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REFURBISHMENT, STRENGTHENING, AND DURABILITY OF EXISTING BUILDING STRUCTURES

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ABSTRACT: The article presents reflections on the renovation of existing building structures, in particular buildings. Particular attention is paid on the durability of structures as an element of sustainable development is considered. The concept of sustainability in the limit state approach to the structural design is proposed. The durability should be treated and considered as a third limit state. Problems related to the use of Life Cycle Assessment (LCA) for the actual estimation of the environmental impact of existing buildings are also presented.

KEY WORDS: renovation of existing building structures, durability, LCA

 JEL: L74, O33, Q56

Introduction

Structures and buildings account for a significant proportion of capital in many countries and contribute to their socio-economic development. However, they are also an important contributor to environmental impacts. Existing construction resources require either continuous repair or demolition investments and their replacement by new facilities. Existing structures are subjected to processes of degradation in time, which leads to a situation in which they became not able to fulfil their initial purpose. Some of these structures, particularly bridges, have already achieved an age of ninety, hundreds or even more years and are still in operation after damages, several phases of repair and strengthening. Many steel structures erected at the end of the XIX and beginning of the XX-centuries are still in function.

Replacement with new structures raises financial, technical and political problems. For the last decades, intensive activities on maintenance, reconstruction, repair, strengthening and rehabilitation of existing steel buildings have been carried out. The reasons for such an extensive reconstruction are the increasing need of residential area, revitalization, and repair of structures that are many years old as well as the improvement of the quality of living of the occupants of those structures. Public funds for reconstruction are limited, but this must not be a barrier to the security of buildings and infrastructure.

Refurbishment of existing buildings with architectural value (enabling the delivery of modern facilities), may be less expensive than a new structure; the degree of refurbishment can vary, from simple repairing to changing the existent structure. When assessing the remaining lifespan of a building, maintenance costs and renovation costs, it may be found that it is more economical to refurbish than to rebuild.

A change in approach from the removal-replacement of buildings toward the rehabilitation of buildings requires the development of the most economical and effective techniques for structural rehabilitation. Various methods must be evaluated for their structural characteristics as well as their cost. Limited research has been directed toward obtaining data in this field in Poland. Much of the available cost data is not widely distributed and, in most cases, the structural characteristics are not well documented.

One of the tools that can be used to estimate the environmental impact of the entire life cycle of buildings is Life cycle assessment (LCA).

The durability of building and civil engineering structures

Durability is defined as the ability of a structure to meet its minimum function for a period of planned use and under the intended conditions, without incurring excessive repair and maintenance costs. It turns out that we have all the possibilities to create such buildings. What's more, such possibilities existed in many centuries earlier, as evidenced by historical engineering objects. Durability is also associated with the concept of reliability concerning building objects, which includes both safety and usability, which can be used in the commonly accepted method of designing structures in the limit state method. Both of these concepts – durability and reliability – relate to a specific period of use, as the operational and other requirements change over time.

In addition to the limit states introduced into the standards, it is necessary to take into account the limit state resulting from the durability requirements. Structural durability can be seen as striving both to ensure a full-service life in normal conditions and at a given time, as well as to avoid disasters and damage resulting from insufficient durability, e.g. as a result of continued use despite signs of wear of structural components.

The structures are designed to meet the requirements before the occurrence of one of the two basic limit states: construction safety and its usability. This means that there must be no situations in which the structure is insufficiently durable or unstable, and also in which there are signs that prevent the use as intended, e.g. excessive deflections, too wide scratches or even unacceptable changes in the appearance. These requirements apply to entire structures, structural elements, and objects during construction and demolition.

The investment planning includes all details of the future functioning of the buildings, which result in the necessary shapes and sizes, ensuring durability, stability, and functionality. Requirements related to this are given in norms and regulations that apply in various fields. All these requirements form the basis for designing, determining costs, controlling the execution and reception of buildings, as well as the ways of using it. Whereas in the current standards, there is a lack of determination of the required durability in many countries; in most cases, only temporary permanent structures are distinguished (Somerville, 1999).

For example, in Poland, the durability of various types of road and bridge constructions is expressed in the number of years in departmental ministries' regulations and revisions. The service life of ordinary structures is assumed for 50 years. However, these requirements are not directly considered in the design or required by the investor, i.e. they are not designed for certain durability. There are unknown cases of demolition of the building due to the passage of time for which it was designed and constructed. The situation is different for example in the aviation industry: engines and aircraft have a certain number of working hours, which cannot be exceeded – after this period of operation they must be transferred for scrap. It is difficult to imagine a completely analogous situation in construction, but isolated cases indicate that similar requirements can be formulated and implemented. For example, bridges and tunnels built in the 1990s by the Danish straits were designed for 150 years, the famous viaduct in Millau in the south of France, put into use in December 2004 – for 120 years. In both cases, designers and contractors had to prove the required durability of the adopted construction and material solutions. Similar exceptional situations also occur in facilities intended for the storage of radioactive waste. It turns out that designing for a definite period of use is possible, and if used sensibly, it could be a way to improve the durability of all structures, not only the exceptional ones.

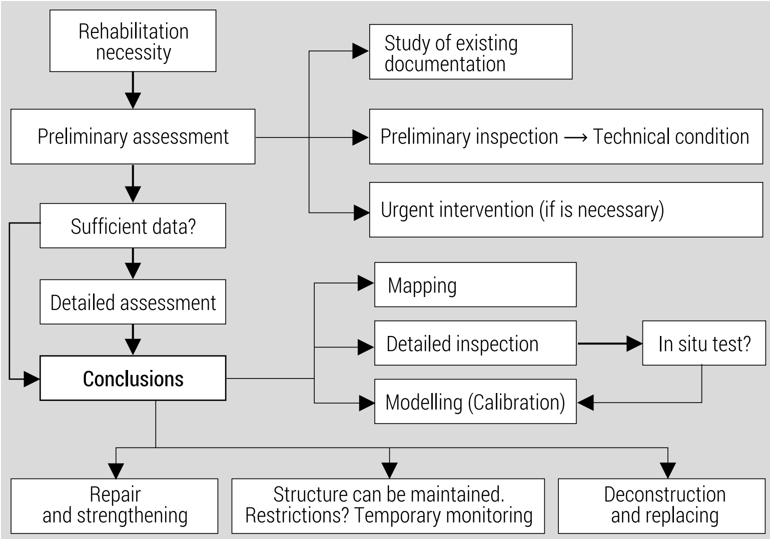
If all constructions that are not explicitly described as temporary are considered to be permanent, then it is not surprising that due to various processes, the durability of many buildings turns out to be insufficient. This applies to the largest extent objects exposed to direct climatic impacts, and thus all bridges and hydrotechnical constructions, road surfaces, etc., because impacts on such objects show changes in intensity during many years of use, are defined in standards in an approximate way, and often insufficiently their combined occurrence, etc. is assessed.

General considerations in refurbishment and rehabilitation of buildings

For information on the construction's resistance, both field measurements and material tests are used to obtain information directly from the structure. Data, characterisation old steel, principles of design or connection between elements differ significantly from present times standards. Therefore, the project, the database of materials, calculations and drawings, as well as additional experiments should first be investigated.

The estimation of the carrying capacity of existing structures is a complex matter. One of the most important aspects is the experience of the expert. In a first step, the expert has to inspect the structure carefully and to make an estimation, based on simplified analysis methods and a preliminary evaluation of the technical condition of the structure. During the visual inspection, the corrosion state must also be evaluated. Figure 1 presents the main steps in the evaluation of the existing structures.

Figure 1. Flowchart regarding the refurbishment of existing steel structures



Source: ECCS, 2008.

A majority of old buildings which could be rehabilitated were used originally for a purpose other than their future use. In assessing the adaptability to new uses, it is important to look into the above three aspects:

1) existing documentation,
2) technical condition,
3) urgent intervention.

It is obvious that new buildings are designed for about one-half the live loads used in the design of old buildings. Moreover, until the beginning of the XX century, the steel factories had own rules without a general standardisation, resulting in a large dispersion of steel characteristics; sometimes for the same structure, it is possible to have different steel qualities. The allowable stresses for rolled steel shapes used were about ⅔ of the present values. Likewise, the allowable shear and bearing stresses for these connections were as low as 40% for shear and 30% for bearing (DS805, 1991/2002).

Strengthening an existing building is a unique problem in design, and each building poses special constraints for the design of appropriate strengthening at a reasonable cost. Existing steel structures can be evaluated using the safety concept existing to the time of the structure's erection, generally the safety concept of allowable stress. Nevertheless, checking according to the Eurocodes is strongly recommended. For the majority of existing steel structures, the documentation is missing. In consequence, the expert has to do some in situ measurements mapping the structure, which is not always easy, taking into account the accessibility on the site.

Two basic types of strengthening should be considered: maintaining the original structural system and strengthening individual members or connections and modification of the structural system. In strengthening individual members or connections, it is vital not only to ascertain the mechanical properties of the material but also to determine geometrical properties to permit a necessary review of design calculations. Generally, the reinforcement of the structures is not recommended if (ECCS, 2002):

- the additional material is more than 40% of the weight of the existing structure or 30% of a new one,
- the rehabilitation cost is higher than the price of a new structure.

Exceptions are the historic structures, monuments of the engineering art; in this situation, every case must be analyzed separately. It is important to emphasize that a refurbished structure is not a new one.

In the case of modification of the structural system, a variety of factors, including structural, architectural, economic, or societal needs, may preclude preservation of the original structural system with appropriate strengthening. In such cases, substantial modifications of the structural system may be necessary to accommodate changes in the use of the building, new loading patterns, or specified increased level of any other resistance.

The result of the survey will generally result in one of three potential outcomes:

a) the current structure is sound, and an extension or modification as envisaged is feasible,
b) the current structure can be modified to make it sound, or sound enough, to accommodate the envisaged changes,
c) the current structure is either not sound, or else not sound enough to be modified to enable the modification.

The most common outcome is the second one, and it is usually the case that modifications are required to existing structures to allow them to be extended, or modified in any substantial way. In this scenario, it is important to look for the safest and most cost-effective route forward to deliver as close to the original specification as possible.

The process of integrating an original structural system with new structural components, such as additional members, frames, or walls, and replacement of floor or roof systems, is similar to that entailed in developing a new design. An analysis of the modified system will require investigation of stresses and deformations under gravity load as well as under combined effects of gravity and lateral forces. Any deficiency in the original components of the system would require strengthening.

A variety of modifications may be introduced. Wood floor systems may be strengthened or replaced by steel decking or reinforced concrete slabs.

Lateral bracing may be strengthened or replaced by reinforced masonry or concrete shear walls. In such cases, connections of the new walls to the floor must provide for the transfer of the design lateral loads. Larger lateral forces may be induced in stiffer buildings, and these should be taken into account in the modification design. Whenever possible, asymmetry in adding new components should be avoided because of torsional effects and possible increased lateral forces in critical components.

Design for durability in semi-probabilistic limit states

Using the method of limit states commonly known in the design of the structure is necessary to specify the planned period of the construction operation, resulting, for example, from the intentions of the investor, type of building, etc. The next step is to determine the characteristic (predicted) durability period t_k by including statistical data and analysis of the probability of requesting all random variables and their intensity in such a task wherein the period of predicted durability t_k should be greater than the period of planned use t_d.

In the case of designing strength and load resistance under given loads, a well-known semi-structural method can be used, including on introducing nominal values of loads or taking into account unknown statistical distributions of values occurring in such an issue by appropriate partial coefficients. Such coefficients, in the absence of sufficient statistical data, may be determined on the basis of experience or in another estimated way. Different methods propose consideration of durability in this method.

Using the semi-probabilistic method of limit states analogously, the projected period t_d can be expressed as (Guide, 1992):

$$t_d = t_k / \gamma_t \, , \tag{1}$$

where:

t_k – is a characteristic (expected) period of building durability,

γ_t – is a coefficient, usually greater than one, being a product of partial coefficients:

$$\gamma_t = \gamma_{t1} \cdot \gamma_{t2} \cdot \gamma_{t3} \cdot \gamma_{t4} \cdot \gamma_{t5} \cdot \gamma_{t6} \cdot \gamma_{t7} \, . \tag{2}$$

Partial coefficients are designed to take into account the basic factors that influence the construction's different behaviour than expected. For example, such factors may include the following circumstances:

γ_{t1} – the significance of the structure and consequences of the occurrence of the limit state,
γ_{t2} – the quality of design and dimensioning (uncertainty of adopted models),
γ_{t3} – the quality of construction and control at the construction site,
γ_{t4} – conditions of the inside of the building,
γ_{t5} – properties of external conditions,
γ_{t6} – the method of use, e.g. the possibility of other loads,
γ_{t7} – the expected quality of building maintenance.

Depending on the circumstances, the number of partial coefficients can be increased to account for different local conditions and requirements. Usually, coefficients should be greater than or equal to one, as in the case of structural strength design. Other methods for determining the γ_t coefficient are known (Sarja, 1997) in determining the expected level of reliability and statistical degradation distribution. This changes the way of designing, but the concept of required durability remains with a certain probability of a limit state.

When using partial coefficients, it may turn out, for example, that in the case of a building designed and manufactured by renowned companies, in the absence of corrosion hazards, the expected durability life is not much different from the required by the investor. However, a structure exposed to inaccurately identified aggressive factors should be made and protected for a period much longer than planned. For example, a structure designed for t_d = 50 years should be able to remain stable for a period of t_d = 70 years or in the second case t_d = 90 years.

The described method of determining the required and planned durability of a building introduces changes in the manner of formulating assumptions by the investor and their proper implementation by the designer. It is necessary to take into account the fact that the growing durability requirements cause the increase of the first cost to, while the total cost of such facilities, including maintenance and repair, can be significantly lower.

The operation of aggressive factors can be introduced into the limit state method in a manner analogous to the effects of loads. In such a case, it is necessary to determine the decisive aggressive action and determine a characteristic period of time T_k, in which it will lead to the emergence of a limit state. To determine the planned period of time T_d, the T_k should be divided by the appropriate coefficient:

$$T_d = T_k / \gamma_d \, , \quad (3)$$

where:
T_k – is a characteristic period of time, after which the considered aggressive action will lead to a limit state of destruction or loss of usability, this value

can be determined by the results of experimental research or observation of objects,

γ_d – is a coefficient, usually greater than one, which takes into account the influence of various random factors, estimated on the basis of experience and observation of similar structures.

The coefficient γ_d can be determined as the product of partial coefficients expressing the influence of various factors:

$$\gamma_d = \gamma_{d1} \cdot \gamma_{d2} \cdot \gamma_{d3} \cdot \gamma_{t4} \cdot \ldots\ldots \qquad (4)$$

For example, in the case of adopting a corrosion of a steel as an aggressive action, and reaching this process up to the reinforcement bars as a limit state of durability, partial coefficients may express:

γ_{d1} – the temperature and pressure changes,
γ_{d2} – the presence of impurities,
γ_{d3} – the pH environment,
γ_{d4} – the stresses in a material.

All these factors are of random nature, but considering of ignorance of statistical distributions of these quantities, the estimated values of coefficients γ_{di} must be determined on the basis of experience, observations of similar structures, etc. As the data on probability distribution is obtained, it is purposeful to use them to evaluate individual phenomena.

The condition of building durability due to the considered aggressive impact is to meet inequalities:

$$T_d > t_d\,, \qquad (5)$$

which means that the period of time before the aggressive influence will cause the occurrence of a certain limit state is longer than the planned period of building exploitation. Then, the durability of the structure is assured with the probability resulting from the assumed values of coefficients or from probability distributions of occurrence and intensity of interactions.

If it is possible to have several aggressive interactions, you can either consider them in succession or take into account their mutual relations, e.g. in the sense of accelerating aggressive processes. In the first case, it will be seen which of the considered impacts leads to the state of the border in the shortest time. In the second case – it is necessary to build an appropriate model, taking into account the combined occurrence of two or more interactions.

The semi-probabilistic method of taking into account durability in the design presented above can be variously developed and expanded. It is therefore proposed to introduce a separate limit state of durability. It can be assumed that the limit state of durability corresponds to the initiation of the process leading to the occurrence of one of the two limit states. This means that in this initialisation state (initiation durability state) durability and usability are not yet endangered, but the construction ceased to be permanent because the process leading to one of these states began. To restore durability, appropriate measures must be applied during this period and the destruction process should be discontinued.

Life cycle assessment of building structures durability

Life cycle assessment (LCA) is a tool that can quantify the environmental impacts of building structures. However, many building LCA studies do not adequately address the actual lifetime of residential buildings and building products, but rather assume a typical value, say 50 years. Including accurate lifetime information into LCA allows a better understanding of the life cycle impacts, ultimately enhancing the accuracy of LCA studies (Aktas, Bilec, 2012).

Unlike most other products, the buildings are occupied for a long time and their use phase may be more significant for the environment than all other connected phases. The problem for LCA applications is how best to characterize the use phase. Scenarios are required to define the role of residents' behaviour. Other scenarios are needed to indicate how building survives – maintenance cycles, repair and replacement schedules, repairs and renewing internal spaces by users. Particularly important to construction efficiency and longevity are assumptions about the effectiveness of the building adapt to changing expectations, changing applications and introducing new one's technologies. Many buildings are abandoned or demolished long before their useful life due to lack of possibilities of refurbishment or adaptability. The creation of usage scenarios is therefore crucial for the assessment of the real long-term performance of a given project or product or system.

Refurbishment of existing buildings is a strategy for expanding the lifetime of buildings. Most of the buildings are destroyed due to technological downtime, no deterioration of the structure. Adaptability can, therefore, prolong life without any significant environmental impact associated with all activities related to investments in the structure of the building and infrastructure. Consider, for example, the energy contained in reinforced concrete – probably the largest source of pollution in a typical commercial building. Or consider other long-term elements a building such as wood, metal, glass, and materials for land development. Or consider energy consumption in construction, demolition, transport and disposal of land, materials, and waste. If flexible projects can extend the average lifetime of buildings by 10% (and possibly much more), we can similarly reduce total global investments in their replacement long-lasting elements of the building. The most environmentally benign building is the one that does not have to be built.

It seems that so far insufficient use has been made of LCA to directly link refurbishment with the environmental burden. It is generally accepted that better use of space and longevity translate into a proportionate improvement in all environmental aspects loads related to building maintenance and material use and disposal.

A research was done by Larson (Larson, 1999) regarding adaptability of office buildings showed that environmental benefits are largely related to two factors: the annualised reduction in embodied and replacement energy, and the annualised reduction in solid waste generation from renovation and demolition. Using data from research studies that document the quantities of embodied energy and demolition energy used by office buildings Larsson estimates an equivalent reduction in two categories of environmental loadings 15% reduction in air emissions, and 15% reduction in demolition solid waste.

Aktas and Bilec (2012), based on an LCA study carried out in the USA, concluded that as a result of interior renovations of residential buildings it is possible to reduce energy consumption by 34%. However, they highlight the imperfections of the existing models used in the LCA. Without such models, it is not possible to develop effective strategies to reduce the environmental impact of existing buildings.

Conclusion

The refurbishment and durability of existing steel buildings are the issues which apply to all types of structures and can be considered, for example, concerning steel structures exposed to direct climatic factors.

The refurbishment which involves in modifying the existing buildings for structural behaviour becomes necessary to improve the performance of structures including those facing the loss of strength due to deterioration or which have crossed their anticipated lifespan. The realisation of retrofitting depends on the durability of the construction and the authentic cause and measures adopted to prevent its further deterioration. This development includes repair, retrofit, renovation and reconstruction wherever required.

Even if the durability of the designed structures is determined, it is generally not taken into account directly in the design or implementation. Instead of designing the structure for durability, achieving strength as a secondary result, it is designed only for durability. The current unsatisfactory situation is influenced by various non-technical factors that create the causes of damage. These are mainly frequent occurrences related with excessive savings at subsequent stages of the construction process, lack of systematic and comprehensive design and execution control and insufficient competence of staff on construction sites, as well as maintenance services.

Lifetime design of construction will in the coming years be the main factor forcing the development of research in the field of building materials. Such a design is one of the elements of sustainable development requirements in the field of construction. It can be anticipated that the development of the economic bases of erecting construction will entail far-reaching and positive changes in construction, requiring new research directions in the near future.

Based on the previous research and described uncertainties, the issue of the refurbishment of buildings is currently not solved. The models are too simplistic at present, and reduce the validity of LCA results. Methods for defining and measuring the durability, reusability and overall adaptability of buildings need to be developed and validated.

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Literature

Aktas, C.B., Bilec, M.M. (2012), *Impact of a lifetime on US residential building LCA results*, “Int. J. of Life Cycle Assessment” Vol. 17:337, https://bazy.pb.edu.pl:2073/10.1007/s11367-011-0363-x, pp. 337-349

DS805 (1991/2002), *Bewertung der Tragfähigkeit bestehender Eisenbahnbrücken* (in German), Deutsche Bundesbahn

ECCS (2008), *JRC: Assessment of Existing Steel Structures: Recommendations for Estimation of Remaining Fatigue Life.* Joint Report Prepared under the JRC – ECCS cooperation agreement for the evolution of Eurocode 3 (programme of CEN/TC 250)

ECCS (2002), *European Convention for Constructional Steelwork – ECCS. European Steel Design Education Program. ESDEP – Society*, Brussel Staalinfocentrum

Guide (2002), Guide to Durability of Buildings and Building Elements, *Products and Components. BS 7543, British Standard Institution*, London

Larsson, N.K. (1999), *Sustainable development and open building*, CIB TG26, Brighton, UK

Sarja A., Vesikari E. (eds) (1997), *Durability design of concrete structures*, RILEM Report Series 14 Vol.VI, p. 165

Somerville G., (1999), *Whole life design for durability and sustainability. Where are we going, and how do we get there?*, Int. Conf. "Concrete Durability and Repair Technology", pp. 1-19

Jankowska-Kłapkowska A. (2001), *Społeczeństwo informacyjne a nowa gospodarka*, in: R. Pajda (ed.), *Wybrane zagadnienia współczesnej ekonomii*, Kraków, p. 11-18

OECD (2015), *Key Nanotechnology Indicators*

Komunikat Komisji Europejskiej do Parlamentu Europejskiego, Rady, Europejskiego Komitetu Ekonomiczno-Społecznego i Komitetu Regionów w sprawie przeglądu wykazu surowców krytycznych dla UE i wdrażania inicjatywy na rzecz tych surowców (2014), Bruksela

Mikoś T. (2008), *Górnicze skarby przeszłości. Od kruszcu do wyrobu i zabytkowej kopalni*, Kraków

Nanotechnology Market Reports – Trends, Analysis & Statistics 2017 (2017), London

Nowy Przemysł (2010-2017)

OECD Science, Technology and Innovation Outlook 2016 (2016), Paris, Directorate for Science, Technology and Innovation OECD Publishing

OECD (2016), *Opportunities and Risks of Nanotechnologies*

Pindór T. (2017a), *Innovative methods of natural gas exploitation as a factor of sustainable development of world economy,* „Ekonomia i Środowisko" No. 4, p. 205-217

Pindór T. (2017b), *Technologie przełomowe w gospodarowaniu nieodnawialnymi zasobami naturalnymi*, „Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu" No. 491, p. 323-331

Pindór T. (2016), *Reindustrializacja Legnicko-Głogowskiego Okręgu Miedziowego*, „Barometr Regionalny: Analizy i Prognozy" No. 1(14), p. 103-109

Pindór T., Preisner L. (2016), *Zagospodarowanie morskich zasobów mineralnych dla trwałości rozwoju,* in: *Ekonomia i Środowisko: księga jubileuszowa profesora Bogusława Fiedora*, Wrocław

Platforma Przemysłu Przyszłości (2017), Nowy Przemysł No. 5, p. 16-22

Postępy Nanotechnologii (2010-2018)

Societal Implications of Nanoscience and Nanotechnologies (2016), UNESCO Report

Stefanowicz J. (2014), *Surowce krytyczne*, Warszawa

Strategia na rzecz Odpowiedzialnego Rozwoju do roku 2020, z perspektywą do 2030 r. (2017), Ministerstwo Rozwoju

Surowce dla przemysłu – plan działań na rzecz zabezpieczenia podaży nieenergetycznych surowców mineralnych (2017), Ministerstwo Rozwoju

Wielka Historia Świata (2008), Oxford Educational, t. 8-12

World Robotics Report 2017 (2017), Frankfurt, International Federation of Robotics Publishing