 - Pa$, and the acceptance probability of a bad quality batch β, should be balanced between producers and clients. However, the equality of rejection probability and acceptance probability does not mean that producer's and the client's risk are the same.

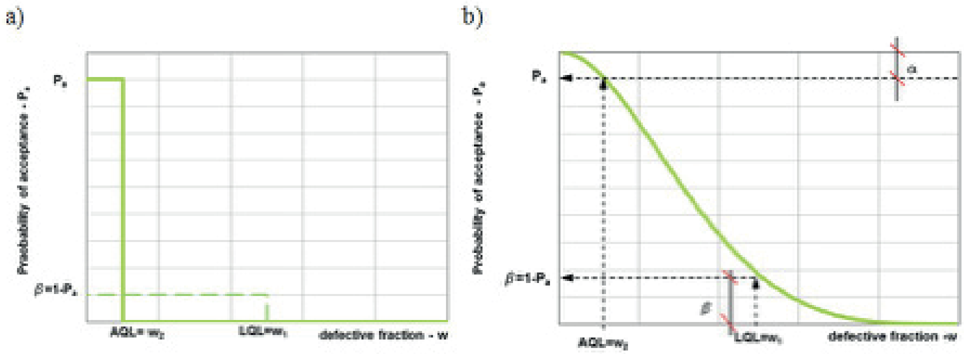

Fig. 2. Diagram of: a) an ideal OC-line and b) a real OC-line

5. Costs analysis of final inspection

Analysis of the conformity criteria based on economic indicators requires the determination of the total cost of final inspection. The analysis was performed for the reinforced concrete deck plate of a three-span bridge structure of the theoretical span $L_T = 28.8$

+ 38.4 + 28.8 m. The dimensions of plate were: thickness 0.25 m, total width 14 m. The plate was made with the concrete class C30/37 for which the real defectiveness of concrete was 0.07. The costs of tests and evaluation were calculated at the assumed recipient and producer risk level. The costs were estimated for a flawless control as well as with qualification errors. It was assumed that the errors α and β are equal 0.05 (Fig. 3). Calculations were performed according to the described procedure.

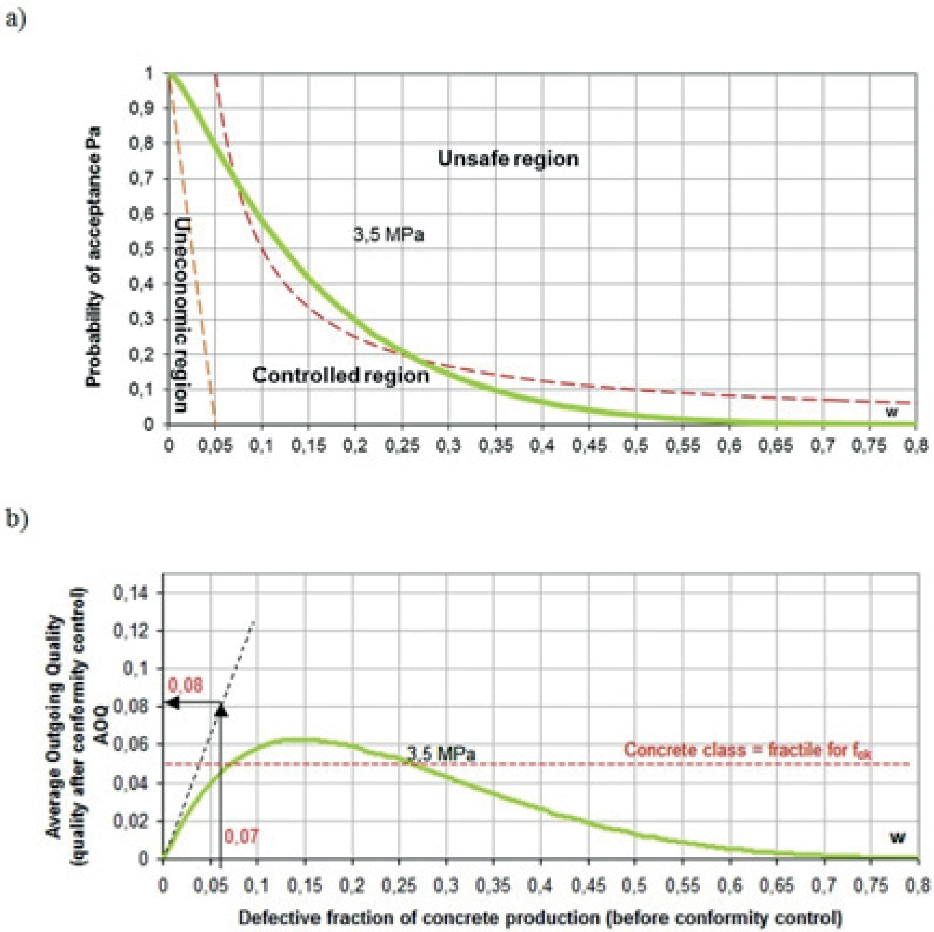

Fig. 3. Diagram of: a) the OC line, b) the AOQ line for conformity criteria for n = 3

and for standard deviation 3.5 MPa

In order to determine costs associated with the verification of the quality of concrete for a small number of samples it was assumed that the cost of testing samples was 100 EURO, the cost of internal deficiency is 1,000 EURO (losses incurred in case of a batch of material understood as a mixer with a volume of 6 m3), the cost of external deficiency 50,000 EURO. The obtained results are presented in Table 2.

Qualification type Control type	A Flawless qualification [euros]	B Qualification with errors [euros]	B/A
Testing and evaluation	358	397	1.11
Losses on internal deficiencies	1 008	1 483	1.47
Losses on external deficiencies	48 029	48 278	1.01
Total cost	49 395	50 158	1.02

Costs of final inspection in case of flawless qualification and control with qualification were obtained on the same level. It showed that when performing testing concrete conformity control on the basis of small sample (the number of specimens n = 3) the test is not reliable. Therefore, the usage of small sample to quality control can lead to refrain accurate final inspection and reliable quality control and, consequently it might be the reason why the quality of a produced concrete is being reduced.

Qualification errors appearing during control do not have a major impact on a formation of costs related to losses on external deficiencies. This means that a sample of a small number is less selective in terms of quality verification, as well as the economy.

6. Conclusions

The control costs in both cases are similar, and thus control for n = 3 is objectively meaningless, although it has psychological effects. The costs associated with quality control as recommended by the European standard EN 206 [1] of dual conformity criteria for a sample of a small number with flawless qualification and qualification errors are comparable, what indicates that the recommended in the norm quality control procedures are not consistent with the requirements of the economy.

In order to avoid costs related to qualification errors and losses on external deficiencies the number should be set larger than the minimum.

In case of conformity assessment of concrete properties, the risk is borne not only by the producer and the recipient of concrete but also the investor, the user of the building and, in case of a construction disaster, the whole society. Disparities of the effects of making wrong decision are obvious and considerable. Recommendations in the current standards include only the producer's risk whereas the risk of the customer remains vague. The principle of equality of market participants suggests that the criteria for conformity assessment should take into account rational and conscious risk-sharing. The EU Directive on the standardization enables treating requirements contained in the norm as a minimum. The recipient of concrete may agree with the supplier conditions that allow a conscious choice of a risk level.

One of possible strategies is to balance the risk of a producer and a recipient. The reconciliation of an acceptable risk of a producer and a recipient of concrete, for instance, presumption of equal risk on both sides, allows to estimate probability of conformity certification and selection of a suitable control plan.

7. References:

[1] EN 206-1:2013, Concrete – Part 1: Specification, performance, production and conformity.

[2] Holicky, M., Vorlicek. M., Fractile estimation and sampling inspection in building, Acta Polytechnica, CVUT Praha, 1992.Vol. 32. Issue 1, 87-96.

[3] Sual I. Gass, and Arjang A. Assad, An annotated timeline of operation research. An informal history. Springer Science and Business Media, 2005.

[4] Harrison. T.A., Crompton, S., Eastwood. C., Richardson. G., Sym, R., Guidance on the application of the EN 206-1 conformity rules, Quarry Products Association, 2001.

[5] Czarnecki, L. et al., Concrete according to PN EN 206-1- The comment - Collective work, Polish Cement and PKN, Cracow, Poland, 2004.

[6] Lynch, B., Kelly, J., McGrath, M., Murphy, B., Newell, J., The new Concrete Standards, An Introduction to EN 206-1, The Irish Concrete Society, 2004.

[7] Montgomery, D.C., Introduction to Statistical Quality Control, 5th Ed., Wiley, 2005.

[8] Taerwe, L., Evaluation of compound compliance criteria for concrete strength, Materials and Structures, 1998, 21, pp. 13-20.

[9] Catarino, J.M.R., Statistical criteria for acceptance of materials performance of concrete standards ENV 206;1993 and prEN206:1997. Proceedings of 12th ERMCO Congress, Vol. 1, Lisbon, 1998.

[10] Brunarski, L., The mathematical basis for shaping the strength of materials conformity criteria, Scientific Work of the Institute of Building Technology, Publishing of the Institute of Building Technology, Warsaw 2009 (in Polish).

[11] Szczygielska, E., Tur, V., The study of the conformity criterion for compressive strength of concrete based on order statistics, Civil Engineering and Architecture, 2013, Vol. 12, Issue 3, 223-230.

[12] Taerwe, L., Caspeele, R., Conformity control of concrete: some basic aspects, Proceedings of 4-th International Probabilistic Symposium, Ghent, Belgium, 2006, 57-70.

[13] Skrzypczak, I., Analysis of criteria of quality assessment for concrete and their influence on risk of the producer and the recipient, The Publisher of the Rzeszow University of Technology,, Rzeszow, Poland, 2013 (in Polish).

[14] Evans, J., Lindsay, W., The Management and Control of Quality, West Publishing Company, 1989.

[15] Banovac, E., Pavlovic, D., Vistica N., Mathematical aspects of acceptance sampling procedure. International Journal of Mathematical Models and Methods in Applied Sciences, 2012, Issue 5, Vol. 6, 625-633.

[16] Dumicic, K., Bahovec, V., Kurnoga Zivadinovic, N., Studying an OC Curve of an Acceptance Sampling Plan: A Statistical Quality Control Tool, Proceedings of the 7th WSEAS International Conference on Mathematics & Computers in Business & Economics, Cavtat, Croatia, 2006, 1-6.

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Pure torsion problem in tensor notation

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Abstract: The paper examines the application of the tensor calculus to the classic problem of the pure torsion of prismatic rods. The introduction contains a short description of the reference frames, base vectors, contravariant and covariant vector coordinates when applying the Einstein summation convention. Torsion formulas were derived according to Coulomb's and Saint-Venant's theories, while, as a link between the theories, so-called Navier's error was discussed. Groups of the elasticity theory equations were used.

Keywords: pure torsion, tensor calculus, covariant/contravariant basses, vector components.

1. Introduction

The tensor notation used here is in accordance with the notation applied in the publications [1-2]. The description is known as index notation, although there are some variants to it. Prof. Jan Rychlewski consequently used the dyadic notation during his lectures on continuum mechanics at the Institute of Fundamental Technical Problems in Warsaw at the end of 1970s. In the monograph [3], vectors and tensors are written as boldface letters without indices. In this case, an additional notation with regard to components is necessary.

There are numerous monographs where tensors are used, albeit without the application of a uniform and consistent method. Let us recall here Sokolikoff's repeatedly reprinted monograph [4], for instance.

The Einstein summation convention (1916) concerns the geometrical/physical objects with upper and lower indices where there are various pairs of identical indices and where one is upper and the other one – lower. This implies summation over the paired indices over the whole range of their values.

In Fig. 1.a-b, the same vector $\vec{u}$ is drawn as an oriented segment in two different dimensional coordinate systems. Although the base vectors are singular, they are different. In Fig. 1.a and Fig.1.b, the coordinate lines are the same, however, the projections of the $\vec{u}$ vector differ significantly. In the case of Fig. 1.a, the parallel projection takes place, and in the case of Fig. 1.b, the orthogonal projection is applied. As a result, base vectors are denoted as $\vec{g}^m$ and $\vec{g}_n$ respectively, where $\vec{g}^m$ creates the contravariant base and $\vec{g}_n$ stands for the covariant base. By virtue of summation convention, respective presentations of the $\vec{u}$ vector are possible.

$$\vec{u} = u_m \vec{g}^m \text{ and } \vec{u} = u^n \vec{g}_n \text{, where } m, n = 1, 2. \quad \text{(i)}$$

The vector coefficients create sets u_m and u^n adequately to their bases.

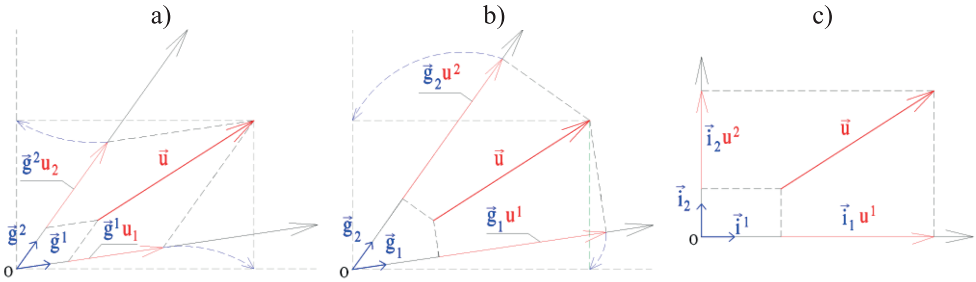

Fig 1. Base vectors as well as the contravariant and covariant vectors' components in two dimensions a) covariant vector components b) contravariant vector components c) Cartesian coordinate system

In Fig 1., the transformation of skew coordinates into a Cartesian system is also suggested. Such transformation reveals that in the case of the Cartesian coordinate system there is no distinction between the contravariant and covariant bases and, as a consequence, the summation convention plays only the role of an "alternator".

The skew coordinate systems were investigated by Kaliski, [5].

The metric tensor includes the information on the coordinate system and is obtained by the scalar product of base vectors

$$g_{mn} = \vec{g}_m \cdot \vec{g}_n \, , \; \delta_{mn} = \vec{i}_m \cdot \vec{i}_n = \delta^{mn} = \vec{i}^{\,m} \cdot \vec{i}^{\,n} = \delta^n_m = \vec{i}_m \cdot \vec{i}^{\,n} \, , \tag{ii}$$

Additionally,

$$g^n_m = \delta^n_m \, . \tag{iii}$$

Where g_{mn} is the metric tensor of an arbitrary coordinate system with the base vectors g_m. δ^n_m is a metric tensor for a Cartesian coordinate system, also known as Kronecker's delta. Here, the m, n indices can run over 1, 2, 3, for instance. The metric tensor allows to increase or decrease an index which leads to associated tensors in the following way

$$A^n_m g_{nk} = A_{mk} \, . \tag{iv}$$

The $\vec{u}$ vector coefficients can be found as a scalar product of the u and base vectors, according to the following formula:

$$u_k = \vec{u} \cdot \vec{g}_k \, . \tag{v}$$

In the linear theory of elasticity there are the following groups of problems:

- deformation, strain tensor ε^n_m,
- constitutive relations, stress tensor σ^j_i,
- equilibrium equation,
- boundary conditions or initial-boundary conditions,
- compatibility relation.

This group set will be used below. The pure torsion problem of a bar belongs to the classical approaches in mechanics. It can be found in [4], [6-7]. One of the latest publications on the theory of elasticity is a monograph [8]. In the field of the continuum mechanics, the book [10] can be worth to mention.

2. Coulomb's theory

We assume:

I) the summation convention and tensor calculus in three-dimensional space will be implemented,

II) the theory of small deformations and the principle of stiffness apply

$$\varepsilon_{ij}^{(sum.)}=\frac{1}{2}\left(\nabla_i u_j+\nabla_j u_i \pm \nabla_i u_m \nabla_j u^m\right) \to \varepsilon_{ij}^{(sum.)}=\frac{1}{2}\left(\nabla_i u_j+\nabla_j u_i\right)=\varepsilon_{ji}^{(sum.)}, \qquad (1)$$

where ∇_i stands for covariant derivative and in Cartesian coordinate system becomes to ordinary derivative $\frac{\partial}{\partial x_i}$,

$$\varepsilon_{ij}^{(sum.)}=\varepsilon_{ij}+\varepsilon_{ij}^{(init.)}, \ \varepsilon_{ij}^{(init.)}=0, \qquad (1.1)$$

III) material is isotropic and homogenous, Hooke's law is valid –

$$\sigma_{ij}=2\mu\varepsilon_{ij}+\lambda J_1 g_{ij}, \ J_1=\varepsilon_{ij}g^{ij}, \qquad (2)$$

where J_1 is the first invariant of the strain tensor, $J_1=\varepsilon_{ij}g^{ij}=\varepsilon_i^i$,

IV) the pure torsion of straight rod of a constant circular section is considered, (Fig.2.), in Cartesian coordinate system we have

$\vec{T}=T_m\vec{i}^m=\vec{0}$, (resultant internal forces vector) (2.3.1)

$\vec{M}=M_k\vec{i}^k=M_1\vec{i}^1+M_2\vec{i}^2+M_3\vec{i}^3=M_3\vec{i}^3=\overrightarrow{\mathfrak{M}}$, (resultant vectors of internal moments) (3.2)

where $\mathfrak{M}=const.\neq 0$; (3.3)

V) x_1, x_2 are the principal axes in the sense of inertial moments,

VI) the Coulomb's assumption is assumed – in case of pure torsion the cross-sections of the rod turn each other like infinitely rigid discs,

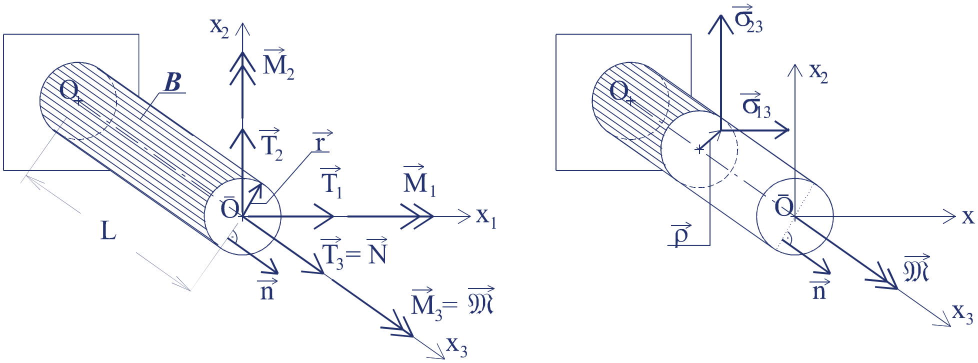

Fig.2. Cartesian coordinate system, internal force vectors and stress vectors

VII) the Cauchy's relation is valid

$$\vec{t} = \sigma_{ij}\, n^i\, \vec{g}^{\,j}\,, \tag{4}$$

the stress vector $\vec{t}$ is related to stress tensor σ_{ij} by cutting the body (point) with plane which is oriented by outward normal vector $\vec{n}$ at any chosen body point; in detail

$$\vec{n} = n^m\, \vec{g}_m\,,\ |\vec{n}| = 1\,, \tag{5}$$

VIII) statics is analysed.

3. Deformation – displacements - geometric relations

Lets repeat again - in case of Cartesian coordinates, for tensors of valence one or two, there are no distinction between covariant, contravariant or shifted indices –

$$\vec{i}_m = \vec{i}^{\,m}\,,\ u_m = u^m\,,\ x_m = x^m\,, \varepsilon_{mn} = \varepsilon^{mn} = \varepsilon_m^n\,, \tag{6}$$

where m =1, 2, 3, (three dimensions).

In initial state, for an arbitrary point P of a rod cross-section, in polar description, its position is uniquely defined by position vector $\vec{\rho}_P$. After torsion, in the actual configuration, the point P rotates to the position P' and is depicted be vector $\vec{\rho}_{P'}$. In analysed case, the difference between actual and initial configurations (P' and P) depicts the deformation, (Fig. 3.).

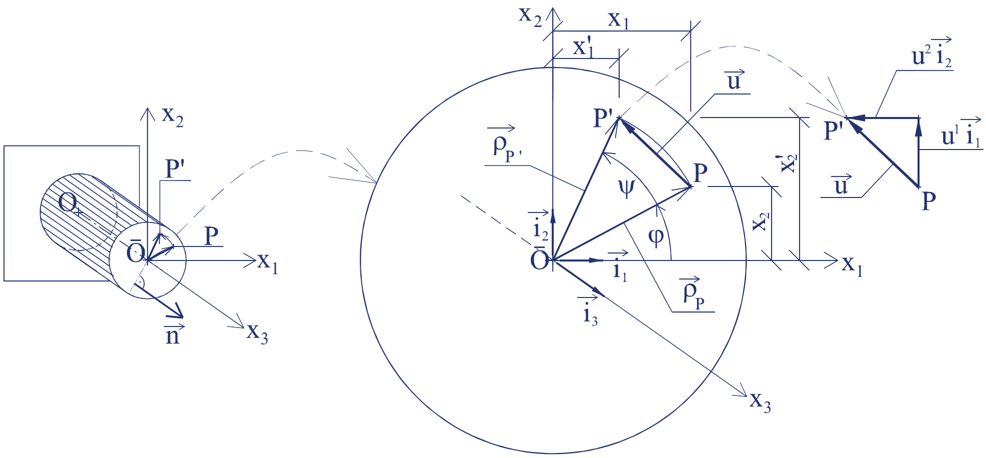

Fig. 3. Deformation

Assumption VI) implies that

$$u_3 = 0\,, \tag{7}$$

it results the only two (of three) non zero displacement vector components

$$\vec{u} = u_1\vec{i}^{\,1} + u_2\vec{i}^{\,2} + 0\vec{i}^{\,3} = u_{\overline{m}}\vec{i}^{\,\overline{m}}\,,\ \overline{m} = 1{,}2. \tag{7.1}$$

and a circular trajectory of movement

$$\left|\vec{\rho}_P\right| = \left|\vec{\rho}_{P'}\right| = \left|\vec{\rho}\right| = \rho \tag{8}$$

and

$$\vec{\rho}_P + \vec{u} = \vec{\rho}_{P'} \, . \tag{9}$$

Where:

$$\vec{\rho}_P = x_{\overline{m}} \vec{i}^{\,\overline{m}} = x_1 \vec{i}^{\,1} + x_2 \vec{i}^{\,2} \, , \; \vec{\rho}_{P'} = x'_{\overline{m}} \vec{i}^{\,\overline{m}} = x'_1 \vec{i}^{\,1} + x'_2 \vec{i}^{\,2} \tag{10}$$

or

$$\vec{u} = \vec{\rho}_{P'} - \vec{\rho}_P \Rightarrow u_{\overline{m}} = x'_{\overline{m}} - x_{\overline{m}} \, . \tag{11}$$

Additionally the polar coordinate system is introduced. By virtue of II) assumption, the rotational angle of a disc $\psi = \psi(x_3)$ is a small one, i.e.

$$\psi \to 0 \, , \tag{12}$$

this implies as follows

$$\begin{cases} \lim\limits_{\psi \to \pm 0} \cos\psi = f_1(\psi) = 1 \\ \lim\limits_{\psi \to \pm 0} \sin\psi = f_2(\psi) = \psi \end{cases} . \tag{13}$$

On the basis of (8) the Cartesian coordinates of P i P' can be written in the form

$$\begin{cases} x_1 = \rho \cos\varphi \\ x_2 = \rho \sin\varphi \end{cases} , \tag{14.1}$$

and

$$\begin{cases} x'_1 = \rho \cos(\varphi + \psi) \Rightarrow \lim\limits_{\psi \to \pm 0} x'_1 = \rho \left(\cos\varphi - \psi \sin\varphi\right) = x_1 - \psi x_2 \\ x'_2 = \rho \sin(\varphi + \psi) \Rightarrow \lim\limits_{\psi \to \pm 0} x'_2 = \rho \left(\sin\varphi + \psi \cos\varphi\right) = x_2 + \psi x_1 \end{cases} . \tag{14.2}$$

Using (11), (14.1-14.2), the non zeros components of displacement vector $\vec{u}$ are as follows

$$\begin{cases} u_1 = -\psi x_2 \\ u_2 = \psi x_1 \end{cases} . \tag{15}$$

4. Strain tensor components

Having known displacement vector (7), (15) we can use (1) to determine the components of strain tensor in Cartesian coordinate system

$$\varepsilon_{ij} = \varepsilon_{ij} = \frac{1}{2}\left(\nabla_i u_j + \nabla_j u_i\right) \xrightarrow{Cart.} \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) = \frac{1}{2}\left(u_{j,i} + u_{i,j}\right), \tag{16}$$

adequately we obtain

$$\varepsilon_{11} = u_{1,1} = 0\,,\ \varepsilon_{22} = u_{2,2} = 0\,,\ \varepsilon_{33} = u_{3,3} = 0\,, \tag{17.1-3}$$

$$\varepsilon_{12} = \frac{1}{2}\left(u_{2,1} + u_{1,2}\right) = \frac{1}{2}\left(\psi - \psi\right) = 0\,,$$

$$\varepsilon_{13} = \frac{1}{2}\left(u_{3,1} + u_{1,3}\right) = \frac{1}{2}u_{1,3} = -\frac{1}{2}\frac{d\psi}{dx_3}x_2 = -\frac{1}{2}\omega x_2\,, \tag{17.4-6}$$

$$\varepsilon_{23} = \frac{1}{2}\left(u_{3,2} + u_{2,3}\right) = \frac{1}{2}u_{2,3} = \frac{1}{2}\frac{d\psi}{dx_3}x_1 = \frac{1}{2}\omega x_1\,.$$

In (17) the above notation is introduced

$$\psi\left(x_3\right) = \int_0^{x_3} \omega\left(\xi\right) d\xi \tag{18.1}$$

where $\omega\left(x_3\right) = \dfrac{d\psi}{dx_3}$. (18.2)

The strain tensor can be presented in the matrix form

$$\varepsilon_{ij} = \begin{bmatrix} 0 & 0 & -\dfrac{\omega x_2}{2} \\ 0 & 0 & \dfrac{\omega x_1}{2} \\ -\dfrac{\omega x_2}{2} & \dfrac{\omega x_1}{2} & 0 \end{bmatrix}. \tag{18.3}$$

Hence, the first invariant of ε_{ij} (dilatation) becomes as follows

$$J_1 = \varepsilon_{ij} g^{ij} \xrightarrow{Cart.} \varepsilon_{ij}\delta^{ij} = \varepsilon_1^1 + \varepsilon_2^2 + \varepsilon_3^3 = 0\,. \tag{19}$$

5. Constitutive relation – stresses

By means of (2) which is valid for isotropic and homogenous material we can find the set of stress tensor components. Applying (19) we get

$$\sigma_{ij} = 2\mu\varepsilon_{ij} + \lambda J_1 g_{ij} = 2G\varepsilon_{ij}\,. \tag{20}$$

Where G is the Kirchhoff modulus. The non zeros components are in only two cases

$\sigma_{13} = -G\omega\, x_2$ and $\sigma_{23} = G\omega\, x_1$. (21)

In matrix notation one arrives to

$$\sigma_{ij} = \begin{bmatrix} 0 & 0 & -G\omega x_2 \\ 0 & 0 & G\omega x_1 \\ -G\omega x_2 & G\omega x_1 & 0 \end{bmatrix} = \sigma_{ji} \tag{21.1}$$

6. Equilibrium state

In the general case, the state of equilibrium expresses two conditions of resetting the resultant vectors of forces and moments acting on/in the body respectively. In the problem of pure torsion, the symmetry of stress tensor (21.1) leads to the first condition of the form

$$\vec{\mathfrak{M}} = \int_A \vec{\rho} \times \vec{\mathrm{t}}\; dA = \int_A \in^{abc} \rho_a \mathrm{t}_\mathrm{b} \vec{g}_c \, dA \xrightarrow{Cart.} \int_A e^{abc} x_a \mathrm{t}_b \vec{i}_c \, dA = \mathfrak{M} \vec{i}_3 . \tag{22}$$

The rod cross-section is characterized by normal vector $\vec{n}$ which Cartesian components (Fig. 1.) are reduced as follows

$$\vec{n} = n_k \vec{i}^{\,k} = 0\vec{i}^{\,1} + 0\vec{i}^{\,2} + 1\vec{i}^{\,3}, \; \vec{n}: \quad n_k = n^k = [0,0,1]. \tag{23}$$

Using (21) we can write the components of a stress vector (4) in the cross-section

$$\vec{\mathrm{t}} = \sigma_{bk} n^k \vec{g}^{\,b} \xrightarrow{Cart.} \sigma_{bk} n^k \vec{i}^{\,b} = \mathrm{t}_b \vec{i}^{\,b}, \tag{24.1}$$

$$t_b = \sigma_{bk} n^k = \sigma_{b1} n^1 + \sigma_{b2} n^2 + \sigma_{b3} n^3 = \sigma_{b3} 1 = \sigma_{b3} . \tag{24.2}$$

On the basis of assumption IV) and appropriately (19), (22) do (24) we obtain

$$\mathfrak{M} = \int_A (x_1 \sigma_{23} - x_2 \sigma_{13}) dA = G\omega \int_A \left[(x_1)^2 + (x_2)^2 \right] \; dA = G\omega\, J_o , \tag{25}$$

which is usually written in the form

$$\omega = \frac{\mathfrak{M}}{G J_o} . \tag{26}$$

By means of – IV), (3.1), (26) we can write

$$\mathfrak{M} = const. \rightarrow \qquad \omega = const., \qquad \psi = \omega x_3 \tag{26.1}$$

$G J_o$ – is torsion stiffness against rotation. Here J_o is a centrifugal moment of inertia.

Now, applying (15), (17), (21), (26) and (26.1), sequentially components of displacement vector as well as strain and stress tensors can be rewritten as follows

$$u_1 = -\frac{\mathfrak{M}}{G J_o} x_2 x_3 , \; u_2 = \frac{\mathfrak{M}}{G J_o} x_1 x_3 , \tag{27}$$

$$\varepsilon_{13} = -\frac{\mathfrak{M}}{2 G J_o} x_2 , \; \varepsilon_{23} = \frac{\mathfrak{M}}{2 G J_o} x_1 , \tag{28}$$

$$\sigma_{13} = -\frac{\mathfrak{M}}{J_o} x_2 , \; \sigma_{23} = \frac{\mathfrak{M}}{J_o} x_1 . \tag{29}$$

Let us find extremes of shearing stresses in the rod cross-section. Now, the stress vector is written as a sum of normal and shearing stresses, see (21), (24) and Fig. 2, then we arrive at

$$\vec{t} = \vec{\sigma} + \vec{\tau} = t_b \vec{i}^{\,b} = \sigma_{b3} \vec{i}^{\,b} = \sigma_{13} \vec{i}^{\,1} + \sigma_{23} \vec{i}^{\,2} = \vec{\tau} \;. \tag{30}$$

The modulus of $\vec{\tau}$ can be calculated as

$$\tau = |\vec{\tau}| = \sqrt{\vec{\tau} \cdot \vec{\tau}} = \sqrt{\sigma_{a3} \vec{i}^{\,a} \cdot \sigma_{b3} \vec{i}^{\,b}} = \sqrt{\sigma_{a3}\, \sigma_{b3} \delta^{ab}} = \sqrt{(\sigma_{13})^2 + (\sigma_{23})^2} =$$

$$= G\omega \sqrt{(x_1)^2 + (x_2)^2} = G\omega R = \frac{\mathfrak{M}}{J_o} \rho \,. \tag{31}$$

Let us analyse vectors $\vec{\tau}$ and $\vec{\rho}$

$$\vec{\tau} \cdot \vec{\rho} = \sigma_{a3} \vec{i}^{\,a} \cdot x_b \vec{i}^{\,b} = \sigma_{a3}\, x_b\, \delta^{ab} = \sigma_{13}\, x_1 + \sigma_{23}\, x_2 = (-G\omega x_2) x_1 + (G\omega x_1) x_2 = 0 \,, \tag{32}$$

or in other way (Fig. 4.) –

$$\vec{\tau} \cdot \vec{\rho} = 0 \Leftrightarrow \vec{\tau} \perp \vec{\rho} \;; \tag{33}$$

$\tau_{extr.}$ occurs at the cross-section circuit, and its vector is tangential to the circuit.

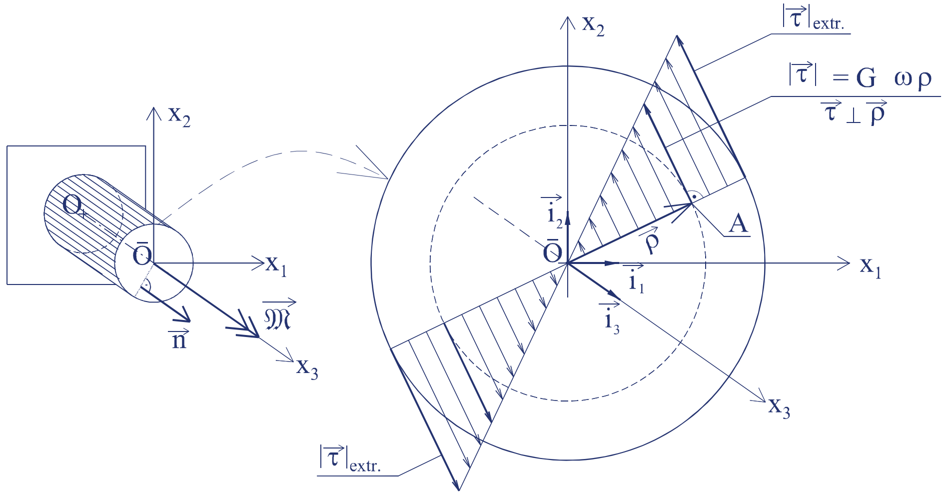

Fig. 4. Shearing stress vector

7. Navier's error

Without success, the Coulomb's theory for cross-sections of any shape was used by Claude-Louis Navier. We will show that assumption VI) is valid only for bars with a circular cross-section.

Consider the equilibrium in the case of pure torsion. The edge surface is free of any load. On this cross-section border surface we select an arbitrary point B, Fig. 5.

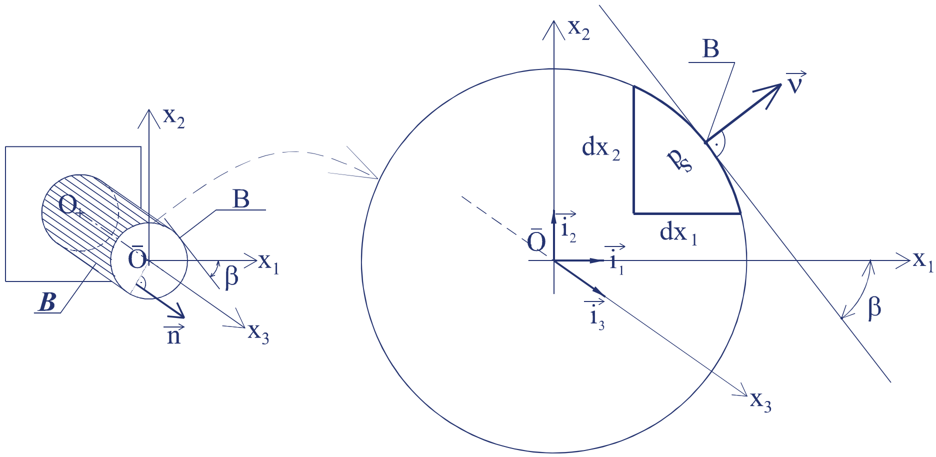

Fig. 5. Vector $\vec{n}$ and geometrical relationships on the side of the rod

We analyze the state of stress in the infinitesimal vicinity of the point B on the distance ds, Fig. 5. The tangent line to the B side is inclined at an angle β to the axis x_1, this results as follows

$$\sin\beta = \frac{dx_2}{ds}, \; \cos\beta = -\frac{dx_1}{ds}. \tag{34}$$

In the Cartesian system coordinates, the normal unit vector to the side surface at the point B has following components

$$|\vec{n}| = 1, \; n_1 = n^1 = 1\sin\beta = \frac{dx_2}{ds}, \; n_2 = n^2 = 1\cos\beta = -\frac{dx_1}{ds}, \; n_3 = 0. \tag{35}$$

The boundary surface is free of external loads, the stress vector is a zero one

$$\vec{\mathrm{t}} = \sigma_{bk} n^k \vec{i}^{\,b} = \vec{0} \Rightarrow \sigma_{bk} n^k = 0 \text{ where } b, k=1, 2, 3. \tag{36}$$

The conditions (36) correspond to three equations of equilibrium, which are explicit in form

$$\begin{cases} b=1 \quad \rightarrow \quad \sigma_{11}n^1 + \sigma_{12}n^2 + \sigma_{13}n^3 = 0 \\ b=2 \quad \rightarrow \quad \sigma_{21}n^1 + \sigma_{22}n^2 + \sigma_{23}n^3 = 0 \\ b=3 \quad \rightarrow \quad \sigma_{31}n^1 + \sigma_{32}n^2 + \sigma_{33}n^3 = 0 \end{cases} \tag{37}$$

On the basis of (21) we state that in the variants b = 1 and b = 2, the equations are met identically, in the case of b = 3 we get

$$\sigma_{31}n^1 + \sigma_{32}n^2 = G\omega\left(-x_2 n^1 + x_1 n^2\right) = -G\omega\left(x_2\frac{dx_2}{ds} + x_1\frac{dx_1}{ds}\right) = 0. \tag{38}$$

Equation (38) is equivalent to a condition

$$x_1\,dx_1 + x_2\,dx_2 = 0. \tag{39}$$

Assuming that (39) is a complete differential equation, we find a solution by integration

$$\phi(x_1,x_2)=\int_{x_{10}}^{x_1} x_1\,dx_1+\int_{x_{10}}^{x_1} x_1\,dx_1=(x_1)^2+(x_2)^2-\left[(x_{10})^2+(x_{20})^2\right]=(x_1)^2+(x_2)^2-\rho^2\,, \quad (40)$$

geometric expression of solutions is a family of circles.

Quod erat demonstrandum.

8. Assumptions of the Saint-Venant theory

The development of Navier's tests is introduced by Saint-Venant, the function of warping/deplanation of the cross-section of the rod in pure torsion. Therefore the assumption VI) is changed and now it reads as follows –

VI') projections of the points of the warped surface onto the cross-section, behave like infinitely rigid discs. We mark the function of warping by

$$\vartheta=\vartheta(x_1,x_2). \quad (41)$$

Consequently, in the case of the validity of formulas (3.1), (15), the component of the displacement vector is now zero and, as proposed by Saint-Venant, is expressed in the form

$$u_3=u_3(x_1,x_2,x_3)=\omega\,\vartheta(x_1,x_2). \quad (42)$$

With the assumptions made (41), (42), now it is necessary to repeat the course of proceedings conducted in the Coulomb theory variant. We receive accordingly relationships:

3'. Strains

$$\varepsilon_{ij}=\frac{\omega}{2}\begin{bmatrix} 0 & 0 & -x_2+\vartheta_{,1} \\ 0 & 0 & x_1+\vartheta_{,2} \\ -x_2+\vartheta_{,1} & x_1+\vartheta_{,2} & 0 \end{bmatrix}. \quad (43)$$

4'. Stresses

$$\sigma_{13}=G\omega\left(-x_2+\vartheta_{,1}\right) \text{ and } \sigma_{23}=G\omega\left(x_1+\vartheta_{,2}\right). \quad (44)$$

5'. Equilibrium equations

$$\mathfrak{M}=G\omega\int_A\left[(x_1)^2+(x_2)^2+\vartheta_{,2}\,x_1-\vartheta_{,1}\,x_2\right]\,dA=G\omega\,J_s\,, \quad (45)$$

where from we get

$$\omega=\frac{\mathfrak{M}}{G\,J_s}. \quad (46)$$

where

$$J_s = J_o + J_\Delta = \int_A \left[(x_1)^2 + (x_2)^2 + \vartheta,_2 x_1 - \vartheta,_1 x_2 \right] dA \quad . \tag{47}$$

The deplanation function introduced must meet the equilibrium conditions on the unloaded side of the rod and, as we will show, it is a harmonic function.

The equilibrium condition on the unloaded side of the bar (38) at $b = 3$ is now given as

$$\sigma_{31} n^1 + \sigma_{32} n^2 = G\omega\left[\left(-x_2 + \vartheta,_1\right) n^1 + \left(x_1 + \vartheta,_2\right) n^2 \right] = 0 \, . \tag{48}$$

Using (34), (35), the above (48) can be expressed as

$$\vartheta,_1 n^1 + \vartheta,_2 n^2 = x_2 \frac{dx_2}{ds} + x_1 \frac{dx_1}{ds} \, . \tag{49}$$

We find that (49) expresses a normal derivative –

$$\frac{\partial \vartheta}{\partial n} = x_2 \frac{dx_2}{ds} + x_1 \frac{dx_1}{ds} \, . \tag{50}$$

When using the gradient vector definition

$$\vec{\nabla} = \nabla_m \vec{g}^m \xrightarrow{Cart.} \frac{\partial}{\partial x_m} \vec{i}^m \, , \tag{51}$$

and assuming VIII), we write the Lamé equation, i.e. the conditions of intrinsic balance in displacements

$$\nabla^2 \vec{u} + \frac{\mu + \lambda}{\mu} \vec{\nabla}\left(\vec{\nabla} \cdot \vec{u}\right) = grad \left(grad + \frac{\mu + \lambda}{\mu} div \right) \vec{u} = 0 \, , \tag{52}$$

which in the index notation in the Cartesian coordinates have the form

$$u_i,^j{}_j + \frac{\mu + \lambda}{\mu} u_j,^j{}_i = 0 \, . \tag{52.1}$$

On the basis of the relation (15), (42), we obtain the components of the displacement vector

$$div\, \vec{u} = \vec{\nabla} \cdot \vec{u} = u_j,^j = u_1,^1 + u_2,^2 + u_3,^3 = \varepsilon_1{}^1 + \varepsilon_2{}^2 + \varepsilon_3{}^3 = J_1 = 0 \tag{53}$$

and hence the equations (52) take the form

$$\begin{cases} i = 1 & \rightarrow \quad u_1,_1{}^1 + u_1,_2{}^2 + u_1,_3{}^3 \equiv 0 \\ i = 2 & \rightarrow \quad u_2,_1{}^1 + u_2,_2{}^2 + u_2,_3{}^3 \equiv 0 \\ i = 3 & \rightarrow \quad u_3,_1{}^1 + u_3,_2{}^2 + u_3,_3{}^3 = u_3,_1{}^1 + u_3,_2{}^2 = \omega\left(\vartheta,_{11} + \vartheta,_{22}\right) = \nabla^2_{(1,2)} \vartheta = 0 \end{cases} \tag{54}$$

The function $\vartheta(x_1, x_2)$, fulfilling the condition $\nabla^2_{(1,2)} \vartheta = 0$, is called a harmonic.

The problem of determining the function of deplanation $\vartheta = \vartheta(x_1, x_2)$, which is harmonic in open area of the cross-section, and on the edge of this area the function ϑ fulfils the condition for a normal derivative (50) is a problem of the potential theory often referred to as the *second boundary problem of Neumann*.

The problem of beam bending with shearing in tensor notation was derived in the paper [10]. The review of the deformation measures – strain tensors – was carried out in [11].

Conclusions

Any, even a simple mechanical problem, can be consistently analysed by means of tensor notation. Nevertheless, the reader should be familiar with the fundamentals of the theory of elasticity in tensor calculus. This necessitates additional classes/lectures for students, or self-study in tensor calculus.

The problem of pure torsion was selected due to the clarity of the assumptions and a relatively small scope of the issue.

The problem discussed in the paper was presented during the Math-Bridge Camp, Muenster 2018. The discussion pointed out that for people not familiar with the tensor calculus, the problem is not clear. Majority of workshop attendees preferred the classic approach to the problem of torsion. Such conservatism is characteristic of academic teachers, while to students the *tabula rasa* principle applies, i.e. they learn tensor calculus without prejudice.

For over 15 years, in the 1970s and 1980s, the team of the Stereomechanics Department of Lublin University of Technology, headed by prof. Jerzy Grycz taught classes in the strength of materials as well as the theory of elasticity and plasticity in tensor calculus. The author was a member of this team, and the classic torsion problem posted was one of several issues developed by the author.

References

[1] Green A.E., Zerna W. *Theoretical elasticity*. Oxford, Clarendon Press, 1968, pp. 457.

[2] Dullemond K., Peeters K. *Introduction to tensor calculus*. 1991-2010. www.ita.uni-heidelberg.de /~dullemond/lectures/tensor/tensor.pdf; pp. 53.

[3] Gurtin M.E., Sternberg E. *Linear theory of elasticity*, In: Truesdell, C., Ed., Handbuch der Physik, Vol. VIa/2, Springer-Verlag, Berlin, pp. 296.

[4] Sokolnikoff I.S. *Mathematical theory of elasticity*. McGraw-Hill, 1956, pp. 476.

[5] Kaliski S. *Pewne problemy brzegowe dynamicznej teorii sprężystości i ciał niesprężystych; (Certain boundary problems of the dynamic theory of elasticity and inelastic bodies).* Warszawa, WAT, 1957. pp. 305.

[6] Kurrer K-E. *The history of the theory of structures: from arch analysis to computational mechanics*, Ernst & Sohn Verlag, 2008, DOI: https://doi.org/10.1017/S000192400008756X; pp 848; [04.07.2019]

[7] Fung Y.C. *Foundation of solid mechanics*, Prentice-Hall, 1965, pp. 525.

[8] Govindaraju L., Sitharam T.G., *Applied elasticity for engineers*, I K International Publishing House Pvt. Ltd, New Delhi, 2016, pp. 256; https://www.bookdepository.com/Elasticity-for-Engineers-T-G-Sitharam/9789385909344 ; [20.05.2019].

[9] Mase G.T., Smelser R., Mase G.E., *Continuum mechanics for engineers,* 3rd Edit., CRC Press, Taylor & Francis Group, 2009, p. 370. https://www.academia.edu/15548859/Continuum_Mechanics_for_Engineers_ Mase_3rd_Edition?auto =download ; [28.05.2019].
[10] Romano G., Barretta A., Barretta R. *On torsion and shear of Saint-Venant beams*, European Journal of Mechanics A/Solids 35, 2012, pp. 47-60.
[11] Raniecki B., Nguyen H.V., *Mechanics of isotropic elastic-plastic flow in pressure-sensitive damaging bodies under finite strains*, ZAMM, DOI: 10.1002/zamm.200900398, Vol.90, No.9, 2010, pp. 682-700.

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Physical modeling of a fire with the use of the Froude number

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Abstract: Ever since the field of Fire Safety Engineering first came into existence, small-scale (model scale) fire tests were the source of much valuable information about the phenomena occurring during combustion. Over the years, several computational methods to determine the criteria for the similarity of fires on both a real and small geometric scale have been developed. The purpose of this article is to present a method of performing fire tests on a model scale using the Froude number. The basics of scaling, similarity conditions that must be preserved, ways of describing fire phenomena, as well as methods of calculating fire parameters from the real and model scale have been discussed. An example of physical tests with the use of reduced research models is also presented. What is particularly emphasized is how important these types of experiments are and what responsibility rests with the people who carry them ouvol. The motivation to conduct research is the safety of people who reside in buildings with fire protection based on model scale test.

Keywords: Physical modeling, Froude Number, fire tests.

1. Introduction

Fire is an uncontrolled phenomenon during which large amounts of heat are emitted, together with the production of toxic combustion products. Although this phenomenon has been the subject of research for many years, the scientists dealing with this issue are yet to fully comprehend the complexity of the combustion process. The continuous development of new materials used in everyday life, as well as other ways to use those already known further deepen this gap.

The constant need to update data requires the development of new fire experiments as well as the re-execution of those already carried ouvol. This approach also allows the validation of results already obtained using more accurate research methods [1], [2]. Undoubtedly, the best way to determine the course of combustion and the flow of smoke in a particular building would be to build it and then burn it completely - although even this does not guarantee success due to the lack of control over the ambient conditions (wind, temperature, humidity). Interestingly, real-scale (1: 1) fire experiments were and are still being carried out [3], [4]. Currently, however, fire tests on a 1: 1 scale are more often carried out for a specific element of interior design or furnishings, such as a desk, sofa or chairs [5]. The results obtained from individual experiments may bring us closer to real fires, but they do not provide a complete solution. Knowledge of the physical aspects of smoke flow (mass and heat) can be extremely helpful in determining the conditions in a building, for example during evacuation. The execution of this type tests for objects with a unique distribution and accessories is virtually impossible. Therefore, model scale research is used for such purposes. They allow to perform many variants of a given test with a few repetitions at a lower expenditure of time and financial resources [6]. Model scale studies do not have to be limited to one small model. Known cases of building a group of a dozen or so houses (on a scale of 1: 3) to assess whether the fire will actually spread between buildings, as the theory assumes [7], appear in the literature on the subjects.

Other studies involved building a train model on a 1: 2 scale. The effects of interior finish, number of windows or location of the stimulus initiating combustion were checked. Another method of approximating the conditions that may occur during a real fire are computer simulations [8], [9]. Nowadays, thanks to the almost unlimited access to significant computing power, the popularity of computational fluid dynamics (CFD) calculations is increasing. It is extremely important that these applications correspond to reality. Model scale fire tests are also performed to validate and verify these types of programs.

But how to relate the results obtained from the model scale test to reality? After years of research by scientists in the field of Fire Safety Engineering (IBP), methods of scaling and converting results from the model scale to the real scale have been developed [10]. This article focuses on approximating the methodology of scaling a physical fire modeling using the Froude number.

2. Basics of scaling

The complexity of the phenomenon of fire is still not fully understood. Currently, many analytical and computer methods for determining the combustion process are known. Still, full-scale physical tests are still the best and most reliable source of information. It is thanks to such research that new ones can be created, and the mathematical combustion equations used in popular computer models can be validated and verified [11], [12]. Despite the unquestionable advantages, conducting such an experiment requires a huge amount of time and money. Therefore, since the 1960s, in the field of Fire Safety Engineering in Poland and in the world, the methodology of testing on a model scale has been developing.

Conducting tests on a smaller scale is characterized by lower expenditure both in time and finances in relation to the real scale (1: 1). In that, it is possible to check how a given phenomenon would take place in an existing building object unavailable for such purposes. With the right amount of free space, materials and knowledge about the theory of scaling, a model of any building (e.g. warehouse, shopping mall), structure (e.g. road / railway tunnel) or any other space (e.g. forest) can be created and experiments can be conducted. With current tests comparing the results of tests on a scale model with the actual scale [13] all subsequent tests may be conducted with greater accuracy and in an easier way. However, to make this possible, an appropriate method of converting the analyzed parameters should be used. In the scaling technique using dimensionless similarity numbers, the starting point is Buckingham's Theorem [14] also known as "Pi theorem" (Π theorem).

The Buckingham Theorem

"Each function of n dimensional parameters $\mathbf{a_i}$, of which **k** has basic dimensions, can be represented as a function of **n-k** dimensionless parameters of type Π. If the dimensionless parameters Π are identical, the phenomenon will occur identically despite the differing parameters of type $\mathbf{a_i}$."

The above theorem (Theorem Π) is based on the principle of dimensional unity. It states that if indeed the equation expresses the proper relationship between variables in physics, this process will be uniform in dimension. Each of its parameters will have the same dimensions [15]. Thus, a dimensionally homogeneous equation containing **n** mathematically variables:

$$Z = f\left(Z_1, Z_2 \ldots Z_n\right) \tag{1}$$

can be written in dimensionless form:

$$\Pi = \Phi\left(\Pi_1, \Pi_2 \ldots \Pi_{n-k}\right) \tag{2}$$

Formula (2) is very important for research conducted on a model scale. Since its derivation, it has ceased to be necessary to always study the functions of variables. It is enough that they are identified, which is a great help for scientists dealing with this topic. In addition, it is worth emphasizing that a change in the value of the Π argument can be introduced by transforming even one of its arguments. With this, conducting experimental research is much easier.

3. Characteristic numbers – the Froude number

3.1. Conditions of similitude

We consider two phenomena to be similar if the value of the measured parameter on the real scale is proportional to the value of the parameter on the model scale. Such phenomena will be similar if the similitude of:

- geometric dimensions,
- physical properties,
- boundary conditions, and
- initial conditions

is maintained.

The purpose of physical tests is to obtain reliable results that can be used to determine the possible conditions occurring in a given facility during a fire. However, in order for the conclusions resulting from the experiments to be put into practice, the theory of similitude should be used. Based on the review of the available literature on the subject, three types of similitude have been identified [16].

Geometric similitude – consisting in maintaining similarity of dimensions and shapes in the model and real objects. When the linear dimensions of the original and the model are proportional to each other, then the original and the model are considered to be geometrically similar.

Kinematic similitude – consisting in maintaining speed fields between the model and the real objects. It occurs when the current line profile in the model and real flow are proportional to each other.

Dynamic similitude – consisting in maintaining one of two criteria:

- dimensional analysis resulting from the Buckingham theorem. It is necessary to know the physical quantities necessary to completely describe the phenomenon;
- analysis of equations defining a given phenomenon (without solving them) in model and real flow.

The use of any of the types of similarity mentioned above allows to obtain dimensionless similarity numbers (criterion numbers).

3.2. Modeling the described phenomenon using dimensionless functions

Table 1 lists the variables that most often appear in dimensionless analysis related to the IBP domain.

Table 1. Dimensional relationships occurring in fire test. Source: Own study based on [15].

Relationship	Name of relationship	Interpretation	Application
$\frac{\rho Vl}{\mu}$	Reynolds number (Re)	$\frac{\text{inertia forces}}{\text{viscous forces}}$	issues of fluid mechanics
$\frac{V}{\sqrt{gl}}$	Froude number (Fr)	$\frac{\text{inertia forces}}{\text{gravity forces}}$	free space flow
$\frac{\Delta pl}{\rho V^2}$	Euler number (Eu)	$\frac{\text{pressure}}{\text{inertia forces}}$	issues of pressure differences
$\frac{gl^3\beta\Delta T}{v^2}$	Grashof number (Gr)	$\frac{\text{buoyancy forces}}{\text{viscous forces}}$	issues of fluid mechanics

This article examines fire modeling methodology using the Froude number. This relationship is named after William Froude, a British civil engineer, architect and mathematician living in the 19th century. He became famous for his pioneering approach to ship design using a model scale.

The Froude number is the ratio of forces caused by the acceleration of a flowing particle (inertia force) to the force of gravity. This equation is of great importance when considering free flows. Mathematically, this can be written using the formula (3):

$$Fr = \frac{V}{\sqrt{gl}} \tag{3}$$

The magnitude of the inertia force component (F1) along the current line can be expressed as:

$$F_1 = a_s m \tag{4}$$

where: a_s is the amount of acceleration along the flow line for a particle with mass m.

It is known from the particle motion studies that the particle lifting path is curved. The phenomenon of particle movement in the convection column is shown in Fig. 1.

The movement shown in Fig. 1 can be written as:

$$a_s \frac{dV_s}{dt} = V_s \frac{dV_s}{d_s} \tag{5}$$

where: s is measured along the lift path in the convection currents.

By writing the speed V and length s as dimensionless numbers:

$$V \cdot s = \frac{Vs}{V} \cdot s = \frac{s}{l} \tag{6}$$

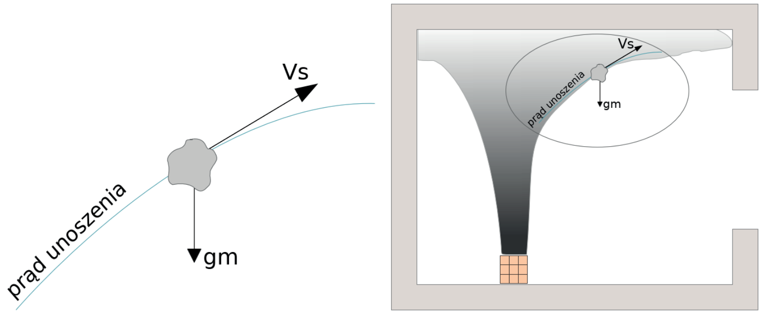

Fig. 1. Impact of gravity on the path of a moving particle. Source: Own study based on [14]

In equation (6) V and l represent, respectively, the characteristic speed and dimension (e.g. length), therefore:

$$a_s = \frac{V^2}{l} V \cdot s \frac{dV \cdot s}{d_s} \tag{7}$$

$$F_1 = \frac{V^2}{l} V \cdot s \frac{dV \cdot s}{d_s} m \tag{8}$$

The particle weight F_G (F_G = gm), so the ratio of inertia to gravity is such that the ratio of force F_1/F_G is proportional to V^2/gl, and the square root of this expression ($V / \sqrt{gl}$) is called the Froude number.

$$Fr = \frac{F_1}{F_G} = \frac{V^2}{gl} = \frac{V}{\sqrt{gl}} \tag{9}$$

3.3. Physical modeling

Equations of flow phenomena (e.g. water, smoke) are currently most often solved using computer programs designed to solve the equations of numerical fluid mechanics. However, there has always been a need to develop a method for mapping real-scale test. Model scale research is the simplest and most accurate. In the 1960s, Thomas [17] performed physical experiments using hot air. The 1970s abounded in model research, which was carried out using a mixture of kerosene and water [18]. In the 1980s, models filled with fresh water were used for this purpose [19]. Salt water with a higher density and the addition of dark pigment was used to represent the flow of smoke. These simple techniques allowed mapping of small-scale fire tests performed in full-size geometries, as well as verification of mathematical models known at that time. Currently, deterministic CFD simulations or stochastic calculations based on multi-simulations are used to predict smoke flow in rooms [9], [20]. A comparison of the older method using the water-filled model and the newer method of solving computer-based fluid mechanics equations is shown in Figure 2.

a) b)

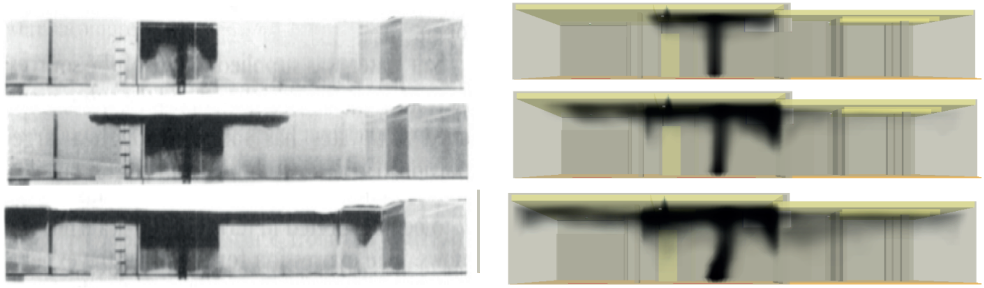

Fig. 2. Simulation of smoke spreading in a building - comparison of methods, a) analog simulation with salt water (inverted image), b) CFD computer simulation, Source: Own study based on [19]

The similarity criterion to fulfill and the corresponding scales can be obtained from equations describing a given phenomenon. Tests carried out on a suitably reduced model should be performed while maintaining the geometric similarity of the model in relation to the real object. It is also important to keep the other selected criteria of similarity of physical phenomena. The above idea is presented in Fig. 3.

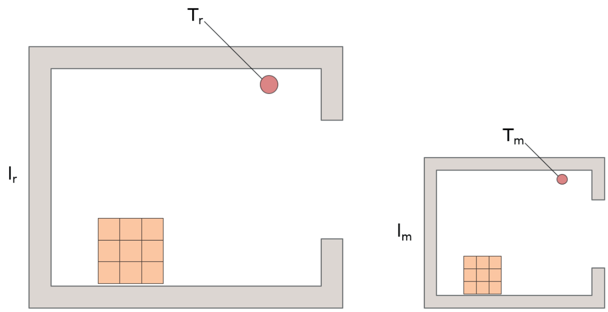

Fig. 3. Similarity of real and model scale. Source: Own study.

Fig. 3 shows two geometrically similar room. One on the real scale (left) with height l_r and the other on the model scale (right) with height l_m. To maintain the similarity, the dimensions of all rooms and objects in the analyzed space must be changed. One should not forget about keeping proportional distances between e.g. measuring devices (T_r i T_m). For phenomena that occur during a fire, the basis for physical modeling is to maintain the Froude number.

The buoyancy force resulting from the difference in fluid density can be mapped in several way. They are presented in Table 2. The buoyancy force arising during a fire and the work of fire ventilation are so dominant that the phenomenon of friction has a limited effect on the flow of smoke. Therefore, maintaining the Reynolds number (Table 2) is not required as long as Re > 10,000. This is a significant simplification of the research method, since the simultaneous maintenance of both Froude number and Reynolds number is extremely difficult and would require scaling kinematic viscosity of the fluid (e.g. smoke) and roughness of building partitions [14]. To be able to conduct research on a model scale, the criterion of similarity of the Froude number should be kept:

$$Fr_m = Fr_r \tag{9}$$

With the equations described in Table. 1 it is known that the Froude number describes the ratio of inertial force to the force of gravity. With its practical application, the mapping of the buoyant force can be implemented in several way. The first and easiest method is to generate heat in a certain amounts. It is important then to accurately calculate the rate of heat release using the formula (10). Other methods are implemented by using helium with air of a certain and known density [21], [22], or mixtures of water with varying degrees of salinity [19], [23]. Other values important for flow modeling in fire tests are additionally described by the equations presented in Table 2.

Table 2. Relationships between model and real scale values. Source: Own study based on [14]

Parameter	Unit	Scale ratio	Number of equation
Heat release rate	[kW]	$\frac{Q_m}{Q_r} = \left(\frac{X_m}{X_r}\right)^{5/2}$	(10)
Air flow rate	[m/s]	$\frac{V_m}{V_r} = \left(\frac{X_m}{X_r}\right)^{1/2}$	(11)
Time	[s]	$\frac{t_m}{t_r} = \left(\frac{X_m}{X_r}\right)^{3}$	(12)
Energy	[kJ]	$\frac{E_m}{E_r} = \left(\frac{X_m}{X_r}\right)^{3}$	(13)
Mass change	[kg]	$\frac{\dot{m}_m}{\dot{m}_r} = \left(\frac{X_m}{X_r}\right)^{3}$	(14)
Temperature	[K]	$Tm = Tr$	(15)

The formulas (10–15) presented in Table 2 describe the relationships between values on the model scale and the real scale. The X_r parameter describes the real scale, and X_m describes the model scale. For calculations from the 1: 1 scale to the 1: 2 scale, it will be $X_r = 1$ and $X_m = 2$, respectively. Parameters and formulas have been widely described and used in the work presented by Quintiere [14]. The equations collected in Tab. 2 are just some of the functions describing the scaling process. However, they are sufficient to carry out the tests underlying the fire tests on a model scale. More information on the dependencies used can be found in the works of Thomas, Quintiere and Morgan 'a [10], [24], [25].

3.4. Application of the Froude number

Modeling fires using Froude similitude is one of the most popular techniques for modeling fire phenomena. The roots of the method date back to the 1960s [26]. It was further developed in the following years. Practical significance is found wherever it is important to determine the relationships describing the flow of smoke in space [25], through openings [18], as well as to optimize fire ventilation systems [27]. In many cases, no research can be done without using the model scale. This is the case, for example, in experiments on road or rail tunnels [28] [29].

The basic issue before conducting experiments is the selection of the appropriate scale of the model for the studied phenomenon. This coefficient cannot be large enough so that the construction costs, time and complexity of the model approach those that occur at full scale. Generating large amounts of heat, which is a significant threat, may be an additional problem. On the other hand, the scale used may not be too small (e.g. 1: 100), because it is important to maintain the correlation between the real and the model phenomenon. In addition, the use of too small a model scale can create difficulties in finding the right measuring equipment. Table 3 presents a list of scales that were used in several experiments. The list contained in Table 3 presents only examples of quantities. It does not include all scales at which fire phenomena are tested.

Table 3. Examples of scale sizes used in fire test. Source: Own study

No.	Scale size	Type of object	Number of tests	Source
1	1:1	road tunnel	5	[4]
2	1:2	railway wagon	10	[30]
3	1:3	single-family housing estate	2	[7]
4	1:7	room	3	[31]
5	1:8	basement	1	[32]
6	1:10	shopping mall	48	[6]
7	1:15	road tunnel	28	[33]
8	1:20	road tunnel	54	[34]
9	1:23	road tunnel	12	[35]
10	1:48	railway tunnel	1	[29]

Based on the analysis of the data presented in Table 3, one universal scale that could be adopted in the study cannot be determined. Often the same phenomenon is reproduced on several different scales. Each time the team conducting the experiment should assess on their own whether the scale used is appropriate for describing a given phenomenon. The choice of this or that scale also depends on the possibilities of using the measuring equipment owned or available space.

Choosing the right scale to conduct experiments is a very difficult task in itself. An additional obstacle deepening this problem may be the selection of appropriate measuring equipment. When choosing the right measuring instruments for model scale testing, there are two key issues to consider. In addition to the obvious justification for the use of a given instrumentation (the possibility of measuring the analyzed parameters), the size of this device should also be taken into account. For a full-scale test room (1:1 scale), the introduction of e.g. one or several thermocouples with a diameter of 1.5 mm will not affect the flow in the test space. However, if the same number of identical thermocouples is entered into the test-room model on a scale of 1: 100, it can have a real impact on the final results of the experiments.

An even bigger problem is the use of flow measurement tools – Prandtl tubes, thermo anemometers or bidirectional airflow probes. Due to their size and inaccurate measurements at threshold response values, the research capabilities on the model scale are decreasing. Laser imaging methods can solve these types of problems. These are relatively new methods that allow the simultaneous measurement of temperature (Digital Particle Image Thermometry, DPIT) and flow velocity (Digital Particle Image Velocimetry, DPIV) of particles in the analyzed space [36]. White light-illuminated particles have the ability to selectively disperse different colors depending on the ambient temperature. Recording this phenomenon using a suitable camera allows to determine the temperature of flowing particles. By comparing the displacement of individual particles on two frames / photos with a known time interval, their movement speed can be determined. In addition to accurate measurements, the advantage of these methods is the lack of need to place relatively large measuring devices in small test space. Thanks to this, the phenomena accompanying fire experiments are not disturbed.

4. Summary

Performing fire tests on a model scale is undoubtedly a huge source of information. It is often the only feasible way for an in-depth study and analysis of many physical phenomena. The results of many studies in recent years have lead to a better understand of the uncontrolled phenomenon of fire. The collected data is used to develop and continually improve CFD computer programs. Knowledge based on the experience drawn from the performed experiments allows to estimate the possible course of events in the event of a fire, and as a consequence – develop projects for more effective fire protection. That is why it is so important that the results obtained from the model scale correspond to the reality in which we - residents and users of secured buildings can find ourselves.

References

[1] Drysdale D., *Fire safety by design: a framework for the future*. Fire Safety Journal vol. 23, no 2, p. 113, 1994.

[2] Wegrzynski W., Sulik P., *The philosophy of fire safety engineering in the shaping of civil engineering development*. Bulletin of the Polish Academy of Sciences: Technical Sciences, vol. 64, no 4, p. 719–730, 2016.

[3] Cooper L.Y., Harkleroad M., Quintiere J., Rinkinen W. *An experimental study of upper hot layer stratification in full-scale multiroom fire scenarios*. Journal of Heat Transfer, vol. 104, no 4, p. 741, 2009.

[4] Li Y.Z., Ingason H., Lönnermark A. *Runehamar Tunnel Fire Tests.* Boras, 2011.

[5] Mehta S. *Upholstered furniture fill scale chair tests – open flame ignition results and analysis*. 2012.

[6] Węgrzyński W. *Partitions and the flow of smoke in large volume buildings*, Architecture, Civil Engineering, Environment, vol. 11, no 1, p. 155–164, 2019.

[7] Himoto K., Shinohara M., Sekizawa A., Takanashi K., Saiki H. *A field experiment on fire spread within a group of model houses*. Fire Safety Journal, vol. 96, no May 2017, p. 105–114, 2018.

[8] Krauze A., Fliszkiewicz M., Maciak T. *Możliwości stosowania programów komputerowych w inżynierii bezpieczeństwa pożarowego.* Bezpieczeństwo i Technika Pożarnicza, vol. 29, ed. 1, p. 47–60, 2013.

[9] Krasuski A., Pecio M. *Application of an integrated risk assessment software to quantify the life safety risk in building during a fire*. MATEC Web of Conferences, vol. 247, ed. 1, p. 11, 2018.

[10] Quintiere J.G. *Scaling applications in fire research*. Fire Safety Journal, vol. 15, ed. 1, p. 3–29, 1989.

[11] Vigne G., Węgrzyński W. *Influence of variability of soot yield parameter in assessing the safe evacuation conditions in advanced modeling analysis. results of physical and numerical modeling comparison*, [w:] 11th Conference on Performance-Based Codes and Fire Safety Design Methods, 2016, ed. May, p. 14.

[12] Vigne G., Gutierrez-Montes C., Cantizano A., Węgrzyński W., Rein G. *Review and validation of the current smoke plume entrainment models for large-volume buildings*. Fire Technology, vol. 55, ed. 3, p. 789–816, 2019.

[13] Wang X.Y., Spearpoint M.J., Fleischmann C.M. *Comparison of results from large-scale and small-scale tunnel experiments*. Fire Safety Journal, vol. 95, ed. August 2017, p. 135–144, 2018.
[14] Quintiere J.G. *Fundamentals of fire phenomena*. 2006.
[15] Zohuri B. *Dimensional analysis and self-similarity methods for engineers and scientists.* Springer US, 2015.
[16] Jezowiecka-Kabsch K., Szewczyk H. *Fluid mechanics*. Wrocław: Wrocław University of Technology Publishing House, 2001.
[17] Thomas P.H. *Modelling of compartment fires*, Fire Safety Journal, vol. 5, ed. 3–4, p. 181–190, 1983.
[18] Prahl J., Emmons H.W. *Fire induced flow through an opening*, Combustion and Flame, vol. 25, ed. C, p. 369–385, 1975.
[19] Steckler K.D., Baum H.R., Quintiere J.G. *Salt water modeling of fire induced flows in a multiroom enclosure.* Chemical and Physical Processes in Combustion, Fall Technical Meeting, The Eastern States Section, p. 143–149, 1985.
[20] Krasuski A., Krenski K. *A-Evac: the evacuation simulator for stochastic environment*. Fire Technology, 2019.
[21] Zhao G., Wang L. *Using helium smoke as a surrogate of fire smoke for the study of atrium smoke filling*. Journal of Fire Sciences, vol. 32, ed. 5, p. 431–447, 2014.
[22] Shanley J., i Beyler C. *Horizontal vent flow modeling with helium and air.* Fire Safety Science, vol. 2, p. 305–313, 1989.
[23] Yao X., Marshall A.W. *Quantitative salt-water modeling of fire-induced flow*. Fire Safety Journal, vol. 41, ed. 7, p. 497–508, 2006.
[24] Thomas P.H., *Modelling of compartment fires*. Fire Safety Journal, vol. 5, ed. 3–4, p. 181–190, 1983.
[25] Morgan H.P., De Smedt J.-C., *Hot smoke tests: testing the design performance of smoke and heat ventilation systems and of impulse ventilation*. International Journal on Engineering Performance-Based Fire Codes, vol. 6, ed. 1, p. 7–18, 2004.
[26] Thomas P.H., Hinkley P.L., Theobald C.R., Simms D.L. *Investigations into the flow of hot gasses in roof venting*. ed. 7. BRE, 1963.
[27] Węgrzyński W., Konecki M. *Influence of the fire location and the size of a compartment on the heat and smoke flow out of the compartment*, [w:] AIP Conference Proceedings, 2018, vol. 1922, ed. January, p. 12.
[28] Li Y.Z., Lei B., Ingason H. *Study of critical velocity and backlayering length in longitudinally ventilated tunnel fires*. Fire Safety Journal, vol. 45, ed. 6–8, p. 361–370, 2010.
[29] Kim D.H., Park W.H. *Experiment by using reduced scale models for the fire safety of a rescue station in very long rail tunnel in Korea*. Tunnelling and Underground Space Technology, vol. 21, ed. 3–4, p. 303, 2006.
[30] Lönnermark A., Lindström J., Li Y.Z. *Model-scale metro car fire tests. Model-scale metro car fire tests of Sweden*. SP Technical Research Institute of Sweden, 2011.
[31] Quintiere J., Mccaffrey J., Kashiwagi T. *A scaling study of a corridor subject to a room fire.* Combustion Science and Technology, vol. 18, ed. 1–2, p. 1–19, 1978.
[32] Arini D., Pancawardani F., Santoso M.A., Sugiarto B., Nugroho Y.S. *Froude modelling of fire phenomena: observation of fire-induced smoke movement in basement structure for firefighting purpose*. Procedia Engineering, vol. 170, p. 182–188, 2017.
[33] Li Y.Z., Ingason H. *Model scale tunnel fire tests with automatic sprinkler*. Fire Safety Journal, vol. 61, p. 298–313, 2013.
[34] Li Y.Z., Lei B., Ingason H. *Scale modeling and numerical simulation of smoke control for rescue stations in long railway tunnels.* Journal of Fire Protection Engineering, vol. 22, ed. 2, p. 101–131, 2012.
[35] Ingason H., Li Y.Z. *Model scale tunnel fire tests with longitudinal ventilation*. Fire Safety Journal, vol. 45, ed. 6–8, p. 371–384, 2010.
[36] Dabiri D. *Digital particle image thermometry/velocimetry: A review*. Experiments in Fluids, vol. 46, ed. 2, p. 191–241, 2009.

An analysis of the resistance of an extended end-plate beam-to-beam connection subjected to tension in fire conditions

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Abstract: This paper presents an analysis of the fire resistance of a steel joint subjected to tension. The authors of this article used prescriptive rules and simple calculation models to present an impact of the value of the load on the fire resistance of the connection. Designers often evaluate the critical temperature and fire resistance time of steel elements. However, they neglect the evaluation of the above-mentioned values for steel connections. In this article a simple engineering method was used to calculate the fire resistance of the joint.

Keywords: beam-to-beam connection, fire resistance, steel joint, critical temperature.

1. Introduction

The fire design of bolted and welded joints is presented in [1–6]. The steel temperature in the joint is always lower than in the element due to the presence of the additional material [7]. The mechanical behaviour of steel joints at elevated temperatures is an important scientific problem, because beam-to-column and beam-to-beam connections are often used in steel structures. The results of the fire tests of these joints were presented in [8].

Malendowski et al. presented a new type of beam-to-column connection [9]. This joint is capable of absorbing both very large rotations and axial movements, due firstly to the thermal elongation and subsequently to the extreme weakening of the connected beam. Maślak and Litwin evaluated the reduction of the beam-to-column joint stiffness under fire conditions [10]. The stiffness of the joints decreases as the fire develops [11]. The problem with flexible joints in fire conditions was presented in [12, 13]. The ductility and the failure of the joint may be evaluated using the component method and a simplified mechanical model with extensional springs and rigid links [14]. A component-based element for end-plate connections in fire conditions was described in [15].

Connections may be subjected only to tension, e.g. an extended end-plate beam-to-beam connection used in the bottom chord of the truss. This type of connection is analysed in this article. The fire resistance of this joint is rarely evaluated by designers, even though it may be easily determined using the method described in Annex D of [2].

2. Problem formulation

The authors of this article used a simple method presented in Annex D of [2] to present the impact of the value of the load on the fire resistance of the extended end-plate beam-to-beam connection subjected to tension. The authors tried to answer the question of what the degree of utilisation of the unprotected bolted joint should be to fulfil the fire resistance criterion R15 for this connection. An unprotected construction needs more steel than a fire protected construction to fulfil the said fire resistance criterion. However, the use of unprotected structural elements and joints may provide for the reduction of the total costs of the construction, because fire protection materials are expensive.

During the analysis, the authors used prescriptive rules:

- a standard fire [16] was used to heat up the joint,
- the effects of actions were determined for time $t = 0$,
- indirect fire actions were not taken into consideration,
- the boundary conditions at the supports and ends of the member were assumed to remain unchanged throughout the time of fire exposure,
- different reduction factors were assumed for structural steel, bolts and welds (see Fig. 1),
- a uniform distribution of temperature was assumed,
- the *A/V* ratio of the joint was assumed as the maximum value of the *A/V* ratios of the connected steel members adjacent to the joint,
- the design value of the tension force in a fire situation was obtained from the value at normal temperature using the reduction factor $\eta_{fi} = 0.65$,
- the critical temperature of the joint was calculated using the iterative method, presented e.g. in [17, 18].
- equivalent T-stub flanges were used to model the joint and to evaluate the design resistance of the end-plate.

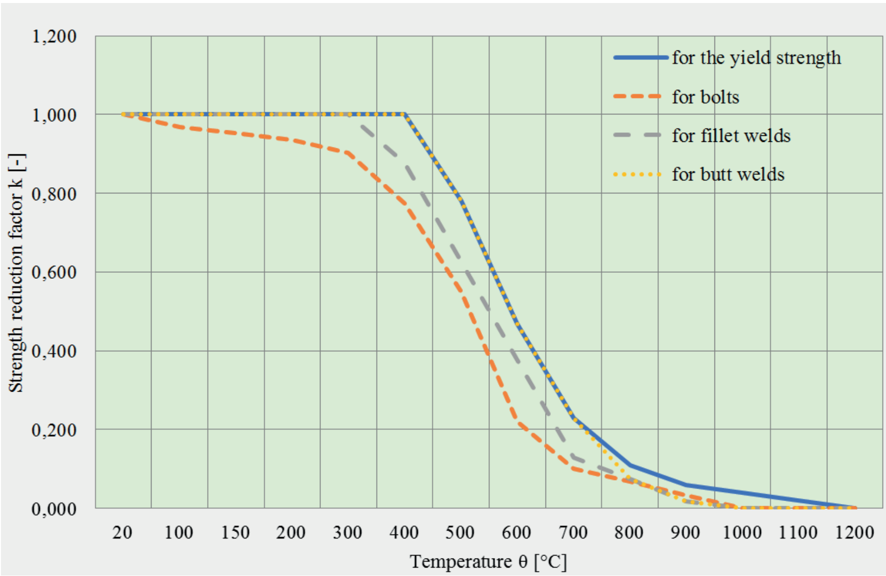

Fig. 1. Reduction factor for structural steel, bolts and welds

According to Maślak et al., the assumption that the temperature in a joint is uniformly distributed is safe [19]. What is more, the assumption that the temperature is calculated using the maximum value of the *A/V* ratios of the connected steel members adjacent to the joint is also conservative, and so is the assumption that the design value of the tension force in a fire situation is obtained from the value at normal temperature using the reduction factor $\eta_{fi} = 0.65$ [1].

In Figure 1 one can see that the strength of the bolt decreases faster than the strength of the steel in the extended end-plate. For this reason the mode of failure of a joint in a fire situation may be different than at normal temperature. For example, at normal temperature, the failure of a T-stub flange may consist of the bolt failure and the yielding of the flange, whereas in the fire situation it may consist of the bolt failure only.

3. Engineering example

In this paper the S355 bolted tension joint was analysed (see Fig. 2). Grade 8.8., M30 bolts were used. The design values of tension forces at normal temperature and in a fire situation are presented in Table 1. The value of the tension force was varied from 20 to 60% of the cross-section design resistance of the connected beam at normal temperature. The transfer of tensile force in the connection was achieved through the end-plate in bending components. The evaluation of the resistance of such components was based on a geometrical idealisation of tension zone (T-stub idealisation) [20, 21]. The formulas presented in [2, 21] were used to determine the resistance of the joint.

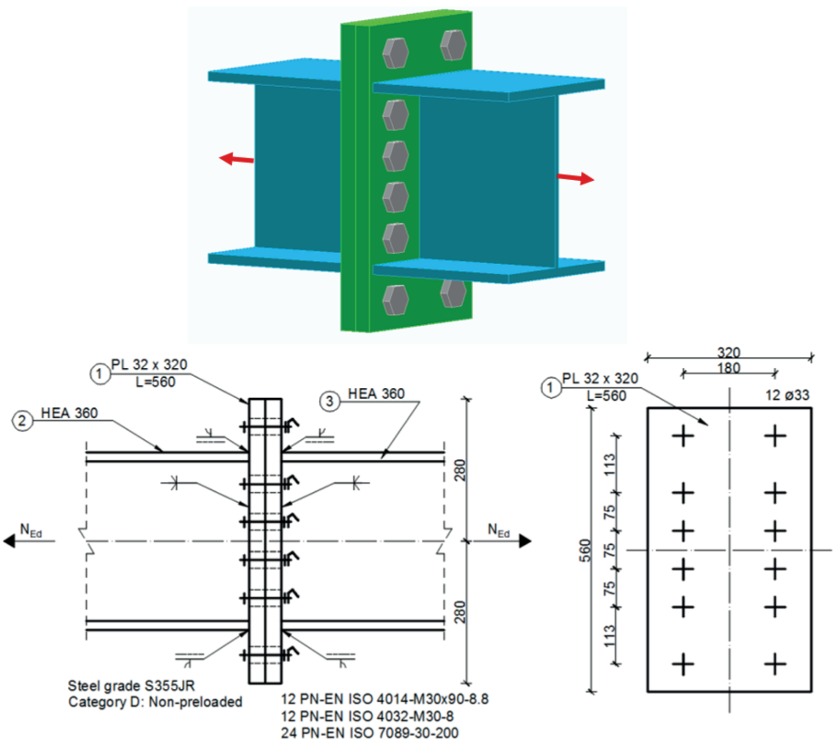

Fig. 2. Analysed joint

Table 1. Design values of the tension forces at normal temperature and in a fire situation

Design values of the tension forces	
At normal temperature	In a fire situation
N_{Ed} [kN]	$N_{fi,Ed}$ [kN]
3045.9 (0.6 $N_{c.Rd}^{*}$)	1979.8 (0.39 $N_{c.Rd}^{*}$)
2538.3 (0.5 $N_{c.Rd}^{*}$)	1675.2 (0.33 $N_{c.Rd}^{*}$)
2030.6 (0.4 $N_{c.Rd}^{*}$)	1319.9 (0.26 $N_{c.Rd}^{*}$)
1523.0 (0.3 $N_{c.Rd}^{*}$)	1015.3 (0.20 $N_{c.Rd}^{*}$)
1015.3 (0.2 $N_{c.Rd}^{*}$)	659.9 (0.13 $N_{c.Rd}^{*}$)

*Cross-section design resistance of HEA 360 at normal temperature

The resistance of the T-stub involving a group of bolt-rows was calculated along with the resistance of the individual T-stubs. The lowest of joint resistance value was chosen (3165.03 kN) (see Fig. 3).

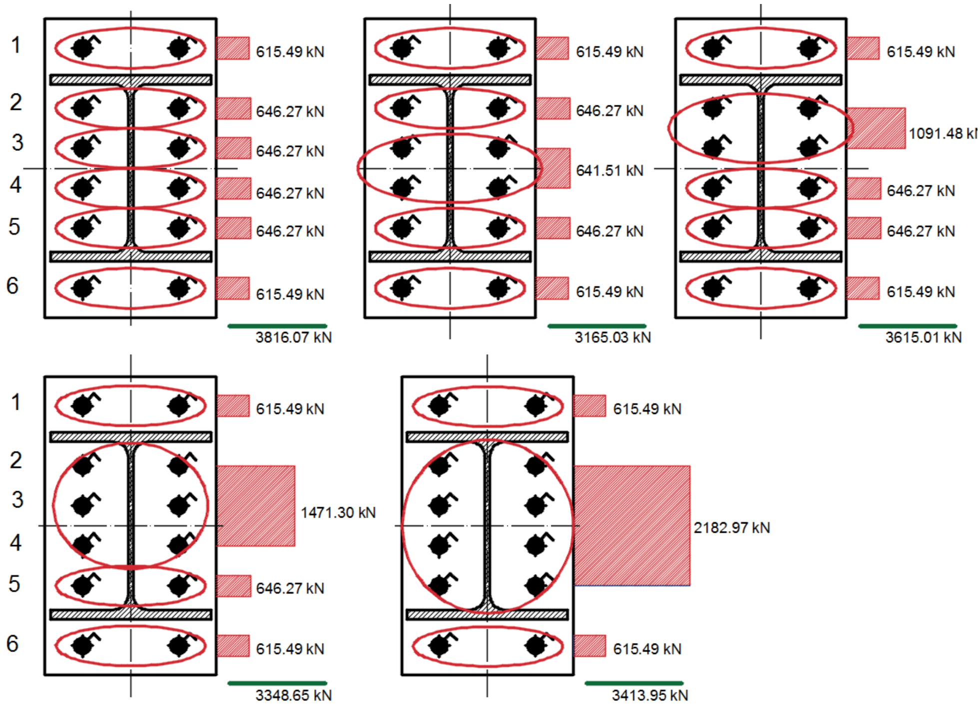

Fig. 3. Resistance of the joint at normal temperature

The A/V ratio of the joint was assumed as the A/V ratio for the tension member – HEA 360 (A/V = 128.3 1/m). The shadow effect was neglected (k_{sh} = 1.0). The critical temperature of the joint was calculated using the iterative procedure. The temperature was increased until the degree of utilisation of the joint reached about 1.0. The resistances of structural steel, bolts and welds decreased as temperature increased (see Fig. 1). For example, the resistance of the joint at 500 °C (2277.61 kN) is presented in Fig. 4.

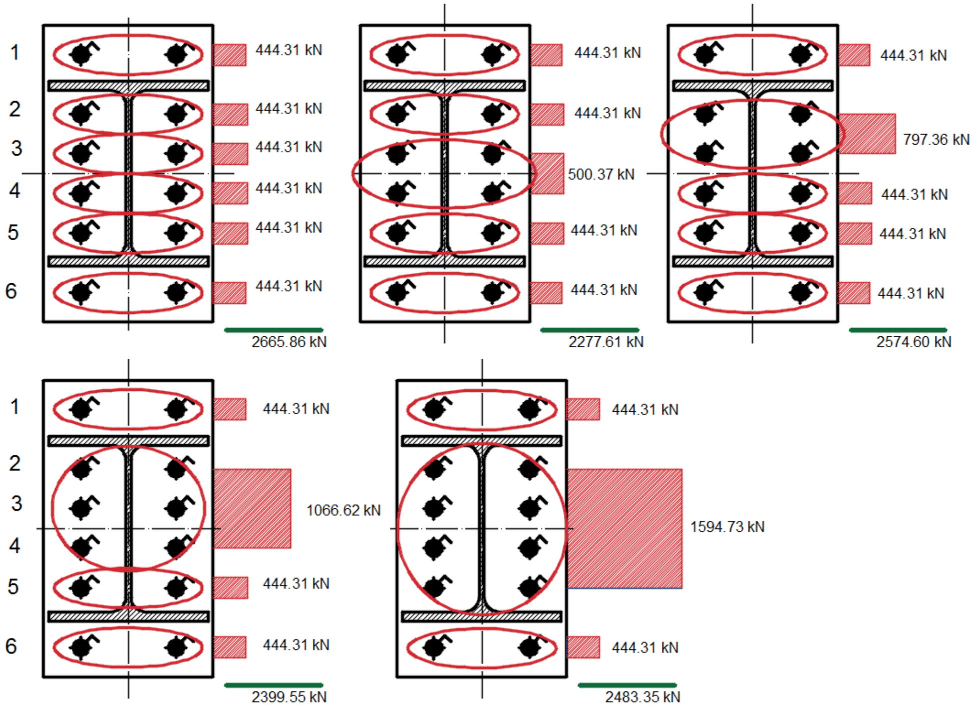

Fig. 4. Resistance of the joint at 500 °C

The critical temperatures of the joint depending on the tension force are presented in Fig. 5.

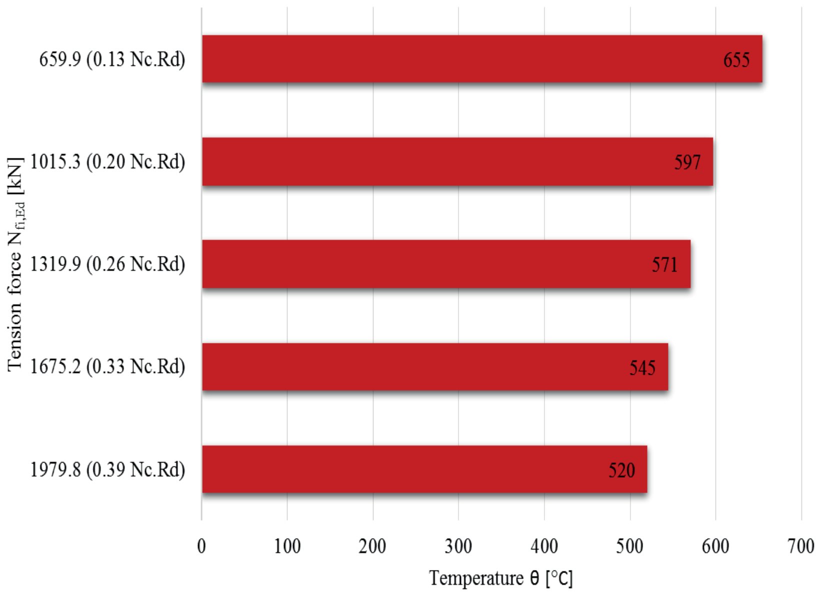

Fig. 5. The critical temperatures of the joint depending on the tension force

After the evaluation of the critical temperature of the joint, the fire resistance time was calculated (see Fig. 6). A standard fire was used to heat up the joint.

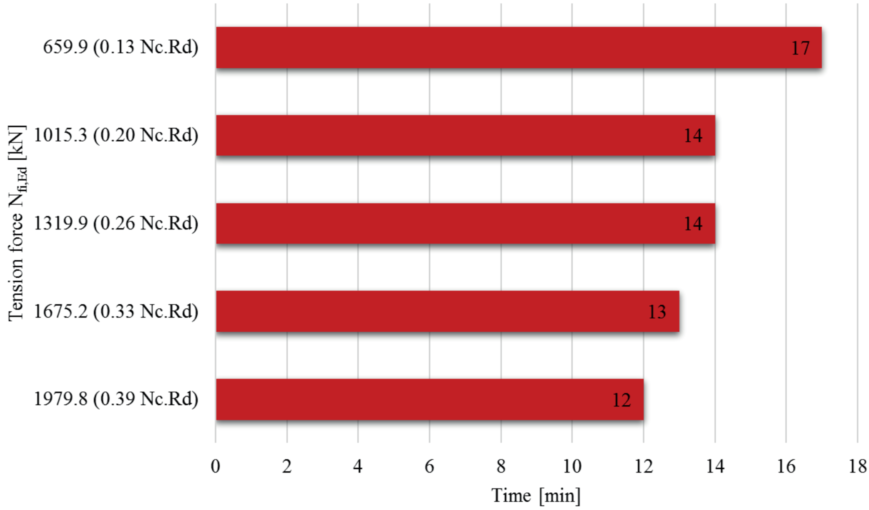

Fig. 6. Fire resistance time of the joint depending on the tension force

The results of the analysis are presented in Table 2. One can see that the value of the load had an impact of the fire resistance of a connection. The connection with the degree of utilisation of 0.96 had a fire resistance of 12 minutes, whereas the joint with the degree of utilisation of 0.32 had a fire resistance of 17 minutes. An unprotected bolted joint may fulfil the fire resistance criterion R15. However, the degree of utilisation of the joint at normal temperature should be low (0.32 in this paper).

Table 2. Results of the analysis

At normal temperature		Fire situation		
Tension force N_{Ed} [kN]	Degree of utilisation [-]	Tension force $N_{fi,Ed}$ [kN]	Critical temperature [°C]	Fire resistance time [min]
3045.9 (0.6 $N_{c.Rd}^*$)	0.96	1979.8 (0.39 $N_{c.Rd}^*$)	520.0	12
2538.3 (0.5 $N_{c.Rd}^*$)	0.80	1675.2 (0.33 $N_{c.Rd}^*$)	545.0	13
2030.6 (0.4 $N_{c.Rd}^*$)	0.64	1319.9 (0.26 $N_{c.Rd}^*$)	571.0	14
1523.0 (0.3 $N_{c.Rd}^*$)	0.48	1015.3 (0.20 $N_{c.Rd}^*$)	597.0	14
1015.3 (0.2 $N_{c.Rd}^*$)	0.32	659.9 (0.13 $N_{c.Rd}^*$)	655.0	17

*Cross-section design resistance of HEA 360 at normal temperature

4. Conclusions

The main conclusions of this paper are:

- The fire resistance of a joint subjected to tension is easy to determine using the method presented in Annex D of [2].

- The fire resistance of extended end-plate beam-to-beam connections subjected to tension strongly depends on the bolt strength, because the strength of the bolt decreases faster than the strength of the steel in the extended end-plate.
- The value of the load has an impact on the fire resistance of a connection.
- An unprotected bolted joint may fulfil the fire resistance criterion R15 when the degree of utilisation of the joint at normal temperature has a low value (e.g. 0.32 in this paper).

References

[1] Franssen J.M., Real P.V. *Fire design of steel structures. Eurocode 1: Actions on structures, Part 1-2: Actions on structures exposed to fire, Eurocode 3: Design of steel structures, Part 1-2: Structural fire design*. ECCS, 2010.

[2] European Committee for Standardization. *EN 1993-1-2 Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design*. Brussels, 2005.

[3] Maślak M. *Trwałość pożarowa stalowych konstrukcji prętowych*. Wydawnictwo Politechniki Krakowskiej, 2009 [in Polish].

[4] Gwóźdź M., Suchodoła M. *Bezpieczeństwo pożarowe budowlanych konstrukcji metalowych*. Wydawnictwo Politechniki Krakowskiej, 2016 [in Polish].

[5] Turkowski P., Sulik P. *Projektowanie konstrukcji stalowych z uwagi na warunki pożarowe według Eurokodu 3*, Warszawa, Instytut Techniki Budowlanej, 2015 [in Polish].

[6] Kurzawa Z., Polus Ł., Szumigała M. *Stany graniczne i odporność pożarowa elementów stalowych według Eurokodu 3*. Wydawnictwo Politechniki Poznańskiej, 2016 [in Polish].

[7] Franssen J. M., Brauwers L. *Numerical determination of 3D temperature fields in steel joints*. Second International Workshop: Structures in Fire, Christchurch, New Zealand, 2002.

[8] Wald F., Simoes da Silva L., Moore D., Santiago A. *Experimental behavior of steel joints under natural fire*. ECCS – AISC Workshop: Connections in Steel Structures, Amsterdam, The Netherlands, 2004.

[9] Malendowski M., Burgess I., Glema A. *Robustness in fire of a new type of beam-to-column connection*, [in:] ce/papers, Special Issue: Proceedings of Eurosteel 2017, Ernst & Sohn, Volume 1, Issue 2-3, pp. 550-559, 2017, doi: 10.1002/cepa.92.

[10] Maślak M., Litwin M. *Flexibility of beam-to-column steel joint under fire temperature*. Inżynieria i Budownictwo 66(8) (2010) 441–454 [in Polish].

[11] Maślak M., Pazdanowski M., Snela M. *Moment-rotation characteristics for flexible beam-to-column steel joint exposed to fire*. Journal of Civil Engineering and Architecture 9 (2015) 257–261, doi: 10.17265/1934-7359/2015.03.002.

[12] Maślak M., Pazdanowski M., Snela M., *Numerically-based quantification of internal forces generated in a steel frame structure with flexible joints when exposed to a fire*, [in:] *Advances in Mechanics: Theoretical. Computational and Interdisciplinary Issues – 3rd Polish Congress of Mechanics, PCM 2015 and 21st International Conference on Computer Methods in Mechanics*. (ed. Kleiber M. et al.). CRC Press, pp. 389-392, London 2016.

[13] Maślak M., Pazdanowski M., Snela M., *Redistribution of internal forces generated in a steel frame structure with flexible joints when exposed to a fire*, [in:] *Recent Progress in Steel and Composite Structures - Proceedings of the 13th International Conference on Metal Structures (ICMS2016, Zielona Góra, Poland, 15-17 June 2016).* (ed. Giżejowski M. et al.). CRC Press, pp. 315-322 London 2016.

[14] Simoes da Silva L., Santiago A., Real P.V. *Post-limit stiffness and ductility of end-plate beam-to-column steel joints*. Computers & Structures 80 (2002) 515–531, doi: 10.1016/S0045-7949(02)00014-7.

[15] Block F., Burgess I., Davison B., Plank R. *The development of a component-based connection*

element for endplate connections in fire. Fire Safety Journal 42(6-7) (2007) 498–506, doi: 10.1016/j.firesaf.2007.01.008.

[16] European Committee for Standardization. *EN 1991-1-2 Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire*. Brussels, 2002.

[17] Szumigała M., Polus Ł. *A comparison of the rise of the temperature of an unprotected steel column subjected to the standard fire curve ISO 834 and to a natural fire model in the office*. Engineering Transactions 63(2) (2015) 157–170.

[18] Szumigała M., Polus Ł. *Fire resistance of the ceiling in the old tenement house*. Procedia Engineering 195 (2017) 178–182, doi: 10.1016/j.proeng.2017.04.541.

[19] Maślak M., Suchodoła M., Woźniczka P. *Temperature distribution in a steel beam-to-column joint when exposed to fire. Part 1: End-plate joint*. Journal of Civil Engineering, Environment and Architecture 65(2) (2018) 25–34, doi: 10.7862/rb.2018.21.

[20] Jaspart J. P., Weynand K. *Design of joints in steel and composite structures, Eurocode 3: Design of steel structures, Part 1-8: Design of joints, Eurocode 4: Design of composite steel and concrete structures*. ECCS, 2016.

[21] European Committee for Standardization. *EN 1993-1-8 Eurocode 3: Design of steel structures - Part 1-8: Design of joints*. Brussels, 2005.