Study of structural reliability of existing concrete structures

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Abstract. Structural reliability of buildings has become an important issue after the collapse of a shopping center in Riga 21.11.2013, caused the death of 54 people. The reliability of a building is the practice of designing, constructing, operating, maintaining and removing buildings in ways that ensure maintained health, ward suffered injuries or death due to use of the building. Evaluation and improvement of existing buildings is becoming more and more important. For a large part of existing buildings, the design life has been reached or will be reached in the near future. The structures of these buildings need to be reassessed in order to find out whether the safety requirements are met. The safety requirements provided by the Eurocodes are a starting point for the assessment of safety. However, it would be uneconomical to require all existing buildings and structures to comply fully with these new codes and corresponding safety levels, therefore the assessment of existing buildings differs with each design situation. This case study describes the simple and practical procedure of determination of minimal reliability index $\beta$ of existing concrete structures designed by different codes than Eurocodes and allows to reassess the actual reliability level of different structural elements of existing buildings under design load.

1. Introduction

Existing buildings in operation, if properly operated, are considered to be safe for people, even if these buildings are more than 100-year-old, or the so called heritage buildings [1]. However, due to technological progress, as well as changes in laws and regulations related to the integration in the European Union, the roles for both employees and maintenance staff regarding the use of buildings are becoming more and more strict. Existing buildings are designed according to the safety requirements of the decade they were built. However, the requirements of the respective safety level today are generally higher. New requirements have been introduced, the provision of which requires proper attention and resources from the building owner [2], and nowadays building safety requires special attention [3].

A lot of buildings depending on their time of construction in Latvia have different safety levels. Taking into consideration that users of the building expect the same level of safety, situations leading to severe accidents can occur. In Latvia there are buildings in operation, most of which were built more than 20 years ago in accordance with the Soviet building norms (SNiP) [4]. Furthermore, there are also buildings which were built before 2010 in accordance with national building norms (LBN) [5] whilst there are also buildings built during the last years already in accordance with the European Union's construction standards or Eurocodes (EC) [6].

Furthermore, the operational duration of the building is longer than life-time of any other system and equipment in the building, which means that the building solutions, their operation and safety lag behind...
up-to-date technologies. If the condition of existing buildings will not be improved in accordance with contemporary requirements and safety level, the number of accidents occurring may rise.

Taking into consideration the above-mentioned circumstances, in the Construction Law [7], Article 21, Clause 4 the Parliament of Latvia has laid down the obligation of the owner of the building to provide proper maintenance of the building and its components during the operation thereof in the condition compliant with the essential requirements defined in the Construction Law, Article 9, Clause 4. These essential requirements are identical to the basic requirements defined by the European Parliament and EU Council Regulation Nr.305/2011 [8]:

- mechanical resistance and stability;
- safety in case of fire;
- hygiene, health and the environment;
- safety and accessibility in use;
- protection against noise;
- energy economy and heat retention;
- sustainable use of natural resources.

In order to meet the above-stated requirements, the responsibility of the building owner is to make sure that:

- the building is safe for its users and building maintenance staff;
- the building is being properly maintained;
- essential risk factors are evaluated during the use of the building;
- relevant improvement measures are carried out in accordance with the results of technical surveys.

Therefore, it is extremely important for the owner of the building to get proper answers from engineers and technical auditors about the condition of existing structures [9-14]. Before the decision of refurbishment or disposal of a building not only economical or technical aspects are to be considered. An important factor due to the climate changes is sustainability [15]. That’s why there are a lot of methods worldwide used for the grading of buildings based of sustainability criteria [16]. Also, improvement of energy efficiency of buildings gives a challenge to improve the condition of existing structures [17].

This paper is in the scope of the first essential requirement for buildings - mechanical resistance and stability. There are a lot of publications worldwide about the proper manner for retrofitting existing structures [18-22]. All those publications give researches of different studies of existing structures and they have one particular issue in common – the question of what is the right safety level of existing structures or the important question of “how safe is safe enough”? [23]

Reliability index $\beta$ is associated with the probability of failure in many publications. For example, in publications [24-26], it is shown as one of the main quantifiers of the reliability and it is also the main approach to reliability concepts in the structural codes of last decades.

An important reason to assess existing structures is the existence of a doubt concerning the actual reliability of a structure and its elements. In the case of retrofitting or repairing the structure, the set of the partial safety factors (a function of the reliability index $\beta$) per current design codes should be established.

This study proposes a simple procedure to derive the reliability index $\beta$ in line with Eurocode of the existing structure that originally was designed by earlier structural design codes. This makes it possible to comparable the reliability levels of existing structures to the target values of the current design practice.

The developed procedure is applied to the case study and the reliability index $\beta$ is derived for hollow core slabs of different length in existing buildings for different intended use.
2. Materials and methods

2.1. Structural reliability in Eurocodes

Generally, it is known that the target reliability levels are calibrated to the existing practice that is proven to be satisfactory and partly introduced through the structural design codes. The most common method is the partial factor design method where partial safety factors are a function of the reliability level [27]. Eurocodes uses two safety factors performing the standard design procedures. These are safety factor for the material property $\gamma_m$ and safety factor for loads $\gamma_f$. A simple method to obtain the relevant partial factor $\gamma_f$ is to divide the design value of a variable action $Q_d$ by its representative or characteristic value $Q_k$. Similarly, could be obtained material partial factor $\gamma_R$. The normal distribution is normally used for characteristic and design values of permanent loads $G$, for material properties $R$ lognormal distribution is used, but Gumbel distribution is used for variable loads $Q$ [28] (see Table 1).

Table 1. Distributions and equations of loads.

| Value | Distribution | Equation |
|-------|--------------|----------|
| $R_k$ | Lognormal    | $\mu_R \cdot \exp(-1.645V_R)$ |
| $R_d$ | Lognormal    | $\mu_R \cdot \exp(-\alpha_R \beta_R V_R)$ |
| $G_k$ | Normal       | $\mu_G$ |
| $G_d$ | Normal       | $\mu_G (1 + 0.7 \beta_G V_G)$ |
| $Q_k$ | Gumbel       | $\mu_Q (1 - V_Q (0.45 + 0.78 \ln(-\ln(0.98))))$ |
| $Q_d$ | Gumbel       | $\mu_Q (1 - V_Q (0.45 + 0.78 \ln(-\ln(\Phi^{-1}(\alpha_Q \beta))))))$ |

In these expressions $\mu$, $\sigma$ and $V$ are, respectively, the mean value, the standard deviation and the coefficient of variation of a given variable, $\alpha$ is FORM (First Order Reliability Method) sensitivity factor and $\beta$ is reliability index, $\Phi$ is failure probability function; $\gamma$ is relevant partial factor.

2.2. Determination of reliability

For this study 5 prefabricated type hollow core slabs according to product catalog [29] are chosen. All slabs have common parameters, except length (see Figure 1 and Table 2).

Table 2. Types and main parameters of the hollow core slabs.

| Type   | Length $l$, mm | Width $a$, mm |
|--------|----------------|---------------|
| PTK-47-12 | 4660          | 1190          |
| PTK-51-12 | 5100          | 1190          |
| PTK-59-12 | 5860          | 1190          |
| PTK-60-12 | 5960          | 1190          |
| PTK-63-12 | 6260          | 1190          |

Figure 1. The geometry of the hollow core slab.
Self-weight of slabs according to data sheets is 3.00 kN/m² and other permanent loads are for this case study assumed 1.22 kN/m² [29].

Five different types of existing buildings are chosen and applied variable loads on slabs are presented in Table 3. Span interval was selected from 4.66 m to 6.26 m, based on recommended spans to 220 slab.

Table 3. Types of existing buildings and applied variable loads on slabs.

| Intended use of building | SNiP [31] Variable loads, Qk, kN/m² | Category | ECI [32] Variable loads, kN/m² |
|--------------------------|-------------------------------------|----------|---------------------|
|                          | Long terms | Short terms |          |                       |
| 1. Residential           | 1.5        | 0.3        | A        | 2.0                   |
| 2. Office                | 2.0        | 0.7        | B        | 3.0                   |
| 3. Restaurant            | 3.0        | 1.0        | D1       | 4.0                   |
| 4. Retail                | 4.0        | 1.4        | D2       | 5.0                   |
| 5. Storage               | 5.0        | -          | E1       | 7.5                   |

According to data sheets chosen slabs made from concrete B20 (relevant with concrete C15/C20 according to Eurocodes). Reinforcement bars are class A-IV [30], with resistance $R_{s,net} = f_{p,k} = 590$ MPa and Elasticity module $E_s = E_p = 190$ GPa.

In this case-study, the following coefficients of variation were used: for variable load $V_Q = 0.25$; for permanent load $V_G = 0.1$ and for material properties $V_R = 0.08$ for steel bars and $V_R = 0.17$ for concrete [31]. The sensitivity factors chosen according to ISO 2394 [32] and equal to $\alpha_Q = 0.7$ for variable load, $\alpha_G = -0.7$ for permanent load and $\alpha_R = 0.8$ for material properties.

The summary of the proposed procedure of the determination of minimal reliability index $\beta$ for structures that were designed in accordance to different structural codes than Eurocodes is presented in Figure 2.

![Figure 2. Determination procedure of minimal theoretical reliability index $\beta$ of existing structure designed by different codes than EC with utilization level 100%](image)

Before starting to determine the reliability index $\beta$ it is recommended to calculate the utilization factor $U$ (design effect / characteristic effect) of each slab according to the design codes that were valid during building construction time (SNiP system [33]).

Correspondingly it is possible for the element under consideration to determine reliability index $\beta$ by using the equations given in Table 1 when the utilization factor $U$ is near 100%. The next step it is
possible to obtain the reliability index $\beta$ using the same Eurocode procedure as before. Eurocode characteristic loads should be applied iteratively and $\beta$ could be found when the utilization factor $U$ is about 100%.

When determination of minimal reliability index $\beta$ for structures according to Figure 2 is done, there are necessary to choose based on risk assessment elements for actual inspection on site (see Fig.3) and compare results with values based on theoretical calculations.

**Figure 3.** Determination procedure of reliability index $\beta$ of existing structure.

The predetermined reliability indexes $\beta$ could be compared with target reliability indexes depending on consequence classes according to EN1990 ($\beta=3.8$ for buildings under consideration).

### 3. Results and discussion

#### 3.1. Minimal reliability index of existing structure designed by different codes than Eurocodes

For this study 25 different situation were analyzed – five different slabs for five different buildings. Table 4 presents results of the case study obtained by the simple and practical procedure developed as the result of the current research. Results are presented per element phenomena.

**Table 4.** Results of research.

|      | Residential | Office | Restaurant | Retail | Storage |
|------|-------------|--------|------------|--------|---------|
| I    | (ITK-47-12)| (ITK-51-12)| (ITK-59-12)| (ITK-60-12)| (ITK-63-12)|
| L=4.7 m | 4Ø10 SNiP EC | 4Ø10 SNiP EC | 2Ø10&2Ø12 SNiP EC | 2Ø10&2Ø12 SNiP EC | 6Ø10 SNiP EC |
| $\beta$= - 4.0 | $\beta$= - 3.6 | $\beta$= - 3.2 | $\beta$= - 3.1 | $\beta$= - 3.3 |
| $U$= 71% 100% | $U$= 84% 100% | $U$= 94% 99% | $U$= 97% 99% | $U$= 88% 100% |
| II   | 4Ø10 SNiP EC | 4Ø10 SNiP EC | 6Ø10 SNiP EC | 6Ø10 SNiP EC | 4Ø10 SNiP EC |
| $\beta$= - 3.2 | $\beta$= - 2.9 | $\beta$= - 2.9 | $\beta$= - 2.9 | $\beta$= - 2.6 |
| $U$= 82% 98% | $U$= 97% 100% | $U$= 99% 100% | $U$= 92% 100% | $U$= 97% 99% |
| III  | 4Ø10 SNiP EC | 2Ø10&2Ø12 SNiP EC | 7Ø10 SNiP EC | 7Ø10 SNiP EC | 2Ø10&4Ø12 SNiP EC |
| $\beta$= - 2.6 | $\beta$= - 2.5 | $\beta$= - 2.5 | $\beta$= - 2.4 | $\beta$= - 2.6 |
| $U$= 97% 98% | $U$= 95% 100% | $U$= 92% 98% | $U$= 95% 98% | $U$= 95% 99% |
| IV   | 2Ø10&2Ø12 SNiP EC | 2Ø10&4Ø12 SNiP EC | 2Ø10&4Ø12 SNiP EC | 2Ø10&4Ø12 SNiP EC | 9Ø10 SNiP EC |
| $\beta$= - 2.5 | $\beta$= - 2.4 | $\beta$= - 2.4 | $\beta$= - 2.4 | $\beta$= - 1.8 |
| $U$= 94% 100% | $U$= 92% 99% | $U$= 98% 100% | $U$= 98% 100% | $U$= 98% 99% |
| V    | 2Ø10&2Ø12 SNiP EC | 2Ø10&4Ø12 SNiP EC | 2Ø10&4Ø12 SNiP EC | 2Ø10&4Ø12 SNiP EC | 9Ø10 SNiP EC |
| $\beta$= - 1.4 | $\beta$= - 1.4 | $\beta$= - 1.1 | $\beta$= - 1.1 | $\beta$= - 0.8 |
| $U$= 90% 99% | $U$= 88% 99% | $U$= 94% 99% | $U$= 97% 100% | $U$= 93% 99% |
to Eurocode for a 50-year design life and 50-year reference period of variable loads for buildings with reliability class RC2 is 3.8.

3.2. Discussion
The reliability index $\beta$ of the structural elements depending on the phenomena varies in limits of 4.0 to 3.1 for residential buildings and 2.5 to 0.8 for retails and storage buildings. The lower values of target reliability index $\beta$ set in the ISO 13822 [36] for buildings with medium consequences of failure and minimum standard period for safety 50 years is 2.5. This target safety level for existing buildings varies from different aspects and will be analyzed in the next researches to look for the optimal ways to reduce it as most of the existing building elements seems to fall below the value denoted in current ISO standard [36].

![Figure 4](image1.png)

**Figure 4.** Reliability index $\beta$, depending on the load level when the cross-section is selected for $U = 100\%$.

There are some “break points” in graphs because from constructional reasons it was not possible for all slabs to achieve the utilization level by SNiP close 100%

![Figure 5](image2.png)

**Figure 5.** Reliability index $\beta$, depending on the span when the cross-section is selected for $U = 100\%$. 

It could be seen from figures 4 and 5, that by increasing the load level and span, the reliability index decrease. The decrease of reliability index $\beta$ is connected with differences in design procedures between SNiP and EC.

The target reliability index $\beta$ given in EN 1990 [28] is provided for new buildings. For the existing structure, target reliability levels can be modified in respect to the current code values assumed for new structures [37]. These modifications are still under discussion in the industry and the next researches will examine the context of geographical location and national traditions.

4. Conclusion
The developed simple and practical procedure of determination of minimal reliability index $\beta$ of existing structure designed by different codes than Eurocodes allows to assess the actual safety level of different structural elements of buildings. It is very important to Latvia, as most of the existing buildings are designed to different structural codes and actual safety level generally is unknown. Therefore, often arises the question do some parts of buildings needs to be strengthened to reach the safety level of the current design codes in force.

The case study of the existing buildings revealed that the reliability index $\beta$ and therefore safety level of elements varies between intended use of building, loads and spans. It has been discovered that the safety level of existing slabs for residential and office building has enough reliability level and if there are no serious reasons (accidents or rebuilding), there no necessary to make safety improvements.

But, it has been discovered that the safety level of existing slabs for storage and retail needs are significantly lower than recommended in relevant standards [36], which means there are necessity to reduce operational loads and to improve safety in closest future.

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