METHODOLOGY OF STRUCTURAL RELIABILITY ASSESSMENT FOR ENERGY-EFFICIENT RETROFITTING

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Keywords: structural assessment, corrosion, energy-efficient retrofitting

Abstract *Many older buildings are retrofitted with the aim to improve their energy efficiency. The most frequent intervention is based on the application of additional thermal insulation to external walls. Practical experience shows that evaluation of existing structure with regard to its capacity to withstand new conditions for a requested period of time is often underestimated or even fully neglected. The evidence of this dangerous situation is the occasional falling of concrete debris together with new layers of insulation due to steel corrosion within few years after the retrofit.*

Commonly, structural reliability assessments rely on visual inspections only. Not only visual inspections are limited by the fact that some structural elements of the building are covered by finishes, but also by the fact that early signs of deterioration and damage appear internally and cannot be detected without performing certain tests, for example to detect steel corrosion.

The methodology of structural reliability assessment developed within the framework of EU project PROFICIENT aims to provide a guideline on how to proceed before measures for energy efficiency are adopted and to prevent structural failures and its consequences.

Methodology consists of following subjects: team qualification, gathering and evaluation of existing documentation, visual inspections, full structural investigation, structural analysis, periodicity of structural assessment and reporting.

1. INTRODUCTION

Structural reliability assessment is the process to determine the ability of structures to fulfil basic requirements for construction works within a service time period according to CPR [1]. Structural assessment procedures available vary in complexity and scope with the overall purpose to determine the structural safety and serviceability of existing buildings. The most complex is the international standard [2] that is supposed to cover all kinds of constructions.

On the other hand, currently there is a growing need to improve the energy efficiency of the European building stock, most of which is composed of low energy performance buildings. The European Commission has recognized this situation and implemented policies to improve the energy use in buildings through its main policy driver, the Performance of Buildings Directive (EPBD) [3] and its recast of 2010 [4]. Amongst these provisions to be adopted by the Member States to comply with the Directives, there are energy performance requirements for buildings undergoing major renovation, but no specific request to check the structural integrity of the buildings. However, it is of utmost importance to recognize that the undertaking of energy efficiency retrofitting projects is a prime opportunity to assess the overall structural reliability of buildings.

Different circumstances can lead to the decision to perform a structural assessment of an existing building. Amongst these reasons, the following can be mentioned:

- Evident degradation of a structure (for example, appearance of cracks, fractures, deflections, etc.)
- Anticipated changes in the use or structural integrity of the building (for example, changes that affect the loadings used in the design phase)
- Planned extension on the service life of a structure
- Reliability check requested by authorities or other interested parties (for example, for seismic assessment or after accidental actions)
- Routine (periodic) checks during the life of a structure
- Evident deterioration of structures due to aggressive environment or repeated loading
- Rehabilitation of a structure (for example, implementation of energy-efficient retrofitting)

This last reason is the focus of this methodology, which aims to help Collective Self-Organised (CSO) housing projects undertake energy-efficient retrofitting projects. The EU project PROFICIENT responding to this EU-wide trend of self-organised housing processes is thus creating an environment for drafting simplified recommendations for those cases.

2. PURPOSE AND SCOPE

The purpose is to address a practical methodology to determine the structural quality of existing residential buildings before making decisions for energy-efficient retrofitting. The motivation to create such methodology is that structural integrity check is often disregarded as a precondition to energy-efficient retrofitting works. Furthermore, even when structural assessment is taken into account, it is often not systematic, and limited to the simplest visual inspection methods only. Consequences might be alarming as shown on Figure 1 when severe corrosion was neglected and concrete cover including additional thermal insulation fell down after 5 years from the application.

Figure 1. Failure of thermal insulation and concrete cover due to steel corrosion.

Given the amount of buildings in need to be retrofitted particularly in Central and Eastern Europe in the coming years, attention to structural reliability assessment methods is needed.

This methodology should give an insight on the topic of structural reliability to Collective Self-Organised (CSO) organisations planning energy-efficient retrofitting projects for housing structures, for example large panel building systems (LPS). From the structural system point of view, the methodology is applicable to concrete-based and masonry-based structures, which are the most common structural systems in the European housing stock subject to retrofitting.

3. STRUCTURAL RELIABILITY ASSESSMENT

3.1. General principles on reliability for structures

The assessment of structural reliability aims to determine whether a structure is reliable to perform safely over a service time period. For example, it can be its remaining service life.

More specifically structures shall, with appropriate degrees of reliability, fulfil the following requirements according to [5]:

- Perform adequately under all expected actions (**serviceability limit state** requirement)
- Withstand extreme and/or frequent repeated actions occurring during their construction and anticipated use (**ultimate limit state** requirement)

- Not be damaged by events like flood, land slip, fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause (**structural integrity** requirement)

Similar requirements are stated in the EU Regulation [1]. For the purpose of this Methodology of Structural Reliability Assessment, these requirements can be translated into two specific objectives: assessment of structural safety and assessment of structural serviceability.

3.2. Assessment of structural safety

According to [1] one of the basic requirements for construction works is mechanical resistance and stability. This means that structures must be designed and built to withstand the loadings that are liable to act on them, and will not lead to complete or partial collapse.

In general, safety verification in structural codes is made by assuring that the carrying capacity (R_d) is larger than the action design values (S_d), as shown in Eqn. (1):

$$S_d \leq R_d \tag{1}$$

This verification must be satisfied for ultimate limit states (ULS). These are the states associated with collapse, or with other similar forms of structural failure according to [5]:

- loss of equilibrium of the structure or parts of it as a rigid body (e.g. overturning)
- attainment of the maximum resistance capacity of sections, members or connections by rupture (in some cases affected by fatigue, corrosion, etc.) or excessive deformations
- transformation of the structure or part of it into a mechanism
- instability of the structure or part of it
- sudden change of the assumed structural system to a new system (e.g. snap through)

Structures should satisfy standards used for design. Local or regional standards could also be required. Safety regulations might vary in individual European countries due to the fact that national governments are responsible for safety.

Design of new structures should follow European standards for structural design, which that have requirements for mechanical strength, stability and safety. These Eurocodes have replaced former national building codes, while National Annexes for individual countries include particular national requirements and so called NDPs (Nationally Determined Parameters).

3.3. Assessment of structural serviceability

Besides being safe, structures are designed to fulfil a purpose in an economic way. In other words they are designed for serviceability, or the ability to serve its intended function. The design therefore can be translated into requirements associated with serviceability, such as functionality, user comfort and aesthetics. These functions are to be carried by the structure under certain loads, providing comfort, allowing unimpaired service to the occupants and equipment, etc., in summary, satisfying certain Serviceability Limit States (SLS). Serviceability Limit States are usually grouped into three main categories:

Deformation of the structure: Deflections and displacements of the structure due to deformation under service loads

Perception of motion: Floor vibrations caused by people or machinery

Deterioration of the structure: Common examples include signs of structural deterioration such as corrosion and fatigue. Other effects might be cracking, weathering, discoloration, etc.

3.4. General structural assessment procedure

As described before, although common European specifications for design of new structures are available (Eurocodes), there are no such standards for the assessment of existing structures. There are proposals to do so but the mandate has not yet been issued. However, general principles, guidelines and procedures are contained in ISO Standards [2] and [5]. Depending on the assessment scope and objectives, the general procedure to follow is shown as flowchart on Figure 2.

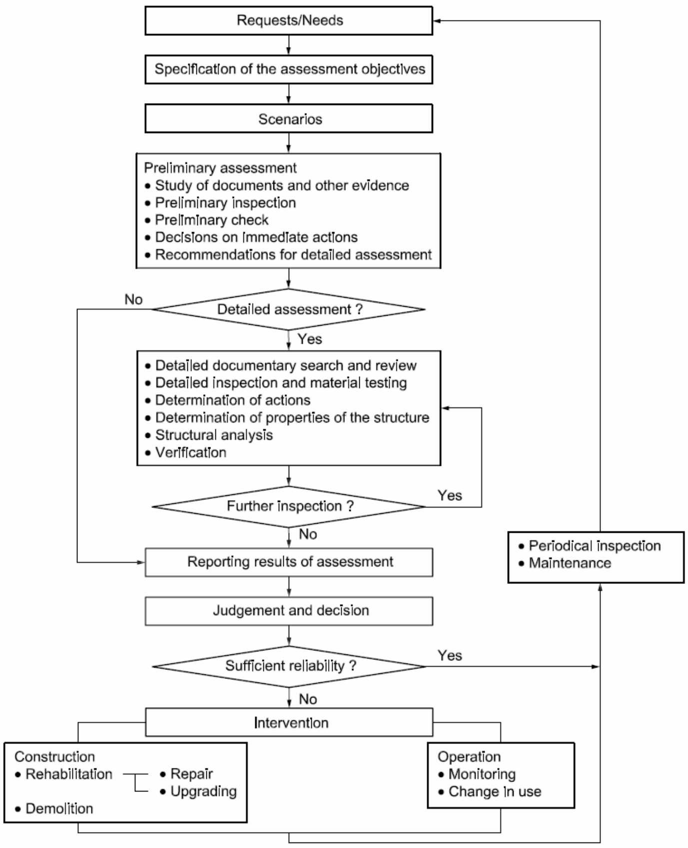

Figure 2. General structural assessment procedure [2].

3.5. Assessment levels

In literature some assessment levels have been proposed. These levels of structural assessment vary from conservative low-level methods to more complex ones. Furthermore, a hierarchical classification of these levels of assessment has been identified. The first distinction is made between “Qualitative assessment” and “Quantitative assessment” levels based on the subjectivity of the assessment. A summary of the assessment levels can be seen on Figure 3.

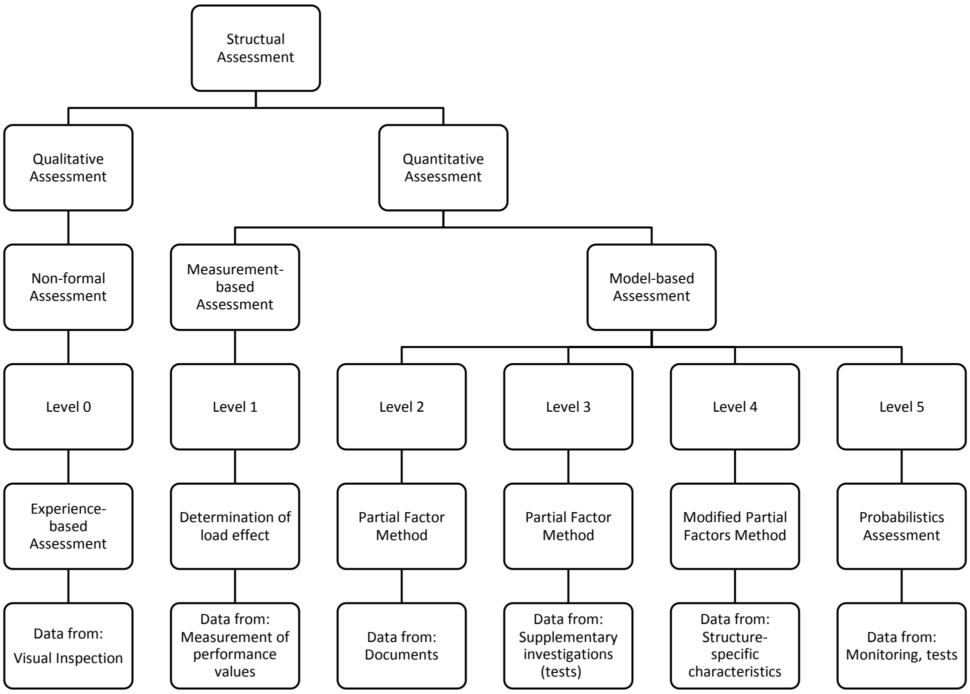

Figure 3. Structural assessment levels. Based on [6].

3.5.1. Qualitative assessment

This level of assessment relies on the experience and judgment of the assessing team. It is also referred as “non-formal assessment”, due to the subjectivity of the assessment. Visual inspection methods fall within this category.

3.5.2. Quantitative assessment

As the name suggest, this level of assessment relies on more refined methods based on numeric measurements and calculations. Two main types of methods can be distinguished based on the nature of the procedures:

Measurement-based assessment: This category covers methods that determine the serviceability of the load and/or effects on the structures by direct measurement rather than by structural analysis.

Model-based assessment: This category covers methods used to assess the serviceability that rely on model-based structural analysis, which can vary from simple methods that depend on data from documents, to more complex one that include tests and probabilistic methods.

4. VISUAL INSPECTIONS

4.1. Scope

Inspection of existing buildings is expected to be carried out with due diligence by engineers with expertise. The main scope of the inspection is to identify situations that might endanger the safety of the users. These situations can be categorized as follows:

4.1.1. Condition of the structure

Defects: Identify design errors, construction issues, defect of materials

Deterioration: Identify degradation of performance due to repetition of loadings, exposure to elements, aging of materials, wear and tear, lack of maintenance

Damage: Identify signs of loss of load-bearing capacity due to natural, deliberate or accidental events

4.1.2. Loading of the structure

Change of use: Identify deviations from the intended use that could result in overloading of the structure

4.1.3. Structural integrity

Alterations: Identify changes to structural elements or non-structural components that could affect how the structural system works.

4.2. Coverage

The coverage of the visual inspection depends on the nature of the inspection and its purpose. In practice access to 100% of the building can be difficult for many reasons, for example difficulty to access certain areas, time constraints, etc. A reduced percentage of coverage can be performed according to the judgment of the inspector, for example starting with a well-distributed sampling. However, critical structural elements (e. g. non-redundant elements) shouldn’t be left out from a full inspection.

4.3. Limitations

Visual inspections are difficult to conduct when structural elements of the building have been covered by finishes. However, engineers can request to uncover critical structural elements according to their professional judgment for further inspection. The engineer usually relies on the structural plans to identify critical points and understand how the structural system works; therefore the accuracy of the documentation is vital.

4.4. Inspection process

Before stating the inspection process the inspector should be already familiar with the structure based on existing plans and documentation. The inspection process consists of walking through the facility and observing the condition of the structure. The main activity is to identify potential structural problems and documenting the existing conditions. Any finding should be recorded and documented properly, for example taking notes of details and its location, taking pictures, drawing sketches and taking measurements. In some cases, evidence should be collected (e.g. falling material) and samples saved.

It is highly recommended to take pictures that clearly show the problem and its scale, for example taking both panoramic pictures (for orientation) and close-ups (to show detail). Placing objects as scale reference is useful if measuring devices are not available.

Note taking and sketch drawing during the walk through helps the inspector to organize the information being collected, and will serve as basis of the report.

4.5. Measuring, testing and sampling

Depending on the condition of the structure being assessed, specific details of the structure and materials might need to be collected in-situ. The purpose of this preliminary testing is to help determining the need to make a more in-depth structural assessment.

Evident signs of structural distress can be directly measured. This is the case of cracks that appear in walls. For example, width of the cracks should be measured and reported during the visual inspection including location and direction. Special attention should be paid to corrosion of reinforcement.

Physical properties of materials can also be collected using special testing equipment, for example to measure moisture content, concrete strength, rebar location, amongst other non-destructive testing techniques (NDT).

5. FULL STRUCTURAL INVESTIGATION

In special cases "full structural investigation" could be required, which might consist from some of the following steps:

a) gathering information related to design, construction, maintenance and history of the building structure;

b) assessing the structural adequacy of the building structure by checking calculations, structural plans and documentation;

c) carrying out tests on used materials of structural elements in consideration;

d) performing load tests on selected parts of the structure;

e) carrying out structural analysis based on real parameters (geometry, materials, actions, etc.).

Structural analysis should be carried out when vertical extension of the building or relevant interventions to the building structure are planned. Investigations must be performed by experienced structural engineers. Professional judgement is of very high importance.

Technical conditions of the building structures can worsen with time. Thus periodical inspections should be considered. Recommended periodicity for residential buildings is 10 years.

6. REPORTING

A structural reliability assessment report is the medium for the structural engineer to present the results from the structural survey to the client. It contains well-documented engineering opinions about the condition of the structure, based on observations, testing, analysis and professional judgment. It should clearly describe any sign of structural distress or deviation from the structure's intended use that might affect the structural reliability of the building, as well as recommendations to ensure structural integrity. To protect public safety the seriousness of any structural deterioration should be clearly judged, and remedial measures, further monitoring and investigation should be recommended. Typical outline of a structural assessment report is presented in Table 1.

Structural Reliability Assessment Report
Title page
Name of engineer and/or firm
Synopsis
Table of contents
1) Scope of the assessment
2) Description of the structure
3) Investigation
a) Examined documents
b) Inspected items
c) Sampling and testing procedures
d) Test results
4) Analysis
5) Verification
6) Discussion of evidence
7) Review of intervention options
8) Conclusions and recommendations
9) Reference documents and literature
10) Annexes

Table 1. Typical outline of a structural assessment report.

7. CONCLUSIONS

Appropriate structural performance and technical condition of load-bearing structures is of vital importance not only for building owners but for the whole society. Some recent accidents indicate that safety of building structures and their surrounding should be secured by taking appropriate measures, such as performing periodic structural reliability assessment.

This guidance for structural reliability assessment not only helps to evaluate the technical conditions of existing buildings, but also helps to identify the risks of investing into unhealthy structures. The improvement of energy efficiency of residential buildings should not be justified only from the economic point of view, but also from the structural safety and sustainability perspective.

It is of special interest for Collective Self-Organised (CSO) housing projects undertaking energy-efficient retrofitting projects to understand and address these risks.

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