Lifetime performance modelling of structures with limit state principles

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Summary

The lifetime performance modelling and the limit state approach are building an essential core of the integrated life cycle design and lifetime management, MR&R (Maintenance, Repair, and Rehabilitation) planning [1,2,3]. Performance based modelling includes the following three classes:

1. Static and dynamic (mechanical) modelling and design
2. Degradation based durability and service life modelling and design
3. Obsolescence based performance and service life modelling and design

The mechanical modelling has been traditionally developed on the limit state principles already starting in 1930`s, and introduced into common practice in 1970`s. Therefore it is not treated in this report, which is focused on durability limit state design and obsolescence limit state design.

1. Introduction

The objective of the integrated life cycle design is the optimised and controlled lifetime quality of buildings or civil infrastructures in relation to the generic requirements listed in Table 1 [4, 5]. The lifetime quality means the capability of the structures to fulfil the multiple requirements of the users, owners and society (Table 1.) in an optimised way during the entire design or planning period (usually 50 to 100 years).

Table1. Generic classified requirements of the structure [4, 5].

1. Human requirements
• functionality in use
• safety
• health
• comfort
	2. Economic requirements
	• investment economy
	• construction economy
	• lifetime economy in:
	  o operation
	  o maintenance
	  o repair
	  o rehabilitation
	  o renewal
	  o demolition
	  o recovery and reuse
	  o disposal

3. Cultural requirements • building traditions • life style • business culture • aesthetics • architectural styles and trends • imago	**4. Ecological requirements** • raw materials economy • energy economy • environmental burdens economy • waste economy • biodiversity

2. Performance based lifetime design methodology

2.1 Development of performance based modelling and limit state design

A schedule of the development of the degradation based durability modelling is presented in Fig.1.

ANALYSIS AND CREATION OF PERFORMANCE AND LOAD

1. PERFORMANCE OF MATERIALS
Physical, chemical and biological performance of materials (concrete, brick, mortar, steel, wood)
- on micro level
- on meso level
- on structural level

2. PERFORMANCE OF STRUCTURES

3. ENVIRONMENTAL LOADS OF STRUCTURES
Environmental degradation loads and their effects onto structures
- mechanical (static and dynamic) natural loads: only to be mentioned
- physical loads
- chemical loads
- biological loads

RESULT 1:
GENERIC MODELS OF LIFETIME PERFORMANCE OF STRUCTURES, INCLUDING:

1. Procedures for identifying and selecting the degrading environmental loads
2. Qualitative and quantitative classification of environmental loads
3. Selected physical, chemical and biological long term performance models of materials
4. Definitions of degradation limit states: serviceability limit states and ultimate limit states
5. Statistical and deterministic risk and reliability analysis and control
6. Lifetime performance and condition forecast in design process and in MR&R (Maintenance, Repair, Rehabilitation) planning

RESULT 2:
APPLICATIONS OF GENERIC PERFORMANCE MODELS INTO DIFFERENT MATERIALS

Concrete structures	Masonry structures	Steel structures	Wooden structures

Fig. 1. Degradation related performance modelling of structures.

A schedule of the development of the obsolescence limit state modelling is presented in Fig. 2.

ANALYSIS OF OBSOLESCENCE FACTORS

Performance of structures in relation to the obsolescence factors

Risk analysis and modelling of the obsolescence loading during the design period

GENERIC MODELS OF LIFETIME PERFORMANCE OF STRUCTURES, INCLUDING:

1. Procedures for identifying and selecting the obsolescence loading
2. Qualitative and quantitative classification of obsolescence loading
3. Selected obsolescence performance models of structures
4. Definitions of obsolescence limit states: serviceability limit states and ultimate limit states
5. Statistical and deterministic risk and analysis and control of the obsolescence
6. Lifetime performance and performance forecast in design process and in MR&R planning

Fig.2. Obsolescence related performance modelling of structures.

2.2 Principles of integrated performance based limit state design

2.2.1 Generic performance limit states

Taking into consideration all classes of limit states: mechanical (static and dynamic), durability and obsolescence limit states, we have to define these limit states first in generic terms. Using the generic definitions we are able to describe more detailed definitions and criteria of limit states in each specific case separately.

The generic durability limit states and their application in specific cases can be described with numerical models and treated with numerical methodology, which are quite analogous to the models and methodologies of the mechanical (static and dynamic) limit states design.

The limit states of obsolescence are quite different from the others, and they often can not be described in quantitative means. Often we have to apply qualitative descriptions, criteria and methods [6]. Even with these quite inexact means we can however reach a level of rational selection and decisions between the alternatives. There is still much potential to develop the methodology, models and tools into more detailed and precise level. Some generic limit state definitions are presented in Table 2.

Table2. Generic, integrated and performance based limit states.

<table>
<tr><td rowspan="2">Classes of the limit states</td><td colspan="3">Limit states</td></tr>
<tr><td>Mechanical (static and dynamic) limit states</td><td>Degradation limit states</td><td>Obsolescence limit states</td></tr>
<tr><td>I. Serviceability limit states</td><td>1. Deflection limit state
2. Cracking limit state</td><td>3. Surface faults causing aesthetic harm (colour faults, pollution, splitting, minor spalling)
4. Surface faults causing reduced service life (cracking, major spalling, major splitting)
5. Carbonation of the concrete cover (grade 1: one third of the cover carbonated, grade 2: half of the cover carbonated, grade3: entire cover carbonated)</td><td>6. Reduced usability and functionality, but still usable
7. The safety level does not allow the requested increased loads
8. Reduced healthy, but still usable
9. Reduced comfort, but still usable</td></tr>
<tr><td>II. Ultimate limit states</td><td>1. Insufficient safety against failure under loading</td><td>2. Insufficient safety due to degradation:
• heavy spalling
• heavy cracking causing insufficient anchorage of reinforcement
• corrosion of the reinforcement causing insufficient safety.</td><td>Serious obsolescence causing total loss of usability through loss of
• functionality in use (use of building, traffic transmittance of a road or bridge etc.)
• safety of use
• health
• comfort
• economy in use
• maintenance costs
• ecology
• cultural acceptance</td></tr>
</table>

2.4.2 Classes of integrated limit state models and design

In order to understand the analogy between the mechanical, durability and obsolescence performance modelling and design, these methodologies can be compared as presented in Table 3.

Table 3. Comparison of static and dynamic (mechanical) limit state method, the degradation limit state method and obsolescence limit state

Mechanical limit state design	Degradation limit state design	Obsolescency limit state design
1. Strength class 2. Target strength 3. Characteristic strength (5 % fractile) 4. Design strength 5. Partial safety factors of materials strength 6. Static or dynamic loading onto structure 7. Partial safety factors of static loads 8. Service limit state (SLS) and ultimate limit state (ULS)	1. Service life class 2. Target service life 3. Characteristic service life (5% fractile) 4. Design life 5. Partial safety factors of service life 6. Environmental degradating loads onto structure 7. Partial safety factors of environmental loads 8. Serviceability and ultimate limit states, related to the basic requirements: Human requirements, lifetime economy, cultural aspects and lifetime ecology	1. Service life class 2. Target service life 3. Characteristic service life (5%fractile) 4. Design life 5. (Partial safety factors of service life) 6. Obsolescence loading onto structure 7. Partial safety factors of obsolescence loading 8. Serviceability and ultimate limit states related to obsolescence in relation to the basic requirements: Human requirements, lifetime economy, cultural aspects and lifetime ecology

3. Integrated limit state design

3.1 Static and dynamic (mechanical) limit state design

The static and dynamic (mechanical) limit state design is widely used since 1970s, and applied in most of the current national and international design codes. There is no need to describe it more in this occasion.

3.2 Durability based service life limit state design

The simplest mathematical model for describing the 'failure' event comprises a load effect *S* and a resistance *R*. In principle the variables *S* and *R* can be any quantities and expressed in any units. The only requirement is that they are commensurable. Thus, for example, *S* can be a weathering effect and R can be the capability of the surface to resist the weathering effect without unacceptably large visual damage or loss of the reinforcement concrete cover. Either the resistance *R* or the load *S* or both can be time-dependent quantities. Thus the failure probability is also a time dependent quantity. Considering $R(t)$ and $S(t)$ are instantaneous physical values of the resistance and the load at the moment t the failure probability in a lifetime *t* could be defined as [4]:

$$P_f(t) = P\{R(t)<S(t)\} \text{ for all } t \leq t \qquad (1)$$

The design service life is determined by formula [4,1]:

$$t_d = t_k ?_t = t_g \qquad (2)$$

where t_d is the design service life,

t_k the characteristic service life

$?_t$ the lifetime safety factor, and

t_g the target service life.

The durability design procedure is as follows [1,4,5]:

1. specifying the target service life and design service life
2. analysing environmental loads onto structures
3. identifying durability factors and degradation mechanisms
4. selecting a durability calculation model for each degradation mechanism
5. calculating durability parameters using available calculation models
6. possible updating the calculations of the ordinary mechanical design (e.g. own weight of structures)
7. transferring the durability parameters into the final design

Durability limit state design has been first applied as a service life safety factor method in 1996 [4] and degradation modelling especially for concrete structures has been presented during several decades in numerous models [4]. The six degradation mechanisms of Table 3. are treated.

Table3. Degradation models treated in durability limit state design [(4].

1 corrosion due to chloride penetration	2 corrosion due to carbonation
3 mechanical abrasion	4 salt weathering
5 surface deterioration	6 frost attack

3.3 Obsolescence limit state design

Obsolescence means the inability to satisfy changing functional (human), economic, cultural or ecological requirements. Obsolescence can affect to the entire building or civil infrastructural facility, or just some of its modules or components. Obsolescence is the cause of demolition of buildings or infrastructures in about 50% of all demolition cases. In the case of modules or component renewals the share of obsolescence is still higher. Some examples of the obsolescence are as follows [3]:

- Functional obsolescence is due to changes in functions and use of the building or its modules. This can even be when the location of the building becomes unsuitable. More common are changes in use which require changes in functional spaces or building services systems. This rises need for flexible structural systems, usually requiring long spans and minimum numbers of vertical load bearing structures. Partition walls and building services systems which are easy to change are also required.
- Technological obsolescence is typical for building service systems, but also the structure can be a cause when new products providing better performance become available. Typical examples are more efficient heating and ventilation systems and their control systems, new information and communication systems such as computer networks, better sound and impact insulation for floorings, and more accurate and efficient thermal insulation of windows or walls. Health and comfort of internal climate is the requirement which is increased in importance. The risk of technological obsolescence can be avoided or reduced by estimating future technical development when selecting products. The effects of technical obsolescence can also be reduced through proper design of structural and building service systems to allow easy change, renewal and recycling.
- Economic obsolescence means that operation and maintenance costs are too high in comparison to new systems and products. This can partly be avoided in design by minimising the lifetime costs by selecting materials, structures and equipment which need minimum costs for maintenance and operation. Often this means simple and safe products which are not sensitive to defects and or their effects. For example, monolith external walls are safer than layered walls.
- Cultural obsolescence is related to the local cultural traditions, ways of living and working, aesthetic and architectural styles and trends, and imago of the owners and users.

- Ecological obsolescence happens often in a case of large infrastructural projects. In large projects this is often related to high waste and pollution production or loss of biodiversity. In case of buildings we can foresee in the future problems especially in the use of heating and cooling energy, because heating and cooling is producing for example in Northern and Central Europe about 80 to 90 % of all CO_2 pollution and acid substances into air. From the viewpoint of technical potential and lifetime economy there is a clear chance to reduce the consumption of the heating energy into 1/3 ... 1/5 from the current standard level.

For each proposed alternative of design or MR&R solution, the following obsolescence procedure will be made:

1. identifying the relevant obsolescence factors
2. analysing relevant obsolescence limit states
3. selecting evaluation methods for the relevant potential obsolescence cases
4. evaluating the characteristic service life against the actual modes of the obsolescence
5. evaluating the required lifetime safety factors for each mode of obsolescence
6. listing the modes of the obsolescence, and the corresponding values of the design service life
7. moving the results into the general design or MR&R planning procedure

The methods of obsolescence design are currently not yet developed in details. Several of the general methods of lifetime design and MR&R planning, for example risk analysis, Quality Function Deployment (QFD) method and Multi Attribute Decision Aid (MADA) can be applied for obsolescence design [1,2].

4. Conclusions

The lifetime oriented and predictive design and MR&R (Maintenance, Repair and Rehabilitation) planning can be based on lifetime performance principle, applying theory of mechanical (static and dynamic), durability (degradation) and obsolescence limit states. The mechanical limit state design is the traditional basic methodology for designing the new structures to fulfil the generic requirements of safety and serviceability. Durability limit state design is aiming to guarantee the long term serviceability and safety towards human requirements, economy, cultural aspects and ecology. The obsolescence limit state design is aiming to guarantee the ability of the buildings and civil infrastructures to have an ability to meet all current and changing requirements with minor changes of the facilities, thus avoiding the need of early renewal or demolition.

5. References

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