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Pēteris Druķis

METHODOLOGY FOR RELIABILITY ASSESSMENT OF EXISTING BUILDINGS

Summary of the Doctoral Thesis

RTU Press
Riga 2022

RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Construction and Reconstruction

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Druķis, P. Methodology for Reliability Assessment of Existing Buildings. Summary of the Doctoral Thesis. – Riga: RTU Press, 2022. – 47 pages.

Printed in accordance with the Promotion Council "P-06" of 20 May 2022, Minutes No. P-2.

https://doi.org/10.7250/9789934228216
ISBN 978-9934-22-821-6 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 2022 7th October in room 342 at the Faculty of Civil Engineering of Riga Technical University, 6 A Ķīpsalas Street, Riga.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Peteris Drukis ……………………………. (signature)
Date: 08.09.2022

The Doctoral Thesis has been written in Latvian. It consists of Introduction, 7 chapters, Conclusions, 60 figures, 50 tables; the total number of pages is 135. The Bibliography contains 83 titles.

CONTENT

1. INTRODUCTION

Topicality of the Thesis and statement of the research problem

According to the Report of European Commission in 2016 on the energy performance of buildings, in 2010, more than 30 % of buildings in Europe were over 50 years old. Today, this proportion is even higher. According to the regulations to which these buildings were designed, the resource of their use has expired. There are different opinions as to whether they should be decommissioned because they pose a risk to society and the environment, or further use of these buildings should be allowed. The report also shows that 70 % of the buildings that the society will use in 2050 were built and had been in use before 2010.

There is also evidence that the volume of new construction in the European Union is declining in terms of design and construction work, with an increasing amount of work on existing buildings (reconstruction or refurbishment).

Thus, it can be concluded that future engineers will have to work not only on the construction of new buildings, but also on maintenance of existing ones. The following issues are relevant in this regard.

1. *Reliability level of existing buildings*

According to current industry practice, existing buildings are considered safe for people and the environment if properly used. However, due to technological progress, as well as changes in regulatory enactments, which to some extent is related to the integration of different countries into a single geopolitical space, the tasks of both owners and service personnel in the use of buildings are becoming more and more complex.

The buildings in operation were designed to meet the level of reliability at the time they were built, while the level of reliability that meets and is expected today is higher. In addition to all this, new requirements have been added (energy efficiency, sustainability and saving of environmental resources, social requirements), the provision of which requires additional resources for building owners. Therefore, special attention is paid to the reliability of building structures in today's conditions. This is especially relevant for buildings with high amount of users or public buildings in accordance with regulatory requirements.

Different buildings, depending on their construction period, for example, in Latvia, have different levels of reliability. Given that the users of a building generally expect the same level of reliability, a situation may arise which causes accidents simply because the building does not provide the level of safety that its occupants expect. Although most of Latvia's buildings have been built more than 30 years ago when the Soviet building codes were in force, or even before them, there are also buildings that have been built between 1990 and 2010 in accordance with national building codes, as well as buildings constructed during the last years when the European Union construction norms and standards have already been in force in Latvia, also Eurocodes.

2. *Buildings with expired design life of structures.*

This issue has become relevant in society in the last two decades. In search of an answer to this question, the following questions arise: Should such buildings be demolished? Should their structures be changed? If not, who will take responsibility for their safety in the future? What should be the level of reliability of the building after its renovation or reconstruction? For how long should the building resource be extended and who is responsible for it?

The current regulatory framework for buildings mainly concerns the design and construction of new structures and does not incorporate requirements for the assessment and safety of existing structures. The construction codes are based on the assumption that the structures will be used for a certain period of time, but they do not stipulate the requirements for how to handle the structures after this period has expired. Should expired structures be considered unsafe and should they be phased out? If not, what is their future use? This issue is especially relevant in cases when a partial reconstruction or renovation of a building is carried out and new structures are combined with existing structures. Question arises whether the designer of the new structure takes responsibility for the old structure? Should the estimated service life of new structures be extended to existing structures?

3. *Assessment of the level of reliability of existing structures.*

There are significant differences between design and assessment. The design uncertainties arise from the load and resistance characteristics of the new structures. These uncertainties represent the dispersion of the characteristics of a wide variety of structures due to the heterogeneity of the quality of materials used in them, the different construction technologies and the distribution of specific loads at a given site. A conservative design does not lead to a significant increase in the cost of construction, whereas a conservative assessment may lead to unnecessary and costly repairs or reconstructions, or in an extreme case, may not reveal significant deficiencies in the use of the building, which could lead to tragic consequences.

These three issues are relevant for today's civil engineers and construction professionals, including those in the construction industry. In 2015, the European Commission's Joint Research Center issued a special science and policy report on regulatory and research activities related to the assessment of existing structures, highlighting issues and challenges in the design of existing structures.

In Latvia, these issues became especially acute after the event in 2013 in Zolitūde. The new building regulations require that all owners of public buildings carry out a technical inspection of buildings every 10 years at the latest by 2019 to identify compliance with the essential requirements, including mechanical strength and stability. But how to assess the reliability of existing structures in practice? What to do in situations when structures have been designed according to previous regulations but today the industry works according to other regulatory requirements? Should they be reassessed and updated to meet today's requirements and levels of reliability? What are the latest trends in the world and are they also applicable to Latvian conditions? These questions serve as a basis for the research conducted in this Thesis.

The author of the research considers it important to establish clear technical requirements and methodology for assessing the reliability of existing building structures in line with today's knowledge of the behavioral nature of structures. Given that the Technical Committee for

Standardization in charge of European Standartization Institute CEN is working on additions to the structural design regulations to establish a common framework for the reconstruction and refurbishment of buildings after 2022, it is important to understand the level of reliability of existing buildings, incl. creating a common methodological basis for determining the reliability of buildings, taking into account the technical, economic and social aspects of Latvia.

The aim of the Thesis

The aim of the Thesis is to develop a methodology for determining the overall reliability of existing buildings based on a quantitative assessment of the overall reliability level of the building, assessing the technical condition of the building load-bearing elements and their connections, their individual role in ensuring the mechanical strength and stability of the overall building structure.

Tasks of the Thesis

In order to achieve the aim of the work, the following tasks have been set:

1. To develop the theoretical basis of the methodology:

(a) to analyze current studies on methods and models for assessing the reliability of existing building structures;

(b) to carry out an analysis of reliability assessment practices for existing building structures in European Member States;

c) to perform a qualitative assessment of the technical condition of the structures of public buildings in operation and a synthesis of the factors influencing it on the basis of the data available in Latvia;

(d) to develop a method for determining the theoretical reliability levels for the various structural elements, including those designed outside the framework of the Eurocodes methodology and to develop examples of practical application of the methodology.

2. To develop a methodology for determining the overall reliability of existing buildings based on a quantitative assessment of the overall reliability level of the building, assessing the technical condition of load-bearing elements and their connections, their individual role in ensuring the mechanical strength and stability of the overall building structure and consequences of collapse.

3. To validate the developed methodology:

(a) to analyze the methodology for determining the overall level of reliability of the building, assessing the results at changes in the relevant parameters and limit states;

(b) to compare the results obtained with other alternative methods;

(c) to develop practical examples for the quantitative reliability assessment of existing buildings using the developed methodology.

4. To provide recommendations for the practical implementation of the methodology.

Scientific novelty of the Thesis

A new methodology has been developed for the quantitative assessment of the overall reliability of existing buildings using practically obtainable information on the reliability characteristics of individual structures. The methodology is based on the introduction of a common reliability index for buildings, which characterizes the mechanical strength and stability of buildings globally.

In addition, several new methods have been proposed in the Thesis which have been used in the developed methodology:

1. A new method based on the principles of risk management for the division of buildings into categories using visually detectable damage and deficiencies, thus qualitatively allowing the identification of the largest risk objects in public buildings of the state.
2. A new method based on the reliability concepts defined in the Eurocodes and suitable for assessing the reliability of the load-bearing components of existing buildings, as well as for comparing the reliability levels of different building regulations systems in general.
3. "Notional volume" method for determining weight coefficients which allows to evaluate the individual role of building components (trusses, ties, columns, slabs, etc.) in ensuring the overall mechanical strength and stability of building structures. The ranges of the relative influence factor W (weight factor) for multi-storey frame buildings with a regular column network have been obtained.

New parameters have been proposed – the global building reliability index Λ and the relative global building reliability index Λ_{GRI}, which characterize the technical condition of a new or existing building and allow for a quantitative comparison of the overall reliability level of different buildings.

Unlike the available methods based on probability theory and system theory for characterizing the overall level of reliability, the developed method is less labor-intensive and less complicated, thus ensuring that it can be used by those engineers who perform engineering inspection/assessment of buildings.

Unlike the available assessment methods of reliability level that are based on specific knowledge of the practical application of probability and system theory algorithms, the methodology developed in this Thesis is less complicated, thus ensuring that it can be used by those engineers who perform building inspections/assessment. The developed method also ensures uniform presentation of results, which ensures that the results obtained for different buildings are independently comparable, which in combination with a unified accounting system allows industry professionals and policy makers to perform the necessary planned measures to monitor the level of safety and make objective decisions.

Practical application of the Thesis

Applying of the new methodology for assessing the reliability of existing buildings will ensure that all parties involved in the reliability of the building (building owner, architects, designers, building authorities and other stakeholders) can obtain numerical information on the level of reliability of the assessed buildings. This would allow easy and qualified identification of the level of risk for the future use of the building and respond in a timely manner to develop adequate solutions to ensure the reliability of structures in accordance with the requirements of the applicable regulations. Although the new method is based on data from surveys and data processing of public buildings, it can also be used to classify the reliability of other buildings, such as residential and industrial buildings, and to assess the reliability of their structures.

Given that the terms and characteristics practiced in the Eurocode are widely used in the building construction industry, the author recommends that in future the building's compliance with mechanical strength and stability requirements be expressed not as a percentage of wear (usage) but used as measurment of the global reliability index of the building, determined in accordance with the method proposed in the Thesis.

In order to achieve this aim in Latvia, the necessary activities have been defined:

a) The responsible technical committee for standardization LVS/STK30 draws up a list of applicable standards that are applied to meet the requirements of LBN405 building regulations. This list needs to include the national, European and international standards that are applicable to the technical investigation and reliability assessment of structures;

b) In parallel, LVS/STK30 develops a national standard in accordance with the recommendations and methodology provided in this Thesis, and after its approval as a national standard, it is included in the list referred to in a).

The method developed as a result of the study also provides the way of monitoring the level of reliability of a building, including the involvement of machine learning algorithms, in order to facilitate and improve the overall level of reliability in the operation of buildings.

Results to be defended

1. Results of the study on the evaluation practice of existing buildings in Europe.
2. A method based on the principles of risk management, categorization of buildings for qualitative identification, as well as informing the society about risk objects in the public buildings of state, using visually detectable structural damage and imperfections.
3. A method based on the reliability concepts defined in the Eurocodes which is suitable for assessing the safety of the load-bearing components of existing buildings and for comparing the reliability levels of different building regulations systems in general.
4. Methodology for quantitative assessment of the overall reliability level of existing buildings, using practical information on the reliability characteristics of individual structures and the introduction of a global building reliability index that assesses the technical condition of building elements and their connections, their individual role in

ensuring mechanical strength and stability of the overall building structure, as well as the consequences of its possible collapse.

5. Ranges of the notional influence factor W for multi-storey frame buildings with a regular column network.

Limits of Thesis

The proposed building reliability assessment methodology is applicable for buildings for which the load-bearing capacity of the structures is ensured by standard load-bearing structures – walls, slabs, bars, columns, trusses and beams made of reinforced concrete, wood or metal. For prefabricated standard structures, objective data on the initial condition of the structures are available and the level of structural degradation (wear) with low dispersion of results can be determined. On the other hand, in the case of custom-made designs, the dispersion limits may be higher than specified in the manufacturing documentation and the choice of suitable test methods is limited. Therefore, further research should be done on adaptation of the methodology in the case of custom-made structures.

The method is also limited to the reliability assumptions given in the Eurocodes, both in terms of load and bearing capacity models, as well as in terms of uncertainties and distributions.

As the expected level of reliability for the structures of existing buildings is not specified at the regulatory level, the developed methodology is more suitable for collecting and comparing data on the level of reliability of a building. There are countries where the reliability of existing building structures (safety index) has been reduced by 1.5 compared to the design of buildings for economic reasons, which is in the range of 1.8–2.8 for the 50-year interval, respectively, or the probability of failure P_f = from 3.6×10^{-2} to 2.6×10^{-3}.

Additional research is needed on the criteria for the overall stability of buildings or the risk of a building overturning due to geotechnical considerations. Stability criteria are not taken into account in the current building reliability assessment.

The overall assessment of the building can also be supplemented by an assessment of other essential requirements, such as fire resistance, safety requirements, acoustics, energy efficiency and sustainability criteria. However, this should be done separately and these criteria should not be included in the building reliability characteristic, as this methodology does not provide for it.

Theoretical and methodological basis of the Thesis

The theoretical basis of the research are the methods of the field of building mechanics and building structures, mathematical analysis, mathematical statistics, probability theory, and systems theory.

Several research methods have been used in the Thesis:

- The qualitative method was used to make direct observations on the construction and operation processes of buildings in Latvia and the analysis of documents on the basis of which a study on the assessment practices of existing buildings in Europe has been carried out.

- Analysis and induction have been used to develop a new methodology for quantifying the overall level of reliability of existing buildings.
- The quantitative method was used in numerical experiments and simulations.

Software used in the study:

- for simulations – open source program Phyton 3;
- for structural calculations – commercial program Dlubal RFM 5.12.

Approbation of results in international conferences

1. 12th International Conference on Modern Building Materials, Structures and Techniques, Vilnius Technical University, Vilnius, Lithuania, 26.05–27.05.2016.
2. 11th International Scientific and Practical Conference "Environment. Technology. Resources", Rezekne Academy of Technology, Rezekne, Latvia, 15.06–17.06.2017.
3. 58.DAfStb-Jahrestagung 2017: "Concrete – keep thinking" and Symposium "Existing structures" (Kaiserlautern Technical University), Kaiserlautern, Germany, 19.09–21.09.2017.
4. 3rd International Conference "Innovative Materials, Structures and Technologies", Riga Technical University, Riga, Latvia, 28.09–29.09.2017.
5. 13th International Conference on Modern Building Materials, Structures and Techniques, Vilnius Technical University, Vilnius, Lithuania, 17.05–18.05.2019.

Scientific publications

1. Druķis, P., Gaile, L., Pakrastiņš, L.: **Inspection of Public Buildings Based on Risk Assessment.** In: Procedia Engineering. **172**, 247–255 (2017). https://doi.org/10.1016/j.proeng.2017.02.106. (SCOPUS).
2. Druķis, P., Gaile, L., Goremikins, V.: **Case study of structural reliability of existing building**. In: Vide. Tehnologija. Resursi. – Environment, Technology, Resources. **3**, 47–52 (2017). https://doi.org/10.17770/etr2017vol3.2615. (Indexed in SCOPUS).
3. Druķis, P., Gaile, L., Valtere, K., Pakrastiņš, L., Goremikins, V.: **Study of structural reliability of existing concrete structures**. In: IOP Conference Series: Materials Science and Engineering. **251**, (2017). https://doi.org/10.1088/1757-899X/251/1/012087. (Indexed in SCOPUS).
4. Druķis, P., Gaile, L., Goremikins, V.: **Structural reliability assessment of existing precast concrete building**. Case study. In: The proceedings of the 13th international

conference “Modern Building Materials, Structures and Techniques” (MBMST 2019) (2019). https://doi.org/10.3846/mbmst.2019.015.

5. Alekseytsev A. V., Drukis, P.: **Optimization steel of structures for buildings with variable desing safety level**. In: Magazine of Civil Engineering**,** Publisher: Peter the Great St. Petersburg Polytechnic University, ISSN:2071-4726E-ISSN:2071-0305 (2020), Scopus CiteScore 2018 – 2.75)

2. LITERATURE REVIEW

Within the framework of the development of the Thesis, a significant analysis of other studies on the topic of reliability was performed. Sources on the development of reliability theory and its application in relation to structural reliability are analyzed. An overview of publications on the concept of structural reliability and structural limit states, as well as the variables and uncertainties that characterize structural safety is provided. A significant review of publications has been performed on the main quantitative characteristic of the reliability of structural elements – the reliability index β, which is used as a quantitative measure of the probability of failure in a certain period of time. Sources on reliability systems, their modeling methods, load and material modeling, and fault analysis are also analyzed. A small section is also devoted to publications on techniques for idealizing complex systems in the context of reliability assessment, as well as standards for structural reliability assessment. The main findings from publications on publicly acceptable risks are also mentioned. A separate section on the reliability assessment of building structures and the reliability assessment of bridge structures is devoted to the study of literature sources.

A total of 79 publications were reviewed and the main conclusions summarized in Section 2.8. are as follows:

1) the most popular measure of reliability that is most widely used by industry and science in relation to safety characterization is the reliability index;

2) evaluation algorithms are becoming more complex, however, the application methods are becoming simpler and the comprehensibility, readability and reproducibility of the results are especially important;

3) economic, social and environmental aspects play an increasing role in drawing conclusions about buildings and their structural elements;

4) the availability of information and its reliability play an important role in decision-making;

5) the level of reliability required by Eurocodes for buildings currently dominate the world, but the use of international and national standards is also to be welcomed;

6) risk analysis is important in decision-making, however, its differentiation depending on the consequences is important at all levels;

7) the depreciation of materials plays an important role in the assessment of the reliability of existing buildings;

8) it is important to take into account the time factor in assessing the reliability of buildings and also in forecasting future operation;

9) a common platform for building reliability data is important if there is a desire to develop future technologies for reliability monitoring (e.g. through artificial intelligence);

10) the safety of persons prevails over any other considerations in the construction and use of buildings.

3. THEORETICAL BASIS OF THE STUDY

Within the framework of the Thesis, several studies have been carried out with the aim to develop a methodology for the quantitative assessment of building reliability, which the author recommends to implement in practice as a component of the technical assessment of buildings:

a) analysis of qualitative assessment of the technical condition of the structures of the buildings in operation and the synthesis of the factors influencing them on the basis of the data available in Latvia;

b) analysis of the reliability assessment practices of existing building structures in European Member States;

c) determining theoretical levels of reliability for the various structural elements, including those designed outside the framework of the Eurocodes methodology.

Based on these studies, a theoretical basis for the development of methodology for determining the overall level of reliability of existing buildings has been obtained.

3.1. Analysis of qualitative assessment of existing buildings

At the beginning of the study, it was found that there are no objective aggregated data available in Latvia on the construction of buildings and their reliability. Therefore, a method based on the use of visually detectable damage and imperfections for the classification of building structures into three risk categories from 1 to 3, where the categories are selected according to the general principles of structural degradation and their limit states (see Fig. 3.1), has been developed.

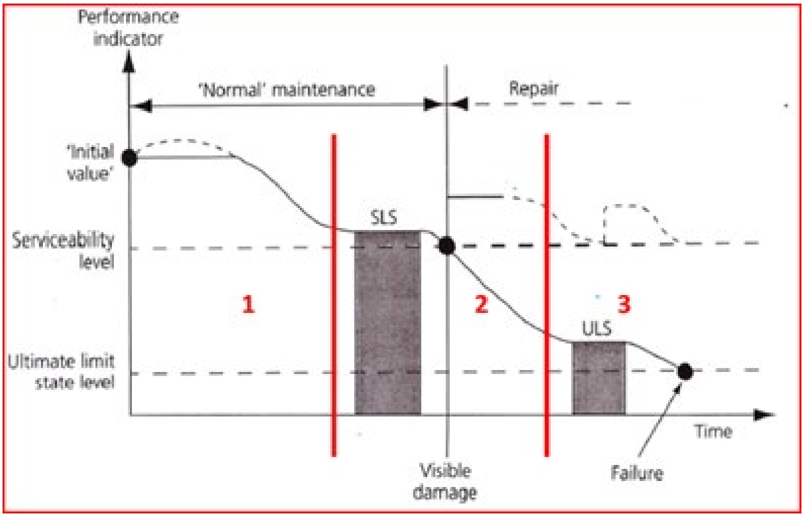


Fig. 3.1. Classification of building structures according to their degradation.

The method offers processing of the obtained data in accordance with the principles of risk management. The possible consequences of an event are placed on the vertical axis of the risk graph, while the probability of an event is placed on the horizontal axis (degree of damage or risk factor). By applying this principle, it is possible to assess and classify structures according to the degree of damage and the significance of the structure (consequence classes) in order to identify the risks and their impact on the operational safety of the building.

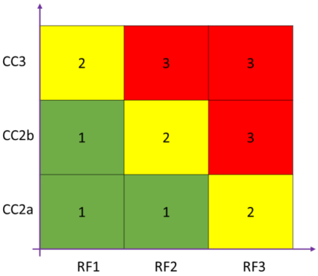
During the technical assessment of the building, the damaged building structures are classified on a scale from RF1 to RF3, using the following classification criteria (see full text of the Thesis for more details).

Table 3.1

Classification of Building Damage for Mechanical Sstrength and Stability

Risk factor	**Results of assessment**
RF1	Minor damages of mechanical strength and stability requirement violation have been identified which do not pose a significant risk to the health and/or life of the users of the building or to the environment.
RF2	Violations of mechanical strength and stability requirements have been identified that pose a significant risk to the health and/or life of the users of the building or the environment.
RF3	Significant damages of the mechanical strength and stability have been identified which pose an unacceptable risk to the health and/or life of the users od the building or the environment.

Based on the classification of the damage performed, a collapse consequence class according to the Eurocode methodology (CC) is assigned to each surveyed building and we obtain the values depicted in Fig.3.2.



	RF1	RF2	RF3
CC3	2	3	3
CC2b	1	2	3
CC2a	1	1	2

Fig. 3.2. Principle of risk classification.

According to the above figure, a conclusion is made on the risk assessment of an existing building on a scale from 1 to 3, where:

"1" – good condition/safe; minor defects have been identified that do not endanger the security of the building; attention must be paid during maintenance;

“2” – poor condition; safety needs to be improved; deficiencies that pose a threat to the security of the building have been identified; damage must be prevented;

“3” – dangerous condition/unsafe; defects have been identified that pose a serious threat to the security of the building; the building or part of it must be taken out of service immediately.

In case the building no damage in the structures have been detected after its assessment, then regardless of the consequence class, the building is rated “0” – excellent condition/safe; no defects have been identified; no action is required.

In cooperation with the State Construction Control Bureau (BVKB) in the period from January 2016 to December 2017, this method was used by the Bureau to implement the function specified in the Construction Law on the Control of Operation of Public Buildings.

Table 3.2

Total number of public buildings in Latvia with more than 100 people and with an area over 1000 m^2 and the number of assessed buildings according to the qualitative assessment method

Type of use of the building according to the classification	Classif. code	Total number of build.	BVKB building	Proportion, %	Number of assessed buildings	Proportion, %
Hotel buildings	121	5 452	525	6.5	127	19.5
Office buildings	1220	7 125	1602	20.5	215	10.5
Wholesale and retail trade buildings	1230	8 116	874	11.2	249	22.1

Table 3.2 continued

Communication buildings, stations, terminals and associated buildings	1241	2 608	174	2.2	27	12.3
Transport buildings	1242	11 569	0	0	0	0
Industrial buildings	125	50 307	0	0	0	0
Public entertainment buildings	1261	1 198	331	7.5	2	0.3
Museums and libraries	1262	562	105	1.3	18	14
Schools, universities and buildings for scientific research	1263	3 800	1972	23.3	766	32.8
Hospitals or other health care buildings	1264	1 341	461	5.2	117	22.3
Sports facilities buildings	1265	1 041	338	4.1	64	15.5
Agriculture buildings	1271	84 300	0	0	0	0
Religious (cult) buildings	1272	1297	67	8.9	20	2.2
Historical buildings	1273	49	15	0.4	1	2.6
Other buildings	1274	828 857	551	9	17	1.9
Total	**1 007 622**		**7 015**	**0.7**	**883**	**12.6**

The data analysis of the surveyed buildings did not find a correlation between the number of surveyed buildings in a particular category and the rating results in the range of 2–3 by type of use or region. Although separately in one category – medical or healthcare buildings, the proportion of detected damage is higher compared to other uses of buildings, in a deeper analysis of the reasons, this situation can be explained by insufficient technical maintenance without devoting adequate resources to timely maintenance. In general, the correlation coefficient of buildings by type of use or region is in the range of 0.07 to 0.09, thus, it can be concluded that the technical condition of buildings in Latvia is not affected by the purpose for which it is used and its location.

Different data were found regarding the age of the building and the material of the building structure. There is some correlation, and the results show that the level of reliability is lower for buildings over 50 years of age and if they are made of masonry or wood (see Figs. 3.3–3.6).

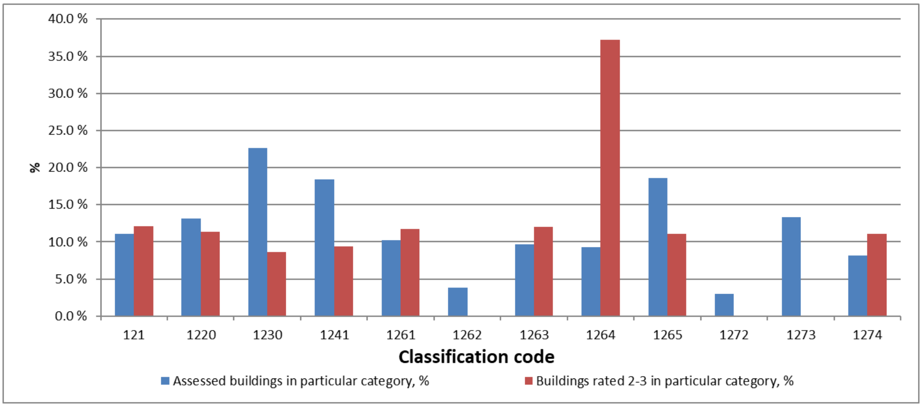


Fig. 3.3. Percentage of buildings rated 2–3 by type of use.

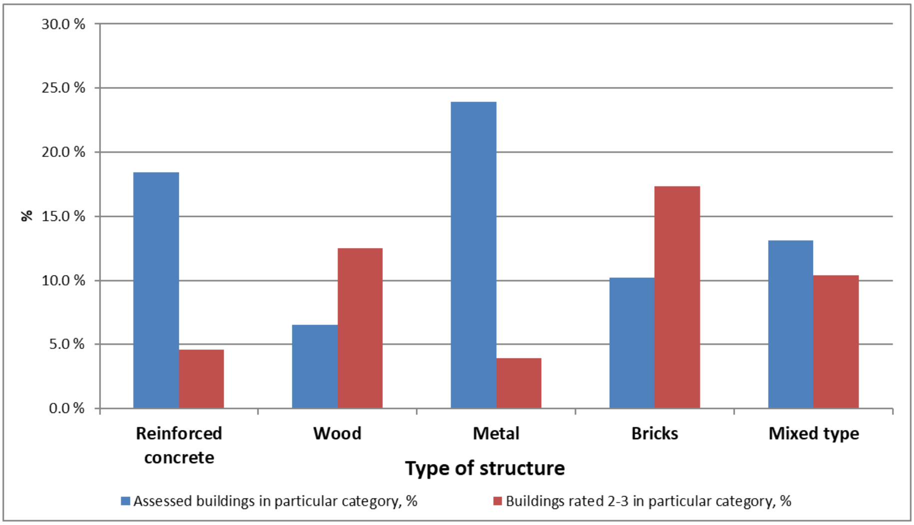


Fig. 3.4. Percentage of buildings rated 2–3 by type of structures.

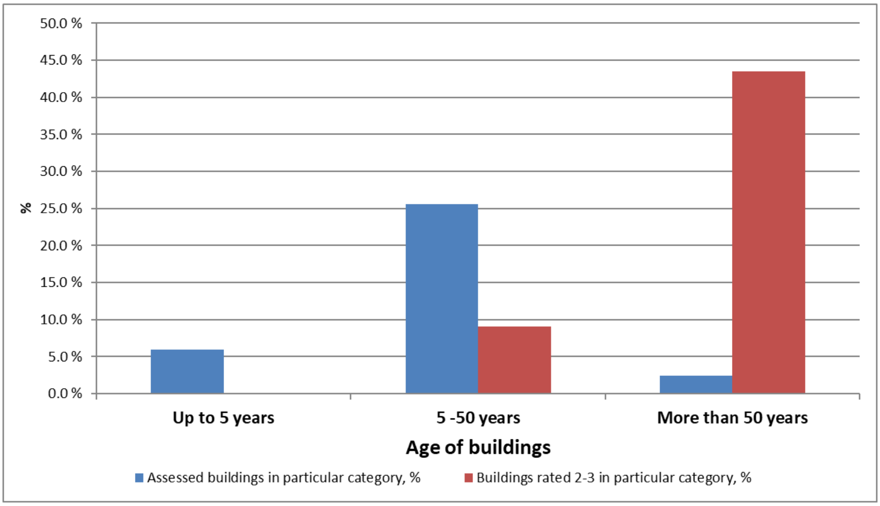


Fig. 3.5. Percentage of buildings rated 2–3 by age.

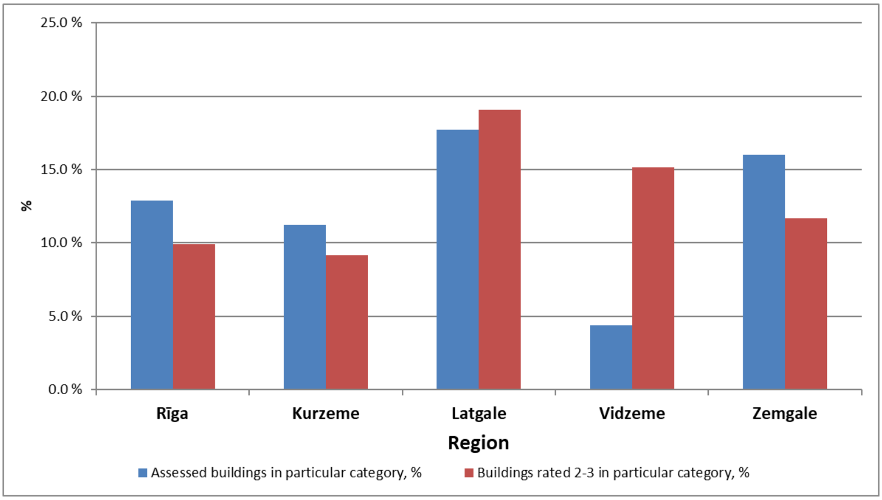


Fig. 3.6. Percentage of buildings rated 2–3 by type of region.

3.1.3. Disclosure of results to the public

In cooperation with the BVKB, it was also decided that it was important to inform the public promptly about the safety of public buildings. For this purpose, an interactive map was developed (see Fig. 3.8), where all the assessment results were presented using the informative traffic light (see Fig. 3.7).

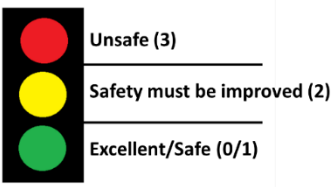


Fig. 3.7. Informative traffic light.

The interactive map is based on Google Map and allows users to interactively read more about the assessment performed on a particular building, the overall result of the assessment, and the location of the building. In August 2020, more than 93,000 unique views were recorded, indicating the timeliness of the information provided.

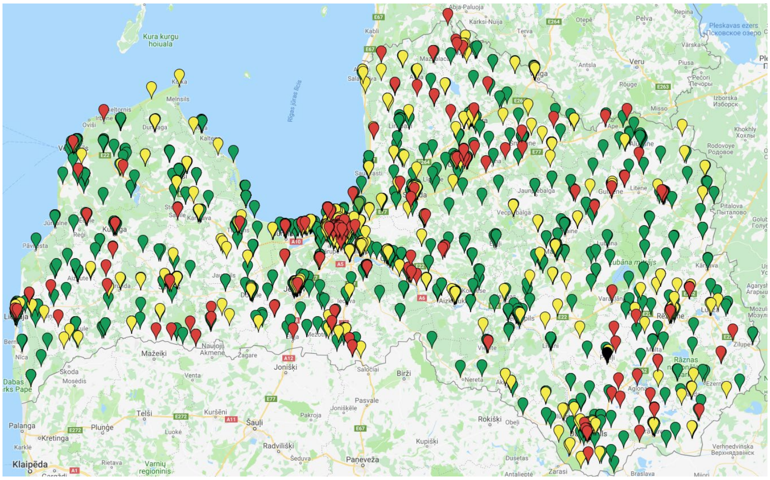


Fig. 3.8. Interactive map showing the results of assessment.

The analysis of qualitative assessment of the buildings in operation allows to make a massive indicative assessment of the condition of the buildings based on visual assessment, as well as to inform the public about the risks related to the reliability of the buildings. The method is time efficient, easy to use, easy to understand, understandable to the public and stakeholders. A rating on a scale of 0 to 3 is appropriate for describing the overall technical condition of buildings.

The proposed method was presented at an international conference in Vilnius in 2016, and a publication was published [75]. It should be noted that this method was introduced in practice in the work of BVKB in 2016, and the evaluation according to these principles is also is being implemented at the time of publishing this study.

From the results of the survey, it can also be concluded that in the field of public buildings it is important to pay attention to the load-bearing structures of the building and their age. Buildings rated 2–3 need a detailed study of their structures. As one of the methods for such a detailed research, the methodology developed within the framework of the Thesis is proposed, which allows to determine both the reliability of the structural elements of individual buildings and overall level of reliability of building structures (see Chapter 4).

3.2. Assessment practices for existing buildings in Europe

Within the framework of the research, a study was conducted with the aim of analyzing the existing practices in the Member States of the European Union regarding the reliability assessment of building structures in order to reveal other experiences and findings on reliability assessment practices. The study is based on an analysis of the data available in [2].

There are differences between Member States as regards the following criteria:

- diversity of monitoring objects – buildings and engineering structures;
- regulatory framework (evaluation is mandatory or voluntary);
- regularity of assessment (assessment is at regular intervals or at certain construction activities, such as change of ownership, change of use, after accidents (earthquakes, transport damage, terrorist attacks) or before reconstruction or rehabilitation work, etc.);
- assessment content (methodology) – whether it is a general visual assessment or a more detailed assessment, e.g. instrumental;
- acceptable (acceptable) level of reliability (level of probability of collapse; lower or equivalent for new buildings).

The differences are formed by the existing traditions, as well as the activities of professional industries (builders, building owners, etc.) and the academic environment (research, publications). However, it is most affected by building accidents that have killed a significant number of people. In the aftermath of such tragedies, society usually demands action to prevent a recurrence of accidents, and this promotes one solution or another on the part of the construction industry.

In this regard, in the last decade, a number of publications have been published on the assessment of structures, which also deal separately with the reliability of structures. This issue has been particularly relevant in recent years, when, according to various reports, policy-makers are beginning to emphasize the need to focus on the refurbishment of existing buildings, including structures.

A document [2] was published in 2015 summarizing the regulatory documents for the reliability assessment of buildings in 12 European Union countries: Cyprus, the Czech Republic, Denmark, France, Germany, Greece, Ireland, Italy, the Netherlands, Spain, Switzerland, and the United Kingdom. The document does not include Latvian practice. It was this fact that seemed interesting and encouraged to compare the data of the study with Latvian practice. The main conclusions are:

1) basically, reliability assessment is determined nationally as mandatory and in accordance with the requirements of national standards and not internationally applied standards;

2) both qualitative and quantified assessment methods are used in the inspection, however, in most cases a combination of both methods is used;

3) In 5 countries the structural reliability index is used as a reliability characteristic, however, different interpretations of the reliability level of existing structures compared to new ones are used, while in the other 8 countries other characteristics (different coefficients, signs of failure, etc.) are defined as reliability measures and there is no correlation with the resource for the use of the structure;

4) Latvia is the only country in comparison with the other 12 where reliability is not measured but an assessment of the depreciation of the building is provided.

3.3. Determining the reliability of structures designed based on different construction codes

3.3.1. Theoretical basis of the method

In order to achieve the goal of a methodology for determining the level of reliability of the overall building structures, one of the tasks was to develop a method to determine the level of reliability of individual structural elements (reliability index β). The determination of the reliability index for individual structural elements is searched by means of an iteration, where the value of β_0 that is closest is found to ensure that the following condition is met:

$$U = (\gamma_G E_{G,k} + \gamma_Q E_{Q,k}) / \gamma_R R_k \rightarrow 1, \tag{3.1}$$

where:

for materials

$$\gamma_R = \frac{\exp(-1{,}645 V_R)}{\exp(-\alpha_R \beta_d V_R)}; \tag{3.2}$$

permanent loads

$$\gamma_G = 1 / (1 + 0{,}7 \beta_d V_G); \tag{3.3}$$

variable loads

$$\gamma_Q = \frac{1 - V_Q(0{,}45 + 0{,}78 \cdot \ln(-\ln(\Phi^{-1}(\alpha_E \beta))))}{1 - V_Q(0{,}45 + 0{,}78 \ln(-\ln(0{,}98)))}; \tag{3.4}$$

γ – relevant partial factor;

V – the mean value, the standard deviation and the coefficient of variation of a given variable;

α – sensitivity factor;

Φ^{-1} – failure probability function;

β – reliability index;

U – utilisation factor.

The basic diagram for determining reliability index β is shown in Figs. 3.9 and 3.10. To make a choice between 3.9 and 3.10, the engineer shall carry out an on-site inspection of the site and compare the data available in the documentation with the situation found at the site. It is permissible to reduce the load-bearing characteristics by using the technical condition of the actual products found during the visual assessment.

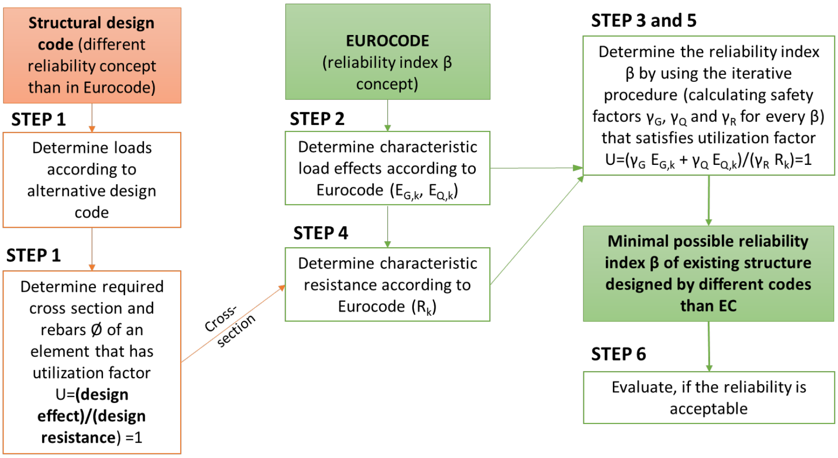


Fig. 3.9. Principle flowchart for determining the reliability index for structures for which it is possible to determine the actual characteristics from *the d*ocumentation.

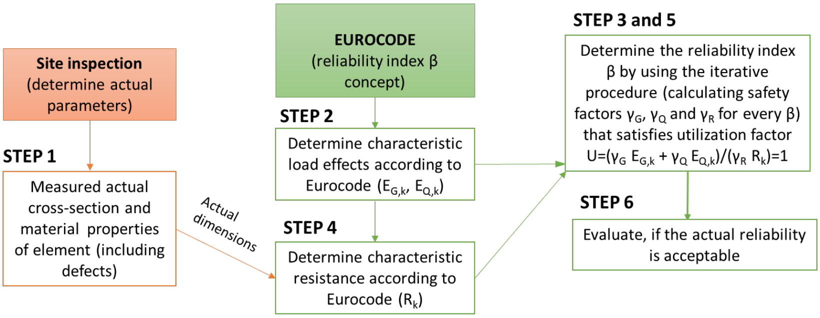


Fig. 3.10. Principle flowchart for determining the reliability index for structures for which it is not possible to determine the actual characteristics from the documentation.

3.3.2. Practical application of determining reliability index β (case study). Steel truss and beam

A study of the practical application of the method described above was performed for an existing building in Liepaja, Latvia, as well as a case if the same building was located in Riga, Latvia. To determine the individual reliability index β, a steel roof truss and floor beam were chosen. It is known that there are differences in the values of loads in different regulatory systems, especially for climatic loads.

The practical examples of detailed outputs can be found in the Thesis; Table 3.3 presents the summary of the research results.

Table 3.3

Reliability index of the truss top chord elements in compression and bending

City	**As built**		**If designed with ~100 % utilization**			
	Liepaja		Liepaja		Riga	
Code	SNiP	Eurocode	SNiP	Eurocode	SNiP	Eurocode
β		**3.8**		**2.6**		**3.2**
γ_Q		1.30		0.90		1.09
γ_G		1.27		1.18		1.22
γ_R		1.12		1.04		1.08
Internal loads	N_d = 388 kN M_d = 4.89 kN·m	N_{Ed} = 546.9 kN $M_{s,Ed}$ = 6.9 kN·m $M_{h,Ed}$ = 8.6 kN·m	N_d = 388 kN M_d = 4.89 kN·m	N_{Ed} = 418.1 kN $M_{s,Ed}$ = 5.3 kN·m $M_{h,Ed}$ = 6.6 kN·m	N_d = 483 kN M_d = 6.08 kN·m	N_{Ed} = 478.4 kN $M_{s,Ed}$ = 6.0 kN·m $M_{h,Ed}$ = 7.5 kN·m
Utilization factor *U*	68 %	98 %	98 %	100 %	95 %	99 %
Cross section	□160 × 160 × 4		□130 × 130 × 4		□150 × 150 × 4	

Table 3.4

The reliability index of the truss bottom chord under tension

City	**As built**		**If designed with ~100 % utilization**			
	Liepaja		**Liepaja**		**Riga**	
Code	SNiP	Eurocode	SNiP	Eurocode	SNiP	Eurocode
β		**4.3**		**2.5**		**3.2**
γ_Q		1.50		0.87		1.09
γ_G		1.30		1.18		1.22
γ_R		1.15		1.03		1.08
Internal loads	N_d = 401.9 kN	N_{Ed} = 633.2 kN	N_d = 401.9 kN	N_{Ed} = 424.2 kN	N_d = 500 kN	N_{Ed} = 496.3 kN
Utilization factor *U*	59 %	99.2 %	95 %	98 %	96 %	97.5 %
Cross section	□140 × 140 × 4		□90 × 90 × 4		□90 × 90 × 5	

Table 3.5

The reliability index of compressed elements of truss diagonal

City	**As built**		**If designed with 100 % utilization**			
	Liepaja		**Liepaja**		**Riga**	
Code	SNiP	Eurocode	SNiP	Eurocode	SNiP	Eurocode
β		**3.3**		**2.8**		**3.3**
γ_Q		1.12		0.96		1.12
γ_G		1.23		1.20		1.23
γ_R		1.08		1.05		1.08
Internal loads	$N_d = 99.2$ kN	$N_{Ed} = 125.2$ kN	$N_d = 99.2$ kN	$N_{Ed} = 111.9$ kN	$N_d = 123.4$ kN	$N_{Ed} = 125.2$ kN
Utilization factor U	81 %	98 %	95 %	98 %	100 %	97.5 %
Cross section	□80 × 80 × 3		□80 × 80 × 2.5		□80 × 80 × 3	

Table 3.6

The reliability index of the beam in bending

City	As built		If designed with 100 % utilization			
	Liepaja		Liepaja		Riga	
Code	SNiP	Eurocode	SNiP	Eurocode	SNiP	Eurocode
β		**3.5**		**2.7**		**3.5**
γ_Q		1.19		0.93		1.19
γ_G		1.25		1.19		1.25
γ_R		1.10		1.04		1.10
Internal loads	$M_d = 589$ kN·m	$M_{Ed} = 777.5$ kN·m	$M_d = 589$ kN·m	$M_{Ed} = 650$ kN·m	$M_d = 732$ kN·m	$M_{Ed} = 777$ kN·m
Utilization factor U	80 %	99 %	100 %	98 %	99 %	99 %
Crosssection	IPE600		IPE550		IPE600	

The predefined reliability indexes β can be compared with the target reliability indexes from the consequence classes according to EN1990 ($\beta = 3.8$ for the respective RC2 class building for a reference period of 50 years). In Liepāja, the difference in the level of reliability for the stretched element of the roof trusses is 34 %, which could be considered significant, as the probability of the respective collapse will increase from 0.0072 % to 0.62 %.

The calculated element reliability index β for the analyzed elements with the Eurocode calculation effects and the load-bearing capacity of the elements at the actual load range from 4.3 to 3.3. The calculated element reliability index β for the analyzed elements with efficiency factor U_{100} = 100 % according to the SNiP calculation loads and element load capacities in Liepāja city vary from 2.5 to 2.8, but in Riga from 3.2 to 3.5.

3.3.3. Practical application of determining reliability index β (case study). Reinforced concrete panels

As there are differences in the values of variable loads of different regulatory systems on the slabs, as well as the precast concrete calculation elements in the same load-bearing capacity calculation methodology, the five standard hollow precast concrete slabs were chosen according to the product catalog as the object of research. The calculation is made on five different buildings.

Full examples of detailed outcomess can be found in the Thesis, but a summary of the research results is given below.

A total of 25 cases analyzed at 100 % utilisation (5 different panels for 5 types of building) are summarized in Table 3.7.

Table 3.7

Reliability index of hollow core slabs

Intended use of building		(PTK-47-12)		(PTK-51-12)		(PTK-59-12)		(PTK-60-12)		(PTK-63-12)	
		L = 4.7 m		L = 5.1 m		L = 5.9 m		L = 6.0 m		L = 6.3 m	
		SNiP	EC	SNiP	EC	SNiP	EC	SNiP	EC	SNiP	EC
Residential buildings		4Ø10		4Ø10		2Ø10&2Ø12		2Ø10&2Ø12		6Ø10	
	β		4.0		3.6		3.2		3.1		3.3
	U	71 %	100 %	84 %	100 %	94 %	99 %	97 %	99 %	88 %	100 %
Office buildings		4Ø10		4Ø10		6Ø10		6Ø10		2Ø10&3Ø12	
	β		3.2		2.9		2.9		2.8		2.6
	U	82 %	98 %	97 %	100 %	89 %	100 %	92 %	100 %	97 %	99 %
Hotels		4Ø10		2Ø10&2Ø12		7Ø10		7Ø10		2Ø10&4Ø12	
	β		2.6		2.6		2.5		2.4		2.3
	U	97 %	98 %	95 %	100 %	92 %	99 %	95 %	98 %	95 %	100 %
Commercial buildings		2Ø10&2Ø12		6Ø10		2Ø10&4Ø12		8Ø10		9Ø10	
	β		2.5		2.4		2.2		2.2		1.8
	U	94 %	100 %	92 %	99 %	98 %	100 %	98 %	100 %	98 %	99 %
Warehouse buildings		2Ø10&2Ø12		6Ø10		2Ø10&4Ø12		2Ø10&4Ø12		9Ø10	
	β		1.4		1.4		1.1		1.1		0.8
	U	90 %	99 %	88 %	99 %	94 %	99 %	97 %	100 %	93 %	99 %

The reliability index β of cladding panels varies from 4.0 to 3.1 for residential buildings, from 2.5 to 0.8 for commercial and warehouse buildings, depending on the type of panels and the type of use.

The target value of the reliability index β for a building designed according to the Eurocodes with a service life of 50 years and an RC2 safety class is 3.8. Lower values of the target reliability index β are specified in ISO 13822. For buildings with an average effect class and a period of 50 years, it is 2.5.

The changes of reliability index β depending on the characteristic variable loads on the floor and depending on the span of the panels are summarized in Figs. 3.11 and 3.12.

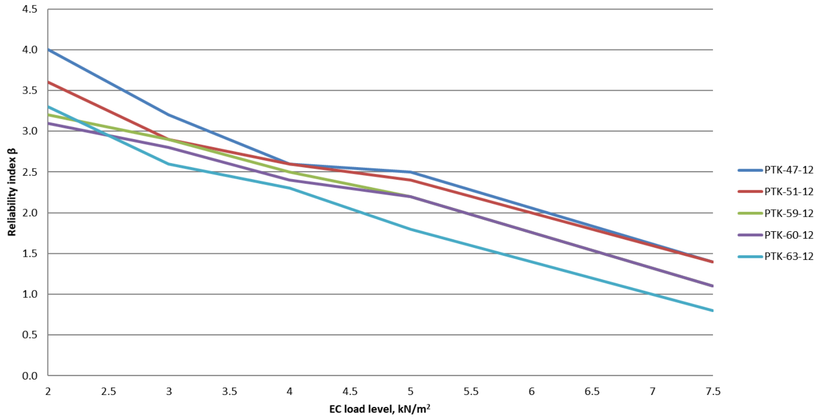


Fig. 3.11. Changes in the reliability index at 100 % load depending on the value of the characteristic variable load.

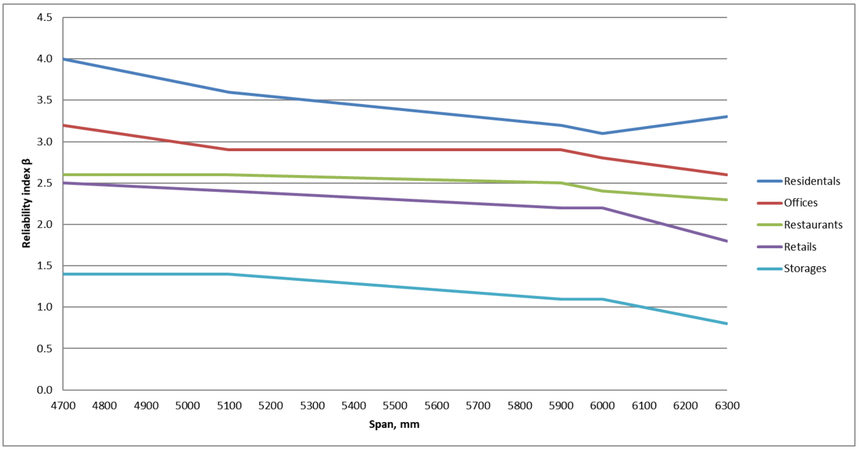


Fig. 3.12. Changes in the reliability index at 100 % load depending on the panel span.

The fractures in the graphs can be explained by the fact that, for structural reasons, it is not always possible to obtain exactly 100 % of load factor U_{100} when calculating according to the SNiP system. It can be seen that in the observed intervals the decrease of the safety index is faster with increasing variable load on the floor than with increasing panel span. Thus, it can be concluded that the differences in the calculation procedures between the considered standards have a lesser effect on the reliability of the element than the defined values of the various variable loads.

4. METHODOLOGY FOR DETERMINING THE GLOBAL RELIABILITY LEVEL OF EXISTING BUILDINGS

4.1. General information

Based on the analysis of previous studies, surveys and results, this chapter summarizes the methodology for determining the overall reliability level of existing buildings based on the implementation of a common building reliability index, thus characterizing the mechanical strength and stability of the building globally.

The methodology can be divided into 3 phases and its concept is shown in the flowchart in Fig. 4.1.

Phase 1 (Steps 1–3)

Within this phase, a general technical assessment of the building is performed visually identifying the damaged structures and providing information on the structural material, conditions of use, the nature of the structural damage, as well as the level of risk of possible collapse. Theoretical description of this phase is given in Section 3.1.

Phase 2 (Steps 4–6)

Technical investigation of building structures. Its task is to obtain objective information that is useful for future calculations. Within this stage, the structural model characterizing the building is compiled, all the limitations and assumptions on both the materials and effects side are studied, as well as the reliability indexes of the individual building structural elements are determined.

Phase 3 (Step 7)

Determining the overall reliability level of a building.

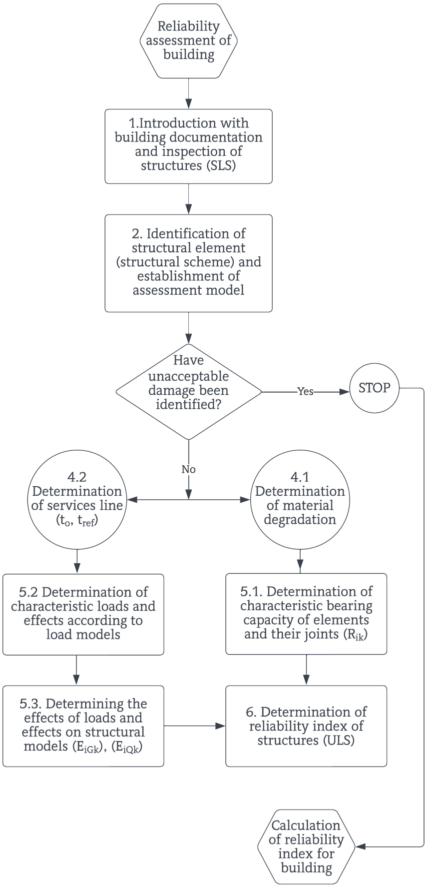


Fig. 4.1. Basic block diagram for determining the reliability level of a building.

4.2. Overall assessment of changes in the level of reliability of the building structure

After careful completion of Phases 1 and 2 and obtaining the relevant information, Phase 3 of the methodology can be started – assessing the level of reliability of the whole building.

The activities of this phase can be divided into 2 sub-phases:

- overall assessment of the level of reliability of the building structure using individual reliability indexes and impact factors of structural elements;
- analysis of recommended proposals to consider whether and to what extent improvements should be made to achieve an effective overall level of mechanical strength and stability.

4.2.1. Determining the global reliability level of a building

The methodology developed in the Thesis for the quantitative assessment of changes in the overall reliability level, which is suitable for practical implementation, evaluates the impact of the following building construction parameters and their characteristics on the reliability of the entire building:

- distribution of the components of the load-bearing structures of the building (trusses, ties, columns, slabs, etc.) by types and their individual role in ensuring the mechanical strength and stability of the overall building structure;
- possible notional part of the volume of the collapse of building in the event of an accident;
- consequences of a possible collapse.

Taking into account that the probability of collapse scenarios of individual elements and the consequences of collapse also correlate the probability and consequences of collapse of the whole building and the fact that parameter averages are objective and characterize the phenomenon as a whole, it is proposed to use the parameter (index), weighted geometric mean of the data set:

$$\left(\prod_{i=1}^{n} X_i^{w_i}\right)^{1/\sum_{i=1}^{n} w_i}, \tag{4.1}$$

where

X_i – a separate element from a set of elements;

w_i – impact factor for element X.

Replacing element X_i in a random sample with the structural component reliability index β and the element weight w with a conditional impact factor W that takes into account the effects described above, gives the equation for parameter Λ which characterizes the total mechanical strength and stability hereinafter referred to as the global reliability index of building.

$$\Lambda = \left(\prod_{i=1}^{n} \beta_i^{W_i}\right)^{1/\sum_{i=1}^{n} W_i} = e^{\frac{\sum_{i=1}^{n} W_i ln \beta_i}{\sum_{i=1}^{n} W_i}}, \tag{4.2}$$

where the data set of the reliability index (within the meaning of the Eurocode reliability concept) of a structural element or component is $\beta = \{\beta_{1,}, \beta_2 \ldots, \beta_n\}$;

$W = \{W_{1,}, W_2 \ldots, W_n\}$ is the relative impact factor of the structural element.

Depending on the purpose of the method, the calculated values of individual elements and components can be accepted or limited to maximum values equal to target reliability index β according to the building consequence class (see Tables 2.2–2.6).

Analyzing the properties of different statistical averages, it has been found that the weighted geometric mean is the most appropriate parameter to characterize this phenomenon, as it is less sensitive to outliers, is always less than the arithmetic mean and best suited for the data set, which can be arranged exponentially.

The parameter that characterizes the change in the total mechanical strength and stability of a building, regardless of the consequence class of the building, can be calculated as a relative value, hereinafter referred to as the global relative reliability index of building Λ_{GRI}:

$$\Lambda_{GRI} = \frac{CC_\beta - \Lambda}{CC_\beta} \, 100\ \%, \tag{4.3}$$

where CC_β is target reliability index β according to the consequence class of the building and Λ is global reliability index of building.

If the reliability indexes β of all individual components are equal to the target reliability index CC_β according to the building censequence class, the global reliability index of building Λ coincides with the target reliability index CC_β for the individual component, i.e. $\Lambda_{GRI} = 0\ \%$ and the global the level of reliability can be considered equal to the corresponding probability of collapse for a new structure.

According to the individual experts of structural reliability, due to human safety aspects, the reliability index β of an individual component should not be allowed to be lower than 1.5. The global reliability index Λ of building can only reach this value if the reliability indexes β of all individual components reach this value or are lower for some, which is not permissible. Thus, it is possible to define the global relative reliability index of building Λ_{GRI}, which would correspond to the emergency condition of the structure.

Other intermediate values of Λ_{GRI} can be used in practice to assess the following effects:

- mutual evaluation of the sensitivity of several types of building load-bearing structures to the risks of degradation;
- impact of different load-bearing reinforcement solutions on changes in the overall reliability level of the building;
- comparison of the levels of reliability between buildings.

The influence of each individual element in the overall reliability assessment is taken into account with the calculated component reliability index β, but the interface and importance of the element in the system, ensuring the mechanical strength and stability of the overall building structure, is taken into account with a relative impact factor *W*.

4.2.2. Notional volume method for determination of weighting factors *W*

The method for determining the relative impact factor W of a structural element or component is proposed in the Thesis, which allows to practically evaluate the individual role of the component in ensuring the mechanical strength and stability of the overall building structure. The range of values of the relative impact factor W of each element is [0; 1] and depends on the relative extent of the building collapse in the event of an accident.

As already mentioned in Section 2.5, the analysis of real structural systems is a very difficult task. The collapse rates of a single element depend directly on the structural scheme of the building as a whole (statically determinable or indeterminable structure, the element is connected to other elements in a series or parallel circuit, individual elements form components (e.g. truss, frame, etc.), scheme may be involved in different ways).

In order for the method for the assessment of changes in the overall level of reliability of the building structure to be successfully implemented in practice for real objects, a method for easier assessment of the extent of collapse has been developed.

The volume of almost all typical buildings can be relatively divided into cubes or parallelepipeds (units of volume), the dimensions of which reflect the span and/or section of the building. For multi-storey frame buildings, it is recommended to assume that the two sides of the parallelepiped are approximately equal to the smallest column step in the plan, but the height is equal to the height of the storey, if it is not twice the dimensions of the other two sides. On the other hand, in industrial buildings with a significantly smaller construction of sections in one direction, accept that all dimensions for the relative volume approximately are equal to this section. The choice of cube or parallelepiped edge size depends on the specific building.

Then the whole volume of the building was characterized by the total number of volume units:

$$V = \sum v, \tag{4.4}$$

where $v = a \cdot b \cdot c = 1$ – conditional cube or parallelepiped (unit of volume).

The number of units of volume is also estimated in the event of the collapse of the element under consideration:

$$V_i = \sum v_i, \tag{4.5}$$

where $v_i = a \cdot b \cdot c = 1$ – conditional cube or parallelepiped (unit of volume) relating to the consequences of the collapse of a given element.

The elements of the load-bearing frame of the building are divided into characteristic types (e.g. floor beams, side columns on the 1st floor, middle columns on the 1st floor, diaphragms, etc.), where in case of collapse of an individual element the same number of collapsed cubes V_i would be provisionally realized. If within the same design type significantly different individual reliability indexes β are found, then they are perceived as different types. The values of impact factors are assigned in proportion to the number of collapsed cubes, considering the collapse scenario of a representative type of element and assuming that the maximum collapse rate in the building has impact factor $W = 1$. Thus, the degradation or reinforcement of the most important structural elements for the mechanical strength and stability of the structure will have a greater impact on the global reliability assessment than the less important elements that are more numerous in the structure.

The weighting factor Wi of the individual component is then determined from relationship

$$W_i = \frac{V_i}{V} \leq 1, \tag{4.6}$$

where V_i is the estimated number of units of volume in the event of the collapse of the element under consideration and V is the notional volume of the whole building, number of units.

In order to determine the characteristic ranges of coefficient W for each building type, the conditional influence coefficients W_i of the typical building components were processed by the clustering method. K-means algorithm is used, which classifies the relevant data set using a certain number of clusters and minimizes the objective function:

$$\textstyle\sum_{k=1}^{K} \sum_{i \in W_k} \sum_{j=1}^{p} \left(x_{ij} - \bar{x}_{kj}\right)^2, \tag{4.7}$$

where W_k is a set of weighting factors in the kth cluster and $\bar{x}_{kj}$ is the *k*-th cluster center variable of the cluster.

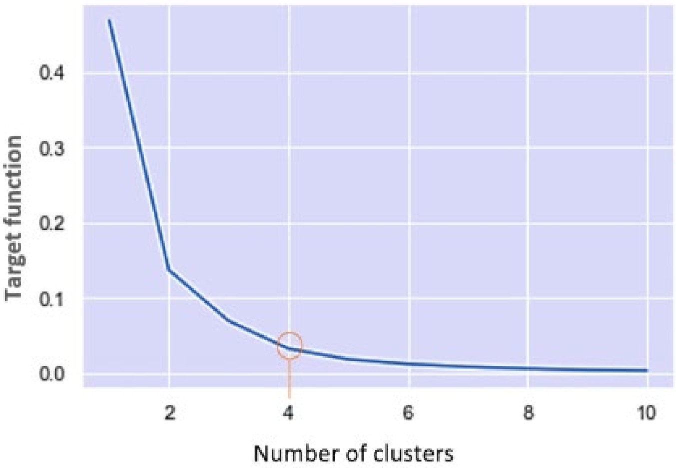


Fig. 4.2. Determining the optimal number of clusters for multi-storey frame buildings with a regular network of columns.

To find the optimal number of clusters, the “elbow method” was used, or the number of clusters at which the change in K-value becomes insignificant was found.

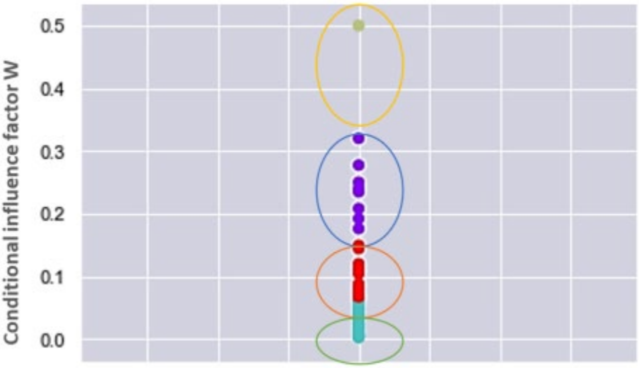


Fig. 4.3. Ranges of the conditional influence factor *W* for multi-storey frame buildings with regular column network (*K*-value = 0.032).

Table 4.1

Ranges of factor W for multi-storey frame buildings with regular column network

Location and description of impact	Possible function of the element	Example	W_i range
Element predominantly in conditional active or passive parallel connection (self-collapse or collapse of a span or two spans at the same floor level)	The element ensures overall stability of the building, participates in the transfer of horizontal and vertical loads	Perimeter ties/bars in the shortest direction of the building	0–0.06
	Element ensures the strength of other elements (in case the element has no other functions, e.g. connections)	Perimeter ties, self-supporting facade elements	
	The element absorbs basically vertical loads	Mezzanine bars, all upper floor columns, stairwells, floor slabs	
Element supporting other elements, collapse of a span or two spans at the level of several storeys (but not more than the height of the building/2) (partial collapse of the building)	The element ensures overall stability of the building, participates in the transfer of horizontal and vertical loads	Perimeter ties/bars in the longest direction of the building	0.06–0.15
	The element absorbs basically vertical loads	All columns that are not in other ranges	
Element in conditional series system (general collapse of the building or part of the building)	The element ensures overall stability of the building, participates in the transfer of horizontal and/or vertical loads	Vertical stiffness diaphragms, vertical bonding systems, stiffness cores if the part of the horizontal effects absorbed by the stiffness element in the direction in question is less than half of the total horizontal effects	0.15–0.5
	The element mainly absorbs vertical loads (VL)	All first floor columns and all columns of other floors in the building of height range/3	

Table 4.1 continued

Element in the conditional series connection for the intake of horizontal effects (general collapse of the building or part of the building)	The element ensures overall stability of the building, participates in horizontal and/or vertical loads (the proportion of horizontal effects absorbed by the stiffening element in the direction in question is at least half of the total horizontal effects)	Vertical stiffness diaphragms, vertical tie systems, stiffness cores	0.5–1

* it is recommended to calculate a more accurate value according to the "conditional volume method" proposed in the Thesis.

4.2.3. Numerical experiment and analysis of results

In order to evaluate the range and sensitivity of the global reliability index Λ under different failure scenarios of individual elements, which was taken into account by changing the reliability index β, the study performed a numerical experiment using the Monte Carlo simulation method.

The types of components that have a greater impact on the overall reliability of a building are usually fewer in number. For multi-storey frame buildings with a regular network of columns, this ratio is found in the study to be approximately 0.1: 0.4: 0.6: 1, with the former referring to significant elements and the latter to minor ones in the context of overall reliability. For example, the total stability of a building is ensured by a smaller number of elements by type than the elements that absorb local loads (slabs, facade elements, bars, stats, etc.). This ratio is included in the simulation settings, but all output data are summarized in Table 4.2.

Table 4.2

Output and conditions of numerical experiment

Variable name or condition	Value or range	Comments
Amount of simulations	15 000	The number corresponds to the case when the average value of the global reliability index Λ does not change by 2 decimal places increasing the number of simulations
Selection of the conditional impact factor Wi	Random variable range (from even distribution)	Range according to Table 4.1

Table 4.2 continued

Individual element reliability index β	Random variable in the range 0 to 3.8 of the normal distribution with a mean value of 3.8 (corresponding to the target value of class CC2 β) and a standard deviation in the range of 0.1 to 5.9	Model the element reliability level, including possible degradation
Number of building component types	Ratio 0.1: 0.4: 0.6: 1, where 1 – respectively less important elements in the context of reliability	See possible item types for a specific range, Table 4.1

Note: The maximum value of the individual reliability index β of a building component corresponds to the collapse probability $P_f = 10^{-4}$, but the lower value of the simulation corresponds to the collapse probability $P_f = 0.5$.

For a graphical representation of the results of the numerical experiment see Fig. 4.5. The global reliability index Λ calculated in the simulations is on the vertical axis, but the standard deviation of the normal distribution of the individual reliability index β is on the horizontal axis. If the standard deviation approaches 0, then all components of the building have a reliability index of at least 3.8, which corresponds to the target reliability index for a new structure. As the standard deviation increases, the number of element types with lower reliability indexes increases due to structural degradation or overload. Examples of the distribution of individual reliability indexes β are shown in Fig. 4.4.

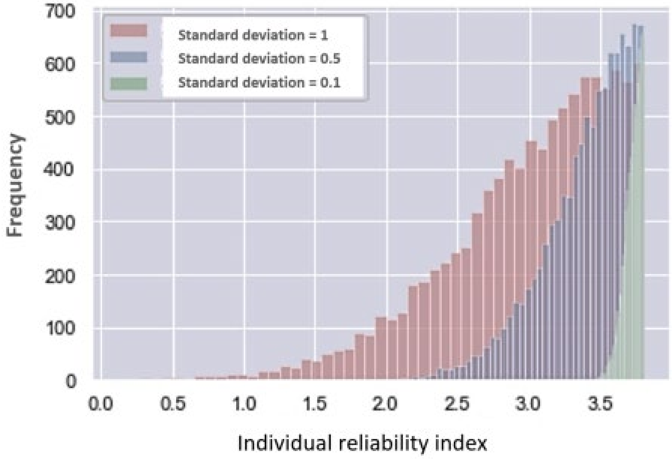


Fig. 4.4. Examples of random selection of individual reliability indexes β for simulation (n = 15000, building consequence class CC2).

In the graphical representation of results (Fig. 4.5), the upper and lower curves limit the possible range of the global reliability index for multi-storey frame buildings with a regular column network, while the middle curve is the relationship between the global value of the global reliability index Λ.

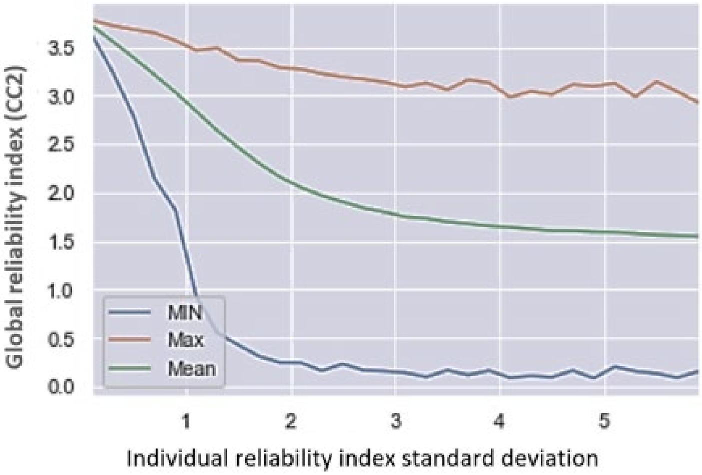


Fig. 4.5. The range of values of global reliability index Λ depending on the distribution of individual reliability levels of building elements (for multi-storey frame buildings with a regular network of columns).

The obtained results show that the value of global reliability index Λ is the most sensitive in the range of standard deviation of the normal distribution of individual reliability indexes β from 0 to 2, which coincides with possible damage distributions in real buildings. In the next chapter, where the object in nature has been assessed in accordance with the methodology developed in the Thesis, the standard deviation of the element reliability indexes falls within this range and is 0.6.

5. PRACTICAL APPLICATION OF THE BUILDING RELIABILITY ASSESSMENT METHODOLOGY (CASE STUDY)

A public building in Valmiera has been chosen as the object for which the methodology developed in the dissertation has been applied. The detailed evaluation results are available in the full version of the Thesis.

5.1. Summary of the reliability assessment of structural elements

According to the research carried out in the first and second phases of the methodology, it has been found that one of the sections of the building (see Fig. 5.1) can be used to assess the overall mechanical strength and stability of the building.

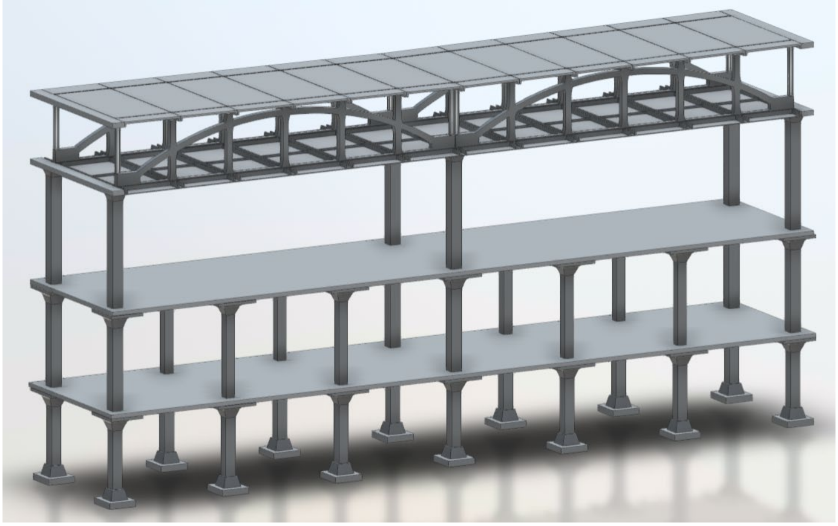


Fig. 5.1. Structural scheme of sections and frames characterizing the mechanical strength and stability of the building in 3D version.

A parallelepiped with the following dimensions is assumed as a notional unit of volume:

- side edge a = frame section = 6 m;
- side edge b = column section in the transverse direction of the frame = 6 m;
- height c = height of the first floor = 4.8 m.

The relative collapse volume of the whole frame is

$$V = 2a \cdot 6b \cdot (0.75a + 2c + 1.6c) = 52.2 \text{ units.}$$

The individual element reliability characteristics and weighting factors obtained from the respective calculations are summarized in Table 5.1. The number of elements in the table and the relative collapse volume refer to the volume at which the middle cross section collapses.

Table 5.1

Reliability characteristics and relative weight coefficients of structural elements of the building

Structural element	**No. of elelements**	**Conditional collapse volume**	**Impact factor *W***	**Reliability index β**	**Probability of collapse P_f**
Basement slabs	12	1	0.02	2.8	$2{,}6\times10^{-3}$
Basement side column	2	26.1	0.5	2.8	$2{,}6\times10^{-3}$
Basement middle column	4	7	0.13	2.8	$2{,}6\times10^{-3}$
Basement central column	1	52.2	1.00	2.8	$2{,}6\times10^{-3}$
1st floor slabs	12	1	0.02	3.6	$1{,}6\times10^{-4}$
1st floor side column	2	21.6	0.41	3.2	$6{,}9\times10^{-4}$
1st floor middle column	4	4	0,08	3.2	$6{,}9\times10^{-4}$
1st floor central column	1	43.2	0.83	3.2	$6{,}9\times10^{-4}$
2nd floor slabs	12	1	0.02	1.2	$1{,}2\times10^{-1}$
2nd floor side column	2	15.6	0.3	3.2	$6{,}9\times10^{-4}$
2nd floor central column	1	31.2	0.6	3.2	$6{,}9\times10^{-4}$
Roof slabs	24	0.5	0.01	2.8	$2{,}6\times10^{-3}$
Roof trusses	2	6	0.11	3,8*	$1{,}9\times10^{-8}$

* the designed roof trusses are designed for a step of 12 m cross-frames, therefore, according to the calculation, reliability index β = 5.5. However, one type of element with a higher level of reliability, for which the relative collapse volume is small, does not increase the level of reliability of the whole building, and further calculations assume β = 3.8 as a new element.

From the graph in Fig. 5.2 it can be seen that in buildings, the most important elements in the context of reliability are usually fewer in number. The proposed method for determining the weighting factors evaluates it.

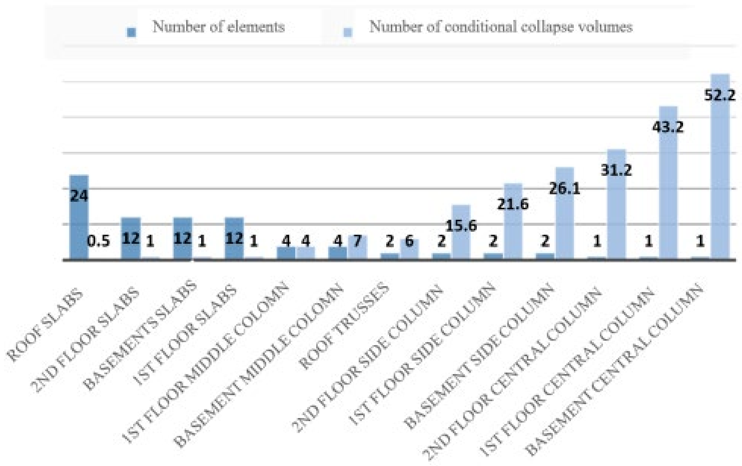


Fig. 5.2. Number of accepted representative elements and collapsed volumes in the building (refers to one collapsed cross frame).

By inserting the relevant reliability index and conditional impact factors in Expression (4.2), the global reliability index or characteristic of the mechanical strength and stability of the building is determined:

$$\Lambda = 3.03.$$

The parameter that characterizes the change in the overall mechanical strength and stability of a building is the relative reliability index of the building according to Expression (4.3):

$$\Lambda_{GRI} = \frac{CC_{\beta} - \Lambda}{CC_{\beta}} 100\% = \frac{3.8 - 3.03}{3.8} 100\ \% = 20.2\ \%,$$

where CC_{β} is target reliability index β according to the consequence class CC2 of the building and Λ is global reliability index of the building.

5.2. Calibration of building reliability results with mathematical simulation

As mentioned in the literature review in Chapter 2, the highest or 5th level assessment of the reliability (probability of collapse) of existing structural systems uses mathematical modeling methods to simulate the probability of structural collapse with the Monte Carlo method. In order to compare the results obtained in the previous chapter with the results of the mathematical modeling probability, the reliability modeling of the same Valmiera building with the Monte Carlo method is performed in this chapter using the open source program Phyton 3

5.2.1. Definition of the design system and limit states

The probability of collapse of such a structural system is predicted (see Fig. 5.3).

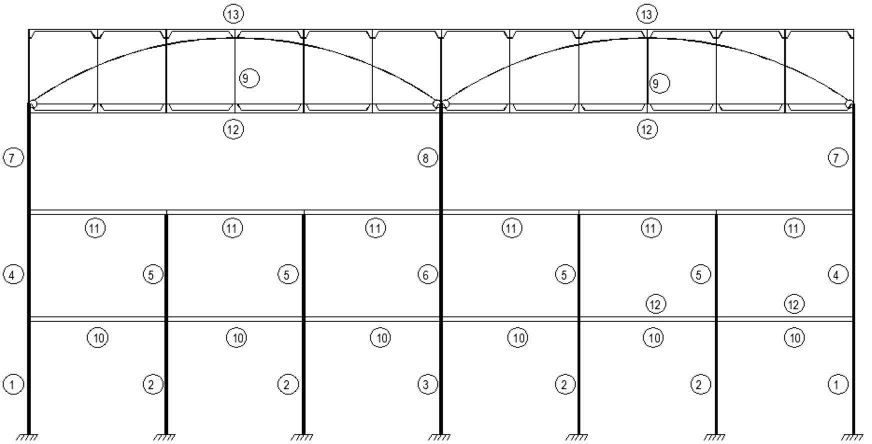


Fig. 5.3. Structural scheme of sections and frames characterizing the mechanical strength and stability of a building in 2D version.

In order to model the failures of a multi-component system, it is necessary to know the probabilities of failures of individual components. As already mentioned in the literature review, there are 2 types of construction systems – a series construction system and a parallel construction system. It is not possible to determine exactly what construction system the Valmiera building has, therefore, both possible variants are accepted. The possible scenarios for failure systems in these cases, depending on the design system, are presented in Tables 5.2 and 5.3. The left side of tables shows the element that collapses, and the right side shows the elements that collapse when the element named in the left side collapses. For example, in Table 5.2, the collapse of the 2nd floor side column (No. 7) in the parallel system will lead to the collapse of one roof truss, the collapse of six 2nd floor ceiling slabs and the collapse of six ceiling slabs.

Table 5.2

Collapse and number of elements in parallel system scenario

No.	The collapsing element	β	Related element and its number												
			1	2	3	4	5	6	7	8	9	10	11	12	13
1	Basement side column	2.8	S			1			1		1	1	1	6	6
2	Basement middle column	2.8		S			1					2	2		
3	Basement central column	2.8			S			1		1	2	2	2	12	12
4	1st floor side column	3.2				S			1		1		1	6	6
5	1st floor middle column	3.2					S						2		
6	1st floor central column	3.2						S		1	2		2	12	12
7	2nd floor side column	3.2							S		1			6	6
8	2nd floor central column	3.2								S	2			12	12
9	Roof truss	5.5									S			6	6
10	Basement slab	2.8										S			
11	1st floor slab	3.6											S		
12	2nd floor slab	1.2												S	
13	Roof slab	2.8													S

But the collapse of the same 2nd floor side column (pos. 7) in a series system will cause the collapse of one roof truss, the collapse of six 2nd floor ceiling slabs and the collapse of six ceiling slabs, as well as one side column and 2 middle columns in the basement. The collapse of the side column and 2 middle columns of the 1st floor, as well as the collapse of 3 more basement floors and three 1st floor floors. (see Table 5.3).

Table 5.3.

Collapse and number of elements in a series system scenario

No.	The collapsing element	β	Related element and its number												
			1	2	3	4	5	6	7	8	9	10	11	12	13
1	Basement side column	2.8	S	2		1	2		1		1	3	3	6	6
2	Basement middle column	2.8		S			1					2	2		
3	Basement central column	2.8	2	4	S	2	4	1	2	1	2	6	6	12	12
4	1st floor side column	3.2	1	2		S	2		1		1	3	3	6	6
5	1st floor middle column	3.2		1			S					2	2		
6	1st floor central column	3.2	2	4	1	2	4	S	2	1	2	6	6	12	12
7	2nd floor side column	3.2	1	2		1	2		S		1	3	3	6	6
8	2nd floor central column	3.2	2	4	1	2	4	1	2	S	2	6	6	12	12
9	Roof truss	5.5	1	2		1	2		1		S	3	3	6	6
10	Basement slab	2.8										S			
11	1st floor slab	3.6										1	S		
12	2nd floor slab	1.2										1	1	S	
13	Roof slab	2.8										1	1	1	S

5.2.2. First order approximation

In the currently available publications, the system of interest is not described in terms of functions of random variables and limit states. As a result, it is not possible to clearly define the correlation structure between the boundary states. Thus, the worst case scenario, or series collapse system, is currently chosen for the first-order simulations. In this case, a wider range of faults and their probability limits are predicted taking into account any possible correlation structure between certain thresholds. The system consists of individual elements, each with its own probability of collapse. Extreme limit states are defined – system conditions that correspond to a specific fault. In a string system, the limit states are given by function $\boldsymbol{g} = \{\boldsymbol{g_1}, \boldsymbol{g_2}, \ldots, \boldsymbol{g_m}\}, \boldsymbol{g_i} \in \boldsymbol{R^p}$, which are defined for the basic random variables $\boldsymbol{X} = \{\boldsymbol{X_1}, \boldsymbol{X_2}, \ldots, \boldsymbol{X_p}\}$. These random variables correspond to forces, resistances, loads, and so on. Limit states are defined as *X* values for which $\boldsymbol{g_i(X) < 0}$.

Applying Expression (2.42) for this case, we obtain the collapse probability interval ≤ $\boldsymbol{P(F)}$**:** ## [FORM] **0.020717-0.003467**

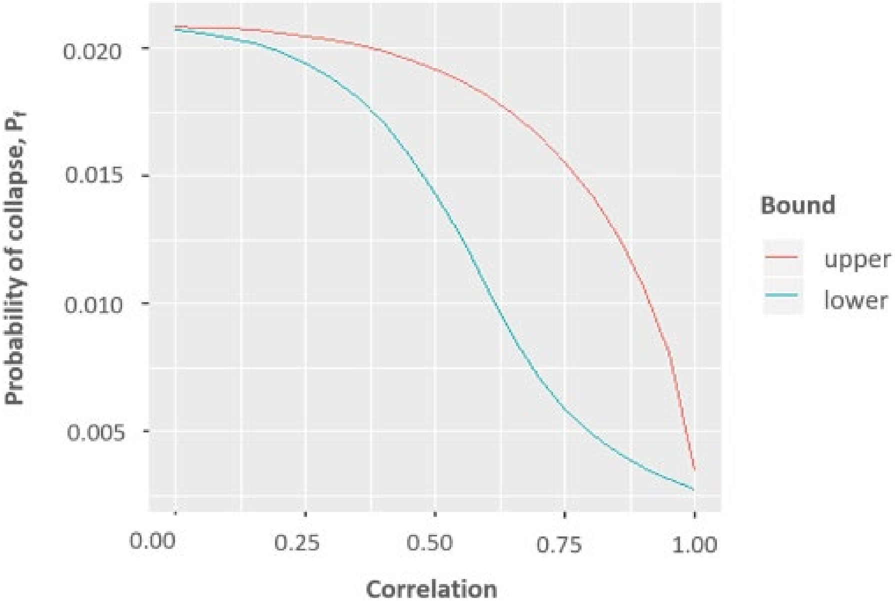


Fig. 5.4. Collapse probability limits in FORM simulation.

The probability of collapse can also be expressed in the interval of the reliability index β: ## [1] **2.039158-2.7**

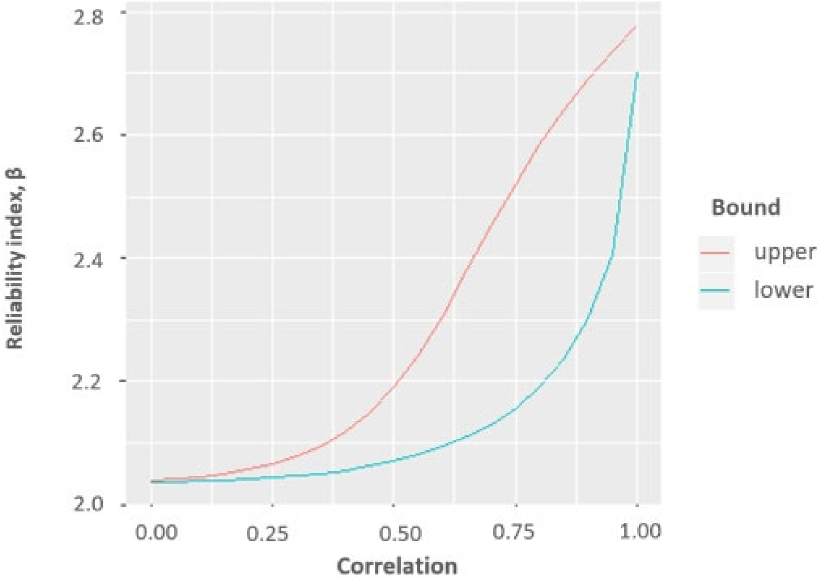


Fig. 5.5. Limits of reliability index β in the FORM simulation.

5.2.3. Second order approximation

Assuming that the construction of the Valmiera building corresponds to the system of parallel construction, we use verification with the second order approximation to determine the boundaries of the limit states. In this case, we need to calculate probabilities $P(F_i \cap F_j)$, which are found using Expression (2.41).

We obtain a 2-dimensional normal distribution function, with which we calculate the probability that both scenarios will occur simultaneously. In addition, we take into account the "events of the second order", i.e. scenario sections $\boldsymbol{P(F_i \cap F_j)}$. This can be done if the correlations between these scenarios (states) are known. As we do not have such information, the simplification goal is an accepta39e correlation coefficient $\boldsymbol{\rho_{ij}}$ in the range of 0–1, performing simulation calculations with a step of 0.05.

Applying the second order approximation Expression (SORM) (2.41), the second approximation gives the probability interval $\leq \boldsymbol{P(F)}$

[SORM] **0.002674-0.000748,**

which is also expressed in the range of reliability index **β**:

[SORM] **2.7853-3.1756.**

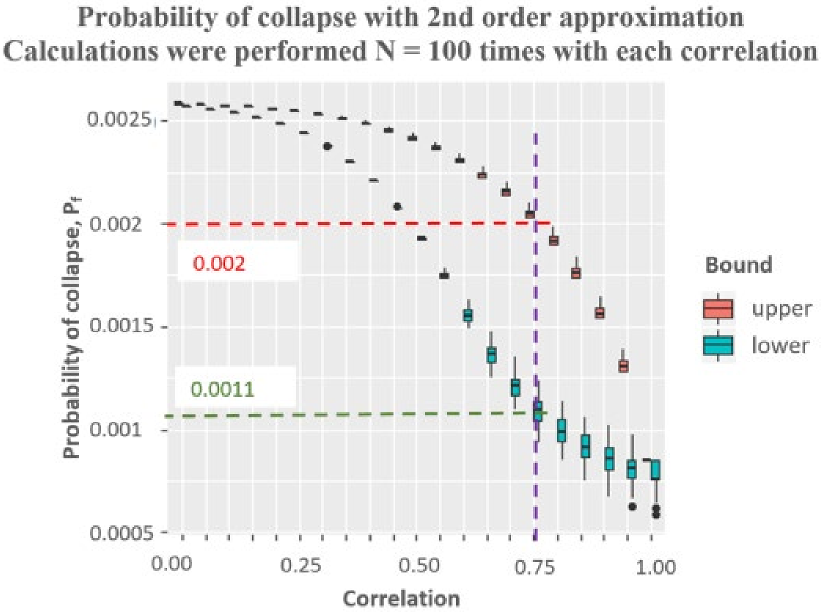


Fig. 5.6. Collapse probability limits in SORM simulation.

Viewing the correlation graphs in the second Approximation (Fig. 5.6), it can be seen that at correlation 0.75 the largest scatter between the limit states is formed.

Assuming that the correlation between the elements is known (0.75), we obtain a collapse probability interval$\leq \boldsymbol{P}(\boldsymbol{F})$

[SORM $\boldsymbol{\rho_{ij}}$ = 0.75] **0.002674-0.000748,**

which is also expressed in the range of reliability index **β**:

[SORM $\boldsymbol{\rho_{ij}}$ = 0.75] **2.8782-3.0617.**

5.2.4. Verification of results

Comparing the results obtained in the first and second order approximations with the results in 5.1 Chapter, we conclude:

(a) the reduction in the reliability level of the first-order approximation as a result of the series system collapse is between 28.95 % and 46.34 %;

(b) the reduction in the reliability level of the second-order approximations as a result of parallel system collapse is between 16.43 % and 26.7 %;

(c) knowing the correlation between structural elements as a result of parallel collapses, the reduction of the reliability level is between 19.43 % and 24.26 %.

6. RECOMMENDATIONS FOR THE PRACTICAL IMPLEMENTATION OF THE METHODOLOGY

6.1. Technical assessment of public buildings

In 2019, the requirements of regulatory enactments came into force in Latvia for public buildings which have reached 10 years since the commissioning, stating that technical assessment is required in order to verify the compliance of buildings with the requirements for mechanical strength and stability.

According to the regulatory framework, mechanical strength and stability is the 1st requirement of the essential requirements of the Construction Law, and according to the EU guidelines, this requirement means that structures must be designed and constructed so that the loads that may affect them during construction and use do not cause the following consequences:

(a) the collapse of all or part of a building;
(b) significant deformations exceeding the permissible limits;
(c) deformation of the load-bearing structure or other parts of the structure or connections or of the equipment installed;
(d) damage which is disproportionate to the cause.

At the same time, the Latvian Construction Code LBN 405 stipulates that a technical assessment shall be performed periodically during the operation of the building, but not less than once every 10 years for the second and third group public and multi-storey apartment buildings. It includes an assessment of the actual technical condition of the building's load-bearing structures throughout the building in terms of mechanical strength, stability and safety of use (falling, collision, burns, fatal electric shock, explosion injury). An assessment of the fire resistance of the actual technical condition of the building structures and their elements, as well as an assessment of the actual technical condition and operability of engineering systems important for fire safety is performed.

The mentioned norm applies also to the inspection of bridges, overpasses, tunnels and retaining walls, providing instructions that the assessment shall be performed in accordance with Standard LVS 190-11: 2009.

In order to ensure that the assessment of buildings is carried out according to uniform principles and content, a national standard should be developed for the assessment of buildings, which incorporates the method proposed in this Thesis to assess the mechanical strength and stability of building structures using a common reliability characteristic – reliability index. In the future, this will allow building users, owners, control authorities and industry specialists to compare the level of reliability of different buildings as well as to detect changes in the reliability of buildings according to the improvements made or not made.

6.2. Establishment of a single platform for technical survey data

In accordance with the requirements of regulatory enactments, the State Construction Control Bureau (BVKB) has started compiling technical surveys of all public buildings in the Construction Information System from 2020. Thus, a unified environment has been created in which, in parallel with the wishes of the legislator regarding the control of the performed assessments, the necessary national information library on structures and their technical characteristics, including reliability, can be developed.

The structured collection of such information will allow the use of this data for research by academia, industry, the legislator and other stakeholders.

It is also important to think about the possibilities of using technology to provide information on the expected level of reliability and the risks involved, namely, artificial intelligence. In order to be able to implement artificial intelligence, it needs data in a certain context in order to draw conclusions and develop (train) the users. In this context, it is recommended that data for each reliability assessment be entered into the unified Building Information System maintained by the BVKB, and that the development of an appropriate algorithm for artificial intelligence predicts both the future reliability of assessed buildings and and/or maintains similar levels of reliability under similar conditions.

7. CONCLUSIONS

Within the framework of the Thesis, a completed methodology has been developed for the quantitative assessment of the level of reliability of existing building structures. The methodology is based on the introduction of the global reliability index which assesses the technical condition of the building's load-bearing elements and their connections, their individual role in ensuring the mechanical strength and stability of the overall building structure, and the consequences of their possible collapse.

Several new methods have been developed to define the methodology:

- a method for qualitative risk classification of buildings to assess the initial condition of existing buildings;
- a method for determining the level of reliability of in-service structures designed on the basis of different regulatory bases;
- a method that characterizes the level of reliability of a building in comparison with the level of reliability specified in the Eurocodes and allows for a quantitative monitoring of the overall level of reliability of different buildings.

Within the framework of the Thesis, research has been carried out on the condition of public buildings in Latvia and the assessment practice of existing buildings in Europe.

The following conclusions have been made within the framework of the Thesis:

1. The developed qualitative risk classification method makes it possible to massively indicatively assess the technical condition of buildings based on visual assessment, as well as to promptly inform the public and control authorities about the risks related to the safety of buildings.

2. The study on the condition of public buildings in Latvia for 2016 has not found a correlation between the number of surveyed buildings in a particular category and the number of assessment results in the range 2–3 (significant deviations from reliability requirements), thus concluding that the category of technical condition of a building is influenced by the type of construction and importance of use, not the size of the data set to be processed.

3. A study of existing building assessment practices in Europe concludes that there is no common methodology for the reliability and assessment of existing buildings, but at the same time reliability is regulated as a criterion in all countries but with different assessments and interpretations of results.

4. The developed new method for finding the element reliability index β is suitable for assessing the reliability of in-service elements for specific objects, as well as for comparing the reliability levels of different building regulations systems in general, without using the labor-intensive and complex FORM simulation method. Applying the developed method, it was found that the reliability index β of the structural elements analyzed in the study for the roofing structures in operation varies from 2.5 to 2.8 in Liepaja and from 3.2 to 3.5 in Riga, depending on the stress condition. Therefore, it is recommended to pay more attention to the elements, the load of which according to the SNiP regulatory system is approaching 100 %.

There is a risk that the likelihood of such elements collapsing is not in line with today's safety requirements in Europe.

5. In the developed method for quantitative assessment of changes in the overall reliability level, the newly introduced parameters – global reliability index of buildings Λ and global relative reliability index of building Λ_{GRI} – characterize the overall reliability level of new or existing building structures and allow quantitative comparison of the overall technical condition of different buildings. Unlike the available methods based on probability theory and system theory for characterizing the overall level of reliability, the developed method is less labor-intensive and thus suitable for practical application in the engineering assessment phase of buildings. The value of the global reliability index Λ is found to be more sensitive in the range of standard deviations of the normal distribution of individual reliability indexes β from 0 to 2, which coincides with the possible distribution of damage in real buildings. For the typical industrial buildings in operation in Latvia, designed in the USSR (consequence class CC2), the distribution of the reliability levels of the elements of which is similar to the normal distribution with a standard deviation of 0.5, the obtained global reliability index may range from 2.79 to 3.68.
6. A new method for determining notional weighting factors has been developed. These factors evaluate the interface of each individual structural element and its role in the overall structural system in ensuring mechanical strength and stability. According to the developed method, the ranges of notional weight coefficients for multi-storey frame building elements in buildings with a regular network of columns are proposed. Using the static clustering method, it was concluded that the structural elements of such buildings can be divided into 4 classes.
7. The results of practical application of the methodology developed in the Thesis, describing the reliability of the existing building with the global reliability index Λ and Λ_{GRI}, compared with the results obtained from FORM and SORM simulations are verifying that the new method provides an equivalent level of reliability assessment.
7. The results of the practical application of the methodology developed in the dissertation show that the relative reliability reduction of the building in operation is $\Lambda_{GRI} = 20.2$ %. Comparing this result with the same level of reliability of the same building using FORM and SORM simulation methods, it has been verified that the proposed new method provides an equivalent level of reliability assessment. The verification results for the first approximation (FORM) show a reduction in the safety level between 28.95 % and 46.34 %, while the second approximation (SORM) shows a reduction in the level between 16.43 % and 26.7 %. Assuming a certain correlation between the structural elements, even at the highest limit state dispersion, the reduction in the reliability level in the second approximation (SORM) ranges from 19.43 % to 24.26 %.

Pēteris Druķis was born in 1971 in Riga. He obtained a Bachelor's degree in Mechanics in 1994, a Master's degree in Quality Assurance and Management in 1997, and a Professional Master's degree in Labour Protection in 2006 from Riga Technical University. Until 2014, he was the Manager of company AS "Inspecta Latvia". From 2015 to 2017 he was the Director of the State Construction Control Bureau. Since 2018, he has been working at AS RERE GRUPA leading the design activities in cooperation with Belgian and Italian partners in joint venture BERERIX implementing the reconstruction of Riga Central Station in the RailBaltica project.