Life Cycle Assessment of Concrete Structures

Asko Sarja
Innokas Consulting, Commandite Company, Espoo, Finland

Abstract
A new paradigm of building and civil engineering for the concretization of sustainable building is called “Lifetime Engineering”, which means a theory and practice of predictive and optimising management of the lifetime quality of assets. The lifetime quality is the capability of the asset to fulfil the requirements of users, owners and society over its entire service life during the planning period (usually 50 to 100 years). The generic requirements of the asset are arising from human usability, economy, culture and ecology.

The process of Lifetime Engineering includes:
1. Lifetime investment planning and decision-making
2. Integrated lifetime design
3. Lifetime Procurement and Contracting
4. Lifetime management of the operation, maintenance, repair, rehabilitation, modernisation
5. End of Life management: Reuse, recovery, recycling and disposal.

Concrete as the dominant construction material plays a central role in the development of sustainable building. Most important properties of concrete are the adjustable resistance, durability, fire resistance and sound insulation as well as a highly adjustable materials composition for example to thermal insulation. Concrete is an ingenious material for different material modifications and structural designs, which can be utilised in the design and management of very different build assets. Advanced mechanical and durability design and optimisation methods are needed for effective use of these possibilities. The structural system must be flexible in order to avoid obsolescence of the assets. The area of “End of Life Management” is a new focus area of development of both concrete materials and structures.

Keywords: Life cycle quality, usability, durability, reuse, recovery, recycling.
Introduction

The challenge of the present generation is to lead the rapid development of a global economy towards a sustainable line in relation to the entire society, economy, social welfare and ecology. Beside the new production of the assets also a major share of the existing traffic infrastructure like bridges, harbours, roads, airports, terminals, tunnels etc. is getting old, and the question of service life, renovation and retrofitting is becoming increasingly acute. The old building stock needs increasingly renovation, repair and modernisation. Concrete as a dominant building material has an important role both in new construction and in renovation. During last decades there have been a lot of discussion on principles and goals of sustainable construction and sustainable build environment. Now it is time to build the real technical content for the sustainable building changing the entire paradigm of building and civil engineering.

Lifetime Engineering as Concretization of Sustainable Building

Methodology

The lifetime engineering methodology is aiming at active control and optimising the life cycle quality of build assets. This is the difference to the more passive traditional methodologies of Life Cycle Analysis (LCA) and Life Cycle Assessment. The term "Lifetime Engineering" can be defined as a theory and practice of predictive and optimising management of the lifetime quality of assets. The lifetime quality is the capability of the asset to fulfil the requirements of users, owners and society over its entire service life, which means in the practice the planning period (usually 50 to 100 years). The lifetime quality of build assets can be described in relation to the generic requirements arising from requirements of human usability, economy, culture and ecology (table 1) (Sarja 2010, 2007a, 2007b, 2006, 2005b, 2004a, 2004b, 2002a).

Table 1 Generic lifetime quality requirements of build assets (Sarja 2010, 2006, 2005b, 2002a).

<table>
<thead>
<tr>
<th>1. Human requirements</th>
<th>2. Economic requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>functionality in use</td>
<td>investment economy</td>
</tr>
<tr>
<td>safety</td>
<td>construction economy</td>
</tr>
<tr>
<td>health</td>
<td>lifetime economy in:</td>
</tr>
<tr>
<td>comfort</td>
<td>operation</td>
</tr>
<tr>
<td></td>
<td>maintenance</td>
</tr>
<tr>
<td></td>
<td>repair</td>
</tr>
<tr>
<td></td>
<td>rehabilitation</td>
</tr>
<tr>
<td></td>
<td>renewal</td>
</tr>
<tr>
<td></td>
<td>demolition</td>
</tr>
<tr>
<td></td>
<td>recovery and reuse</td>
</tr>
<tr>
<td></td>
<td>recycling of materials</td>
</tr>
<tr>
<td></td>
<td>disposal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Cultural requirements</th>
<th>4. Ecological requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>building traditions</td>
<td>raw materials economy</td>
</tr>
<tr>
<td>life style</td>
<td>energy economy</td>
</tr>
<tr>
<td>business culture</td>
<td>environmental burdens economy</td>
</tr>
<tr>
<td>aesthetics</td>
<td>waste economy</td>
</tr>
<tr>
<td>architectural styles and trends</td>
<td>biodiversity and</td>
</tr>
<tr>
<td>imago</td>
<td>geodiversity</td>
</tr>
</tbody>
</table>
Process

The process of Lifetime Engineering (figure 1) includes:
1. Lifetime investment planning and decision-making
2. Integrated lifetime design
3. Lifetime Procurement and Contracting
4. Integrated lifetime construction, management in operation, maintenance, repair, rehabilitation and modernisation (MRR&M)
5. End of Life management: Recovery, reuse, recycling and disposal

![Figure 1 Linear process schedule of the lifecycle engineering of build assets (RIL 2012).](image)

Lifetime investment planning and decision-making is a basic issue in starting the construction, but also in lifetime asset management. Generally the investment planning and decision making is used in evaluating project alternatives, either in planning of a construction project or in MRR&M planning. The procedure includes consideration of characteristics or attributes which decision makers regard as important, but which are not readily expressed in monetary terms. Examples of such attributes in case of buildings are: location, accessibility, site security, maintainability, and imago.

Integrated lifetime design includes a framework, a description of the design process and its phases, special lifetime design methods with regard to different aspects: human usability, economy, cultural compatibility and ecology. These aspects will be treated with parameters of technical performance and economy, in harmony with cultural and social requirements, and with relevant calculation models and methods (Kelly and Male 1996, Sarja 2004a, 2004b, 2002a).


End of life management: Recovery, reuse, recycling and disposal is the last phase of the life cycles, including the selective demolition, recovery and reuse of components and modules, recycling of materials, and wasting of non-usable modules, components and materials (Schultmann in Sarja 2006).
**Energy Economy**

About 80% of the energy of the buildings is consumed during the operation phase (figure 2). Therefore the implementation of low energy and nearly zero energy building concepts and products is utmost important.

In case of the civil infrastructures the share of construction phase, construction materials production, demolition and end-of-life management is higher and the share of operation phase is lower than in case of buildings.

The production of cement is a globally a big consumer of energy, building about 5% of the global energy consumption as well as CO2 production. This can be reduced especially with the use of by-products like blast-furnace slag and wastes like fly ash in concrete. Utmost important is to utilise and guarantee the long service life of concrete structures.

![Figure 2 Energy consumption at different phases of the life cycle (World Business Council 2010).](image)

**Methods, Codes and Standards for Sustainable Building**

**Life Cycle Analysis (LCA)**

Ecological Assessment methods for Life Cycle Analysis have been developed as the first step towards Sustainable Building mainly in 1990’s (Abu Sa’deh and Luscuere (2000)).

The family of ISO 14000 standards include *Environmental Product Declarations, EPDs*, to support Life Cycle Analysis, LCA. A complete and up-to-date set of EPDs is a key-enabler for environmental design.

**Directives, Codes and Standards of European Union EU**

A number of EU Directives and member States legislations concern directly and indirectly sustainability issues related to construction assets, the construction activity itself or the construction product industry, in particular the Building Energy Performance. Central directives are for example:

- Directive (2002/91),
- Directive (98/83/EC), the Construction Product
- Directive (89/106/EC), the Equal Treatment in Employment and Occupation Directive (78/2000/EC), etc.
To safeguard the direct public interest in building products, and thus buildings, the EU Construction Product Directive (EU, 1988) specifies six essential requirements:

1. Mechanical resistance and stability.
2. Safety in case of fire.
3. Hygiene, health and the environment.
4. Safety in use.
5. Protection against noise.

The framework Directive for the European Product Directives provides a basis for establishing minimum eco-design requirements for energy using products (Öberg 2005). The aim of this Directive is to reduce the environmental impact of these products, contributing to sustainable development and ensuring the free movement of products in the EU (figure 3).

EPBD has significantly raised awareness of the issue of energy performance of buildings amongst stakeholders, and that it has indirectly led to the introduction of some new national legislation that goes beyond the requirements of the Directive. Implementation is also thought to have raised the numbers and skills of inspectors and to have led to development or wider usage of appropriate software tools for the application of the of minimum energy performance requirements that are also ‘cost-optimal’ (figure 4).

**Figure 3 European codes and standards of sustainable building (CEN/TC350 2012).**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Building level</td>
<td>Framework for Methods of Assessment of Environmental Performance (ISO 21937-1)</td>
<td>pEN 16309 Assessment of Social Performance (WG8)</td>
<td>Assessment of Economic Performance (WG9)</td>
<td>Service Life Planning - General Principles (ISO 15686-1)</td>
</tr>
<tr>
<td>Product level</td>
<td>(see Note below)</td>
<td>(see Note below)</td>
<td>(see Note below)</td>
<td>CEN Standards on Energy Performance of Buildings Directive (EPBD)</td>
</tr>
</tbody>
</table>

*Note: At present, technical information related to some aspects of social and economic performance are included under the provisions of EN 15504 to form part of EoP.*
Life cycle oriented maintenance and facility management

Process Model

The life cycle maintenance planning and management includes all generic sustainability aspects: life cycle performance and usability, life cycle monetary economy, life cycle economy of nature (ecology) and cultural aspects (Sarja 2006). These indicators can be modelled and optimised applying the same basic methods as presented in the description of the life cycle design methods (Sarja 2002a). Future long-term maintenance, repair and renewal plans can be optimised by applying the multiple requirements optimisation and decision-making procedure (figure 5, figure 6).

Figure 5 Scheme of a life cycle oriented facility maintenance and management system.
Dictating Quality Requirements of the Assets and Materials

For the life cycle management of buildings, the compatibility and easy changeability between load-bearing structures, partition structures and building service systems is important. The energy efficiency of the building is a dictating factor regarding the lifetime ecology of buildings. Envelope structures are responsible for most of the energy consumption, and therefore the envelope must be durable and have an effective thermal insulation and safe static and hydro-thermal behaviour. The internal walls have a more moderate length of service life length, but they have the requirement of coping with relatively high degrees of change, and must therefore possess good changeability and re-usability. In the production phase it is important to ensure the effective recycling of the production wastes in factories and on site. Finally, the requirement is to recycle the components and materials after demolition. Obsolescence of buildings is either technical or functional, sometimes even aesthetic in nature. Technical and functional obsolescence is usually related to the primary life time quality factors of structures. Aesthetic obsolescence is usually architectural in nature (Sarja 1999, 2000, 2002a, 2004b, Öberg 2005).

Civil engineering structures like harbours, bridges, dams, off shore structures, towers, cooling towers etc. are often very massive and their target service life is long. Their repair works under use are difficult. Therefore their life cycle quality is tied to high durability and easy maintainability during use, saving of materials and selection of environmentally friendly raw materials, minimising and recycling of construction wastes, and finally recycling of the materials and components after demolition. Some parts of the civil engineering structures like waterproof membranes and railings have a short or moderate service life and therefore the aspects of easy re-assembly and recycling are most important. Technical or performance related to obsolescence is the dominant reason for demolition of civil engineering structures, which raise the need for careful planning of the whole
civil engineering system, e.g. the traffic system, and for selection of relevant and future oriented design criteria (Sarja 2006, 2000).

**User’s Manual**

The user's manual will be produced gradually during the design process in co-operation with the partners in design, manufacture and construction. Ordinary tasks of the structural designer are:

- Collating a list of maintenance tasks for the structural system
- Collating and applying instructions for the operation, control and maintenance procedures and works
- Checking and co-ordination of operation, control and maintenance instructions for product suppliers and contractors
- Preparing the relevant chapters for the user’s guidebook
- Checking relevant parts of the final user’s guidebook

**Demolition for Recycling and Re-use**

Most of the wastes in the construction sector, up to 80 %, are produced in renovation and demolition, only about 20 % come from the construction of new facilities. The dominant waste materials are earth, concrete, masonry, gypsum and wood. The active reduction of wastes in renovation and demolition is possible through the selective dismantling for recycling of structural systems, components and materials. Selective dismantling includes the detailed planning of dismantling phases, optimising the work sequences and logistics of the dismantling and selection process. The main goal is to separate the different fractions of materials and different types of components at the demolition phase in order to avoid multiple actions (Schultmann 1999, Schultmann in Sarja 2006).

**Sustainability with Concrete**

**Materials Technology**

There are a lot of new advanced concrete materials, which are already in use or at the phase of implementation into practice. As examples, self compacting concretes, fibre reinforced concretes, thermal insulating lightweight concretes and composites of recovery materials and by products. Besides the ordinary reinforcements also fibre reinforced plastic reinforcements, high strength steel reinforcements and stainless steel reinforcements and fasteners can be mentioned. Related to the strength, high strength concrete (compressive strength 80-110 Mpa), extra high strength concrete (compressive strength 120-190 MPA) and ultra high strength concrete (compressive strength 200-400 MPA) have been developed and even used in special cases and strengthening of structures.

Often a combination of two or several innovations can lead to success. This may lead into combination of materials as composite materials or composite structures. Often the structural solution and even the entire structural system together with production technique has to be changed.
in order to achieve the potential benefits of new materials. As an example, the use of ultra-high strength concrete can change structures towards the shape of steel structures.

**Methods for Lifetime Design of Concrete Structures**

*Reliability Criteria*

In the integrated lifetime design are needed calculation methods for three types of generalised limit states, which are (Sarja 2010, 2005a, 2005b, 2004, 2003):
- Mechanical limit states under static and dynamic loads
- Durability limit states under physical, chemical and biological loads
- Usability limit states under obsolescence loads (changes of use or requirements)

There is an analogy between the terms and parameters of mechanical design against static and dynamic loads, durability design against degradation, but the variables and degrading models of durability are different from the models and variables of static and dynamic design (table 2). The durability design can be carried out with the same kind of statistically based deterministic safety factor methods as mechanical design (EN 1990 2002, ISO 15686-1 2000).

Table 2 Generic mechanical, degradation and obsolescence limit states of concrete structures Sarja 2010).

<table>
<thead>
<tr>
<th>Classes of the limit states</th>
<th>Limit states</th>
<th>Limit states</th>
<th>Limit states</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Serviceability limit states</td>
<td>Mechanical limit states</td>
<td>Degradation limit states</td>
<td>Obsolescence limit states</td>
</tr>
<tr>
<td>1. Deflection limit state</td>
<td>1. Surface faults causing aesthetic harm (colour faults, pollution, splitting, minor spalling)</td>
<td>1. Reduced usability and functionality, but still usable</td>
<td></td>
</tr>
<tr>
<td>2. Cracking limit state</td>
<td>2. Surface faults causing reduced service life (cracking, major spalling, major splitting)</td>
<td>2. The safety level does not allow the requested increased loads</td>
<td></td>
</tr>
<tr>
<td>3. Carbonation of the concrete cover (grade 1: one third of the cover carbonated, grade 2: half of the cover carbonated, grade 3: entire cover carbonated)</td>
<td>3. Reduced healthy, but still usable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Reduced comfort, but still usable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Ultimate limit states Insufficient safety against failure under loading</td>
<td>Insufficient safety due to indirect effects of 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 safety of use health comfort economy in use MR&amp;R costs ecology cultural acceptance</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Descriptions of generic limit states of concrete structures (Sarja 2010).

<table>
<thead>
<tr>
<th>Classes of the limit states</th>
<th>Limit states</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mechanical limit states under static and dynamic loads</td>
</tr>
<tr>
<td></td>
<td>Durability limit states under physical, chemical and biological degrading loads</td>
</tr>
<tr>
<td></td>
<td>Usability limit states under loads causing obsolescence through changes of use and requirements</td>
</tr>
</tbody>
</table>

1. Serviceability limit states

1. Deflection limit state
2. Cracking limit state

1. Carbonation or penetration of salts or chemicals in concrete cover (grade 1.1: in one third of the cover, grade 1.2: in half of the cover, grade 1.3: in entire cover)
2. Surface faults causing aesthetic harm (colour faults, pollution, splitting, minor spalling)
3. Surface faults causing reduced service life (cracking, major spalling, major splitting)

Reduced usability and functionality, but still usable
- The safety level does not allow the requested increased loads
- Reduced healthy, but still usable
- Reduced comfort, but still usable

2. Ultimate limit states

Insufficient safety against failure under loading

Insufficient safety due to indirect effects of degradation:
- heavy cracking or spalling causing insufficient anchorage of reinforcement
- heavy spalling causing reduced cross section
- corrosion of the reinforcement causing insufficient safety.

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
- MR&R costs
- ecology
- cultural acceptance

When looking at the statistics of demolitions of buildings and civil infrastructures the following reasons for refurbishment or demolition have been stated (Aikiviuri 1994, Izuka 1988):

- Degradation is the dominant reason for maintenance and minor repair of concrete structures
- Degradation is the main reason for refurbishment of buildings in 17% and in 26% (steel) to 27% (concrete) of demolition of bridges. In individual cases degradation can be a dictating reason for refurbishment or demolition of the structures, which are working in highly degrading environment.
- Obsolescence is the cause of refurbishment of buildings in 26% and the reason of demolition of bridges in 74% of demolition cases.
- In the case of modules or component level renewals of facilities the share of obsolescence is still higher.

This means that the obsolescence is the dominating reason for refurbishments and demolitions of the build assets and their structures.
A conclusion of this, and a challenge for structural engineering is, that we have to include the degradation and obsolescence criteria into the design, as well as into the MR&R (Maintenance, Repair and Rehabilitation) planning of structures. In this use we need new methodology, models and methods for analysis, optimisation and decision making (Iselin and Lemer 1993, Sarja 2010, 2006, 2005a, 2005b, 2004b, 2003, 2002b).

There is an analogy between the terms and parameters of mechanical design against static and dynamic loads, durability design against degradation, but the variables and degrading models of durability are different from the models and variables of static and dynamic design.

The durability design can be carried out with the same kind of statistically based deterministic safety factor methods as mechanical design (Sarja 2010, 2003, 2002a, 2002b, 2000b, Sarja and Vesikari 1996).

Usability design against obsolescence can be based on statistical risk analysis methods (Sarja 2010, 2006). A comparison of the terms and variables of mechanical design and durability design is presented in table 4.

Table 4. Comparison of static and dynamic (mechanical) limit state method, the degradation limit state and obsolescence limit state (Sarja 2010),

<table>
<thead>
<tr>
<th>Mechanical limit state design</th>
<th>Degradation limit state design</th>
<th>Obsolescence limit state design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Strength class</td>
<td>1. Service life class</td>
<td>1. Service life class</td>
</tr>
<tr>
<td>2. Target strength</td>
<td>2. Target service life</td>
<td>2. Target service life</td>
</tr>
<tr>
<td>3. Characteristic strength</td>
<td>3. Characteristic service life (5% fractile)</td>
<td>3. Characteristic service life (5% fractile)</td>
</tr>
<tr>
<td>5. Partial safety factors of</td>
<td>5. Partial safety factors of</td>
<td>5. Partial safety factors of</td>
</tr>
<tr>
<td>materials strength</td>
<td>service life</td>
<td>service life</td>
</tr>
<tr>
<td>onto structure</td>
<td>loads onto structure</td>
<td>structure</td>
</tr>
<tr>
<td>7. Partial safety factors of</td>
<td>7. Partial safety factors of</td>
<td>7. Partial safety factors of</td>
</tr>
<tr>
<td>static loads</td>
<td>environmental loads</td>
<td>environmental loads</td>
</tr>
<tr>
<td>8. Service limit state (SLS)</td>
<td>8. Serviceability and ultimate</td>
<td>8. Serviceability and ultimate</td>
</tr>
<tr>
<td>and ultimate limit state (ULS)</td>
<td>limit states.</td>
<td>limit states.</td>
</tr>
</tbody>
</table>

**Lifetime Design of Concrete Structures**

**Durability Design**

**Design Procedure**

Durability design procedure is presented in figure 7.
**ORDINARY MECHANICAL DESIGN**
Dimensioning of the structure by ordinary design methods
- static
- dynamic
Results:
- preliminary dimensions of the structure
- amount and locations of reinforcements
- strength of concrete

**FINAL DESIGN**
Alternative 1 (separated design method):
- integration of the results of ordinary mechanical design and durability design
Alternative 2 (combined design method):
- mechanical redimensioning of the structure taking into account the durability parameters
Checking of final results and possible feedback

**DURABILITY DESIGN**
- Determination of target service life and design service life
- Analysis of environmental effects
- Identification of degradation mechanisms
- Selection of durability models for degradation mechanisms
- Determination of durability parameters, e.g.:
  - depth of deterioration of concrete and corrosion of reinforcement
  - concrete cover
  - diameter of rebars
Factors to be taken into account, e.g.:
- strength of concrete
- permeability of concrete
- type of cement
- curing method
- type of reinforcement
- structural dimensions

Figure 7 Flow chart of the durability design procedure, concrete structures as an example (Sarja 2005b, 2002a).

**Degradation Models of Concrete Structures**
The principal degradation process of concrete structures is presented in figure 5.

Figure 7 Service life model and limit states related to reinforcement corrosion (Sarja and Vesikari 1996, Andrade et al 2005, FIB 2006).
Two principal types of degradation models have been presented:

- RILEM TC130 CSL models (Sarja and Vesikari 1996)

Characteristic properties of these models are as follows (Sarja 2005c):

- Statistical degradation models are based on physical and chemical laws of thermodynamics, and thus have a strong theoretical base. They include parameters, which have to be determined with specific laboratory or field tests. Statistical reliability method can be directly applied with these models (Sarja 2010, 2006).
- RILEM TC 130 CLS models are based on parameters, which are available from the mix design of concrete. The asset of these models is the availability of the values from the documentation of the concrete mix design and of the structural design (Sarja and Vesikari 1996).

The European standard -“EN 206-1 Concrete - Specification, performance, production, and conformity” (CEN, 2001) is a practical quantitative methodology for durability design. EN206-1 contains an agreed qualitative classification system as a synthesis of “best available” knowledge, covering the relevant degradation mechanisms and exposures in atmospheres, fresh water, seawater, and soil, indicating the decisive character of moisture and chloride (CEN 206-2001 Sarja 2005c, 2006)). The exposure classes of CEN-206 are defined for different degrading loads, as presented in table 5.

Table 5 Exposure classes for concrete structures (CEN-206 2001).

<table>
<thead>
<tr>
<th>Class designation</th>
<th>Description of the environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No risk for corrosion</td>
<td>X0 - Plain concrete structure, if no chemical attack</td>
</tr>
<tr>
<td>2. Corrosion induced by carbonation</td>
<td>XC1 - Dry or permanently wet</td>
</tr>
<tr>
<td></td>
<td>XC2 - Wet, rarely dry</td>
</tr>
<tr>
<td></td>
<td>XC3 - Moderate humidity</td>
</tr>
<tr>
<td></td>
<td>XC4 - Cyclic wet and dry</td>
</tr>
<tr>
<td>3. Corrosion induced by chlorides other than sea water</td>
<td>XD1 - Moderate humidity</td>
</tr>
<tr>
<td></td>
<td>XD2 - Wet, rarely dry</td>
</tr>
<tr>
<td></td>
<td>XD3 - Cyclic wet and dry</td>
</tr>
<tr>
<td>4. Corrosion induced by chlorides other than sea water</td>
<td>XS1 - Exposed to airborne salt but not in direct contact with sea water</td>
</tr>
<tr>
<td></td>
<td>XS2 - Permanently submerged</td>
</tr>
<tr>
<td></td>
<td>XS3 - Tidal, splash and spray zones</td>
</tr>
<tr>
<td>5. Freeze/thaw attack with or without de-icing agents</td>
<td>XF1 - Moderate water saturation, without de-icing agent</td>
</tr>
<tr>
<td></td>
<td>XF2 - Moderate water saturation, with de-icing agent</td>
</tr>
<tr>
<td></td>
<td>XF3 - High water saturation, without de-icing agent</td>
</tr>
<tr>
<td></td>
<td>XF4 - High water saturation, with de-icing agent</td>
</tr>
<tr>
<td>6. Chemical attack</td>
<td>XA1 - Slightly aggressive chemical environment</td>
</tr>
<tr>
<td></td>
<td>XA2 - Moderate aggressive chemical environment</td>
</tr>
<tr>
<td></td>
<td>XA3 - Highly aggressive chemical environment</td>
</tr>
</tbody>
</table>
The design service life control is based on minimum requirements of concrete cover against corrosion in different exposure classes of CEN-206 and for different types of reinforcement. These are specified for reference service lives of 50 years and 100 years in table 6 (Sarja 2005c). The strength class of concrete is C35-C40 and there are in some cases also specific requirements for cement and admixtures.

Table 6 Minimum required thickness of concrete cover (Sarja 2005c).

<table>
<thead>
<tr>
<th>Exposure class</th>
<th>Minimum concrete cover for service life of 50 years (mm)</th>
<th>Minimum concrete cover for service life of 100 years (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>reinforcement sensitive against corrosion (prestress)</td>
<td>ordinary reinforcement</td>
</tr>
<tr>
<td>X0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>XC1</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>XC2</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>XC3, XC4</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>XS1, XD1</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>XS2, XD2</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>XS3, XD3</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

Usability Design against Obsolescence

The obsolescence analysis and optimisation is always made with comparison of planning or design alternatives especially on assets level, comparing their response towards changing requirements and supposed changes of user demands. The following methods can be applied in obsolescence analysis, control and optimisation (Iselin 1993, Sarja 2006):

- Quality Function Deployment method (QFD)
- Multiple Attribute Decision Aid (MADA)
- Risk Analysis (RA) Life Cycle Costing method (LCC)
- Simulations

Design for health

The healthy checking can follow national and international codes, standards and guides. The main issues in the case of buildings are to avoid moisture in structures and on finishing surfaces, and in the case of both building and civil engineering structures, to check that all materials used do not cause emissions or radiation, which are dangerous to the health and comfort of the users and workers. In some regions the radiation from the ground must also be eliminated though the insulation and ventilation of the foundation. Thus, the main tools for health design are: selection of materials, especially finishing materials, eliminating risks of moisture in structures through water proofing, drying under construction and ventilation, and elimination of possible radioactive earth radiation with air proofing and ventilation of ground structures (Sarja 2006).
Re-use, Recovery and Recycling

It is important to recognise that the recycling possibilities of the building components, modules and even technical systems shall be reconsidered in connection with design. The higher the hierarchical level of recycling, the higher also the ecological and economic efficiency of recycling. Therefore the re-use of entire components, modules, systems or even assets has to be preferred, even if there are difficulties in quality requirements and quality control in re-use (Schultzmann in: Sarja 1999, 2006), Willkomm 1990).

Materials recycling is a tool used to save raw materials, but the reduction of environmental burdens and energy consumption is usually small. The components of the environmental profile of the basic materials usually already include the recycling efficiency.

The recycling ability of the structural materials and components depends on the degree and/or the technical level of the desired re-use. Special issues to be treated in the design of structures and materials for re-use and recycling are (Schultzmann in: Sarja 2006, Sarja 1997a, 1997b):

- separability of the structural components or materials during demolition of a structure e.g. the use of demountable structural components using suitable connections and joints
- structural separation of components, modules or systems with different service lives and different recycling techniques.
- reduction in the variety of materials
- separation ability of materials, which cannot be recycled together
- avoidance of insoluble composite substances and/or composite substances that are either only slightly soluble or soluble only with a high expenditure or energy input.

Several civil engineering structures, like roads and streets, are major consumers of raw materials. In those structures, materials consumption can be reduced with the use of industrial by-products like fly ash and blast furnace slag, and construction and demolition waste materials like crushed concrete and masonry. Detailed quality specifications and an effective quality control are needed for the use of these secondary materials.

EU initiatives include the EU Raw Materials Initiative (EU 2008), which proposed an integrated strategy to deal with the various challenges related to access to raw materials, including secondary raw materials that can be obtained in the EU through more and better recycling. It clarifies the basic concepts such as the waste hierarchy, the prevention of waste, and the incorporation of life-cycle thinking. The Directive lays down important targets for the recycling of waste for the year 2020: 50% for household waste recycling and 70% for construction and demolition waste.

Conclusions

Incorporating life cycle principles into the practical design, construction and maintenance of traffic structures is quite an extensive process. Application of life cycle principles is widening the scope of structural design to the extent that the entire working processes must be re-engineered. The tradition of structural engineers in applying mathematical and physical calculation methods in design will
serve as a good basis for applying the additional multiple calculation methods that are needed in life cycle structural engineering.

Concerning concrete materials and structures, new basic knowledge will be needed especially regarding environmental impacts, hydrothermal behaviour, durability and service life of materials and structures in varying environments. Special lightweight concretes and composites are serving the energy efficiency of buildings. Structural design methods that are capable of life cycle design, multiple analysis decision-making and optimisation will have to be further developed. Recycling design and technology demand further research in design systematics, recycling materials and structural engineering. The knowledge obtained will have to be put into practice through standards and practical guides.

References


CEN/TC 359-“Sustainability of construction works” 2012.


EN 15643-1 Sustainability of construction Works.


Sarja, Asko 2002b, Reliability based life cycle design and maintenance planning. Workshop on Reliability Based Code Calibration, Swiss Federal Institute of Technology, ETH Zurich, Switzerland, March 21-22.


