DESIGN FOR DURABILITY - A PRACTICAL APPROACH

Design for durability

E. ROBERTSEN
Department of Building Science, Narvik Institute of Technology, Narvik, Norway

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Abstract

Today’s building practice has led to a lot of premature failure and lack of durability, which can cause serious safety, serviceability and functional problems. Traditionally design for durability has been performed in an empirical, often unstructured manner based upon implicit durability requirements. A new approach, which ensures that materials and components are suitable and will perform satisfactorily during the intended life, is necessary. Service life estimations are complex and information intensive. In spite of scientific imperfections and lack of information on right format, there is a need for the practical engineer to start using the accessible knowledge. The suggested framework for service life based design, construction and management of building assemblies will ensure that performance requirements are fulfilled during the design life, allows optimisation of the whole life cost of buildings and permits life cycle assessments. The service life influence in different phases, from client’s brief till demolition or major refurbishment, can be assessed in five consecutive stages; conceptual design, modelling and prediction, engineering stage, construction and in service period. The target design life must be determined in an early design stage and will serve as a basis for materials selection, detailed design, execution procedures and maintenance strategy. After predesign the gradual deterioration induced by the interaction between alternative materials and the actual surrounding environment can be estimated. Different approaches can be used for predicting the future behaviour. Models must be based upon a clear phenomenological understanding of the degradation process. In the engineering stage materials selection, detailed design and a quantitative description of products and procedures are executed. In the construction period key factors for durability will be quality assurance of solutions and execution procedures including environmental control. The degradation process and thereby the obtainable service life in terms of performance can in the service period be controlled through adequate operation-, inspection-, maintenance- and repair activities.

Keywords: service life, durability, design life, modelling, execution, maintenance

1 Introduction

The construction industry is currently experiencing numerous envelope problems and premature material breakdown. Failure is often rooted in misunderstanding of the particular requirements, improper initial design, defective installation, or a disregard for the need to provide routine and regular maintenance. Failure or level of service less than expected can result in serious adverse consequences to building value, operational costs, occupant comfort or environmental impact. The functional failure rate of building assemblies will often follow a bathtub curve as illustrated in figure 1. The simple total failure rate may be considered as the sum value of three imaginary components. The first part is caused by deficiencies in planning and construction not attended by the quality system. Number of premature failures will gradually decrease. Another cause of deficiencies is sudden deterioration caused by random events like fire and earthquake. The probability of such failure can be seen as constant during the service life, and will not be treated further in this paper. The third component is the gradual deterioration induced by the interaction between the material and the outdoor environment combined with in use influence.

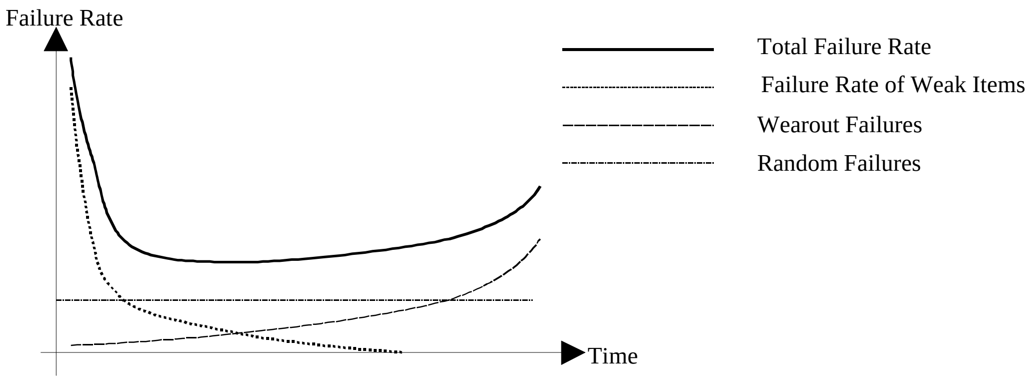

Fig. 1: The Bathtub Curve illustrates the probability of failure over time

The envelope of modern buildings is subjected to higher stresses than were those of earlier buildings. New and increasing demands impose new constraints, which combined with the increasing variety of materials, systems and assemblies make construction and prediction of performance considerably complex. Service life can be defined as the period of time all essential performance characteristics of a properly maintained item in service exceeds the minimum acceptable values with reasonable economy. The service life limit can be both technical, economical, functional or aesthetic. Service life predictions are needed whenever a new material without a significant performance history or exposure to new environmental exposure is proposed. Despite the sparse information available it is in many cases possible to make reliable service life predictions for the progressive degradation of materials, components and assemblies due to environmental exposure based on sound knowledge of degradation mechanisms and kinetics of degradative reactions in the actual service environment. Prediction of service life is however a highly complex issue as it require detailed information in all life stages. A major problem is that performance- and service life data are too scarce or on a wrong format to provide adequate input to service life analyses. Through a systematic consideration of all factors affecting serviceability of assemblies, components and materials it is however possible to give a reliable forecast of service life, required maintenance, and thereby the cost of building ownership. Collecting and analysing of input data for service life predictions are expensive and time-consuming activities.

2 Conceptual design life

The service life influence in case of progressive degradation due to the environmental exposure, can be considered in five consecutive stages;

- 1.Conceptual Design Life
- 2. Predesign, modelling and prediction
- 3. Engineering stage
- 4. Construction period
- 5. In service period

The design life can bee see as the period of use for a product, a component, an assembly or a construction intended by the designer. The target design life must be determined in an early design stage and will serve as a basis for materials selection, detailed design, execution procedures and maintenance strategy. The design life of the building (DLB) as a whole must be specified according to the actual building category and main construction system. After a conceptual design phase materials, components and assemblies are classified in permanent, exchangeable or maintainable parts. The expenses and difficulties in replacement must be estimated when the different parts are classified as life long, replaceable or maintainable. For each part the performance requirements are listed and a target design life for components and assemblies (DLC) are specified in classes based on functional requirement, cost and accessibility (ISO/DIS 15686, 1997).

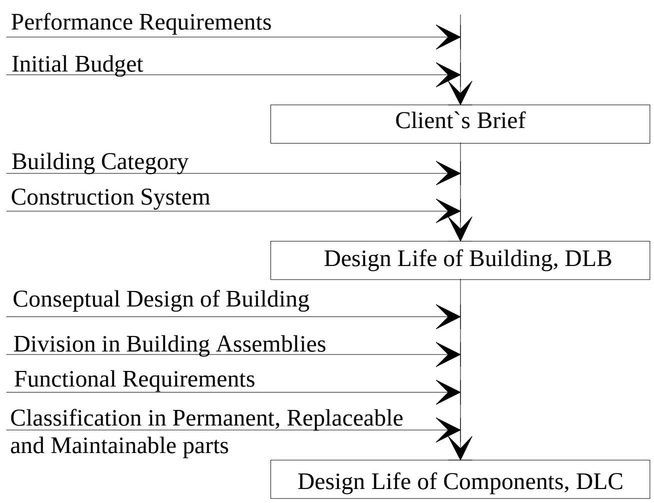

Fig. 2: Schematic illustration of input parameters in design life determination

Each component is assigned a design life used as a planned time for replacement or major repair. If the correct predicted damage is less than corresponding to the performance limit, the required design life can be maintained and the cost of maintenance and repair can be estimated. The suggested design life of building and inaccessible or structural components is 10 to 150 years, while major replaceable components may have a design life (DLC) up to 40 years (ISO/DIS 15686, 1997). Where replacement is expensive or difficult DLC could be up to 100 years. The recommended design life for service installations and external cladding is normally 10 to 25 years.

3 Predesign, modelling and prediction

Components and assemblies are given a preliminary design based on the fixed design life in accordance with the principle of parallel service life, where no layer with longer design life must be dismantled for maintenance or replacement of another layer. Based on overall judgement materials limitations are recommended. Material selections are based upon functional, technical, economical, environmental and aesthetic requirements. The requirements must be satisfied both initially and during the design life. Deterioration of building materials often occurs as a result of chemical or biological processes combined with physical action. Chemical composition and microstructure of the material thus determines the durability for a given exposure. Today's macro level durability design are based on simple «deemed to satisfy rules» on a structural level. Instead durability can be quantitatively expressed as service life based on a materials engineering level using simplified service life models, or on more or less correct micro-level physical/chemical models for degradation and environmental actions on a materials science level. Different models with unequal complexity and accuracy are thus available. Appropriate level depends on the intended service life, degradation mechanism, the severity of the exposure condition, consequences of failure and accessible knowledge. Among sources of service life data are historical reference service life data, benchmark level of specifications with «insured life» and adjustment factors like the HAPM component life manual (HAPM, 1997) and the proposed ISO factorial system, use of expert judgement or different deterministic or statistical prediction models. The nature and progression of deterioration mechanisms are of main interest in models for reliable service life predictions. For mathematical modelling all functional requirements must be expressed quantitatively in terms of measurable material properties. For high reliability the service life methodologies must be based upon a clear phenomenological understanding of the degradation process, and be able to identify degradation mechanisms which are sensitive in means of that only minor changes in materials or climate may cause severe damage to the materials. For mathematical modelling on a material scientific level the following are needed for high reliability;

1. Quantitative expression of functional requirements in terms of quantifiable, measurable parameters such as stress, strain, area reduction, loss of mass, temperature, moisture content etc. included limit states for functional level (end of life criteria)

2. Environmental description in quantitative terms on a micro level as a function of time
3. Material data included transport coefficients which allow prediction of the time dependent concentrations and temperatures as a function of depth from the surface
4. Detailed phenomenological understanding of all deterioration mechanisms that may occur in the specific material-environment combination
5. Knowledge of deterioration rate based upon theoretical considerations, exposure or empirical data
6. A maintenance strategy plan with service life effects

The service life prediction can partly be based on verifiable data such as material properties, geometric design and surface treatment, but must also rest on assumptions of execution level, environmental exposure, in use conditions and effect of maintenance efforts. Quality assurance must ensure that prediction assumptions are satisfied during engineering, execution and use if the service life management is to be credible.

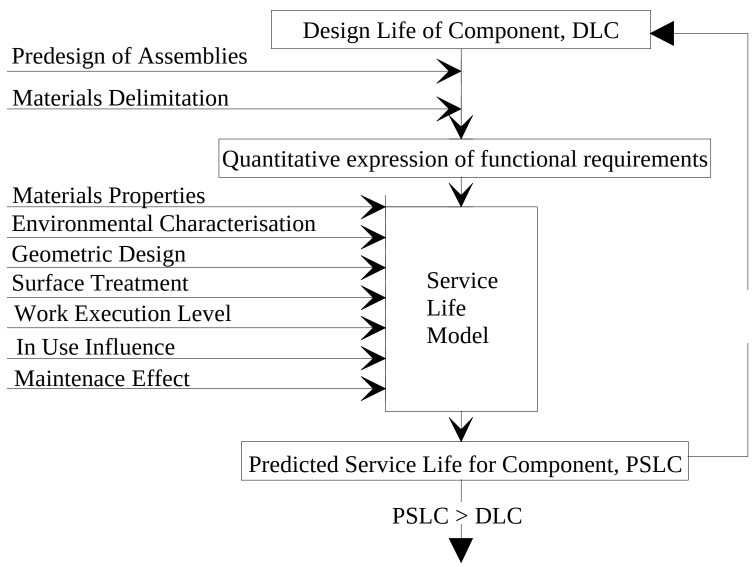

Fig. 3: Illustration of parameters necessary for service life prediction

Under RILEMS`s direction a general framework for service life prediction based upon a combination of field investigations and laboratory testing has been prepared (Masters & Brandt, 1987). In addition to the generic standard methodologies there is a need for specific guidelines for service life prediction for different building materials. The deterioration process may occur gradually, with or without delay, cyclically (as with seasonally effects) or as a stepwise change under extreme environmental loads or combinations of loads. For some individual deteriorating mechanisms a number of several different service life models are available, examples are models for service life estimation for corrosion of reinforcement in concrete and dose-response functions for different metals. For other mechanisms present knowledge is too scarce to build models. Knowledge of and ability to characterise the exposure condition on a microclimate level are today a major obstacle for service life modelling. In many practical cases materials are exposed simultaneously to different deterioration factors leading to synergy effects where the combined effect is worse than the sum of the effects of the individual mechanisms. Service life models for interactions between several deterioration mechanisms are modest available.

Service life management in building industry requires easily accessible mathematical service life models and input data on right format. Description of degradation given in scientific documents for limited objectives is often rather complicated to extract. Service life modelling must to some extent rest on previous experience, collected as standard service life data like the HAPM Component Life Manual (HAPM, 1997). Collection and analysis of historical life time data are time consuming since data often are stored in a unstructured way in maintenance sources. Use of historical data has limitations for practical service life estimations due to changes in material properties, execution techniques and unknown exposure history. In service life prediction historical data must be combined with expert judgement based on knowledge of the underlying failure mechanism.

The service life for a number of presumptive identical parts will vary due to the variations in material properties and exposure condition (Robertsen, 1996). Depending on the intended use, recognising the uncertainty's associated with deterministic testing and modelling, service life safety factors may be established based on the consequences of failure. Recognising the stochastic nature of variables in service life predictions, a probabilistic approach is needed if the uncertainties in the prediction are to be properly assessed. The service life can then be presented as the intended service life period where the limit states may, with certain reliability, not be reached within the design life or as lifetime where the reliability is related to the probability that the design life is exceeded.

4 Engineering phase

The main objective in the engineering stage is to prepare for safe, functional, economical and durable constructed facilities in the context of sustainable development. The prediction of performance, both initially and during the service period, is an integrated part of the design process. For structural design available quantitative data enables designers to reach fairly precise conclusions regarding structural performance. This is not the case with durability. An assessment of service life is however in most cases possible by equating required performance level to predicted functional level. Based on the preliminary design and service life estimations for alternative materials and solutions which meet the functional requirements, both initially and over time, an economical optimisation can be executed based on life cycle cost, LCC. In the same way a life cycle assessment, LCA, of the alternative solutions can be carried out.

The service life is directly related to the design efforts. It is insufficient and risky to merely copy details from previous projects without considering the surrounding environment. Prescribed solutions must be based on detailed analysis of the performance requirements for the actual component as a basis for service life modelling for the interaction between the material and the exposure condition. In the engineering stage detailed geometric design and materials specifications are outlined. Modern materials are designed to satisfy a multitude of specific functions. Individually their performance characteristics tend to be reasonably predictable, the designers challenge is thus to predict the behaviour of the complete assembly, both initially and over time. For each component and assemblies the future maintenance, repair and replacement needs must be identified, and the impact of any repair and replacement options upon future performance and service life must be considered.

Building design is a creative process aiming to create optimum solutions by detailed comparison of alternative possibilities. Also health, environment and security aspects must be considered, both in the construction period, in the permanent service stage and under demolition. Connected materials must be chemically and physically compatible, and detailing, lead-troughs, joints, and tolerances are to be accommodated. Connections between adjacent parts are often critical to the overall performance for assemblies. The geometric design must minimise accumulation of moisture and other degradation factors and permit accessibility for execution, cleaning, maintenance and replacement. The written specifications and drawings must meet the performance requirements, be technically, economically and environmentally optimal, in accordance with national building regulations and must undergo quality assurance.

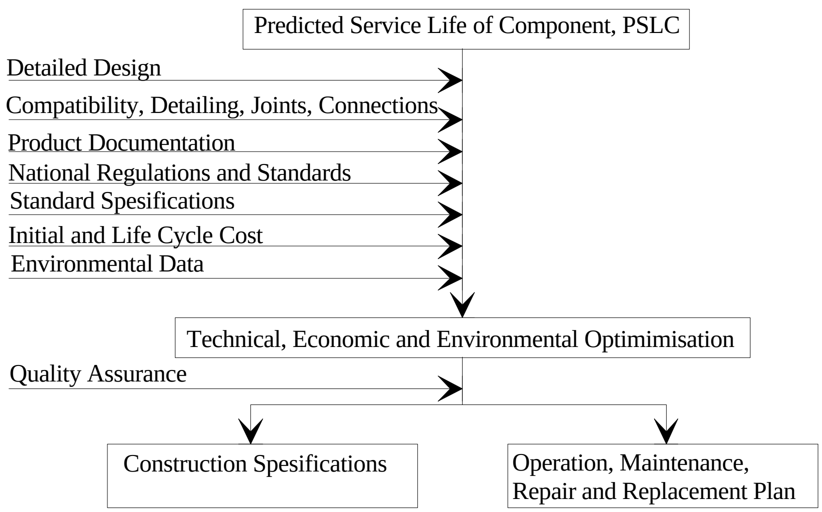

Fig. 4: Illustration of input necessities for engineering optimisation

5 Construction period

The potential functional levels and service life for the different assemblies are determined in the engineering stage by material selection, geometric design and chosen surface treatment. The contractors primary task is to execute the described solutions in accordance with good workmanship. The functional requirements must be analysed in order to detect critical points and procedures. The information turnover between different participants in the consecutive stages in the building process is a key factor in order to fulfil performance requirements. Execution of complex building assemblies and connections with expected service life are secured by detailed specifications, use of formerly well educated personnel and adequate quality assurance. As with design the result considerably depends on the competence and engagement of persons involved in the process. As far as possible verified standard solutions and execution procedures shall be used. The site organisation, management, process equipment, project economy and time available will influence on the workmanship level and thus the functional level for components and assemblies. Satisfactory storage of materials and protection of manufactured assemblies are necessary to prevent premature deterioration and damage. While building envelopes are designed to withstand a particular environment and its attendant conditions, insufficient recognition is given to the environmental conditions that exist during the construction phase and the effect they have on the durability of building components. Climatic restrictions and precautions for different parts have to be listed in the specifications.

Trough design, modelling, engineering and construction the initial quality and thus the potential installed service life for components and assemblies are set. If the potential service life after construction not exceed the design life, precautions are to be done. This can imply technical improvements as replacement, repair and surface treatment or economical compensation for future expenditure du to reduced service life. After completion of the construction work as-built documentation must be added to the operation, maintenance, repair and replacement plan.

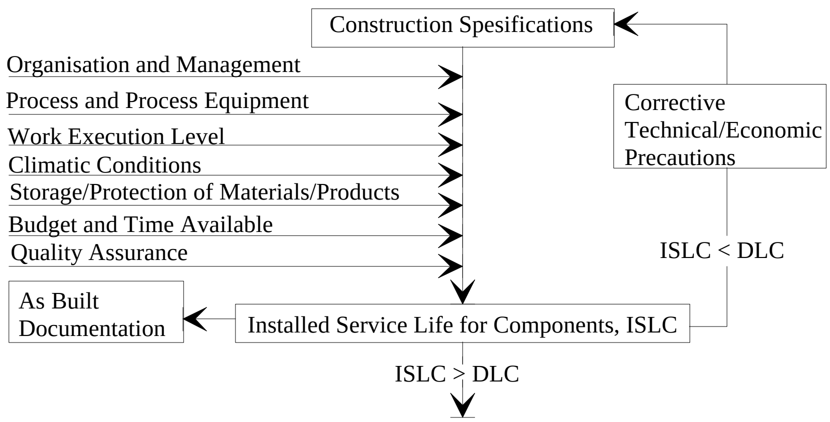

Fig. 5: Illustration of service life influence during construction

6 Use

The effort to obtain optimal performance does not end once a part has been constructed. After installation strains from environmental exposure, use and internal incompatibility will gradually reduce the functional level for materials, components and assemblies. Through adequate operation-, maintenance- and repair activities it is possible to control the degradation processes and thereby the reduction in functional level so that the design life can be reached. The challenge is to identify the degree, quantity and appropriate timing of corrective and remedial action, and the influence of different actions in terms of service life.

The in-service period can from maintenance perspective be divided into three phases, as figure 1 illustrates. In the guarantee period building deficiencies are detected and repaired. The ordinary in-service period is characterised by planned activities in accordance with the maintenance strategy plan. Towards the end of the service life failure frequency, and thereby necessary maintenance efforts will increase. In the engineering stage a maintenance strategy and a maintenance plan based on preventive actions and replacements are worked out. In addition minor defects must be repaired.

Combined planned and response maintenance are essential to ensure satisfactory performance for the whole design life.

Through the in-service period condition assessment has to be worked out periodically. Destructive and non-destructive assessment methods must be combined. The inspection, manual or performed by condition monitoring, may be performed on demand, at predefined intervals or on a continuos basis. Different concepts have been used to describe the condition of a system at the time of inspection. Among these are performance indicators, true condition and health monitoring (Reinertsen, 1997). The assessed condition is to be compared with the predicted condition at the actual time. Corrective actions necessary if the service life shall exceed the design life can thus be foreseen. The service life ends when technical, economic, functional or aesthetic requirements no longer are fulfilled. The component or assemblies are then to be downgraded, repaired or demolished.

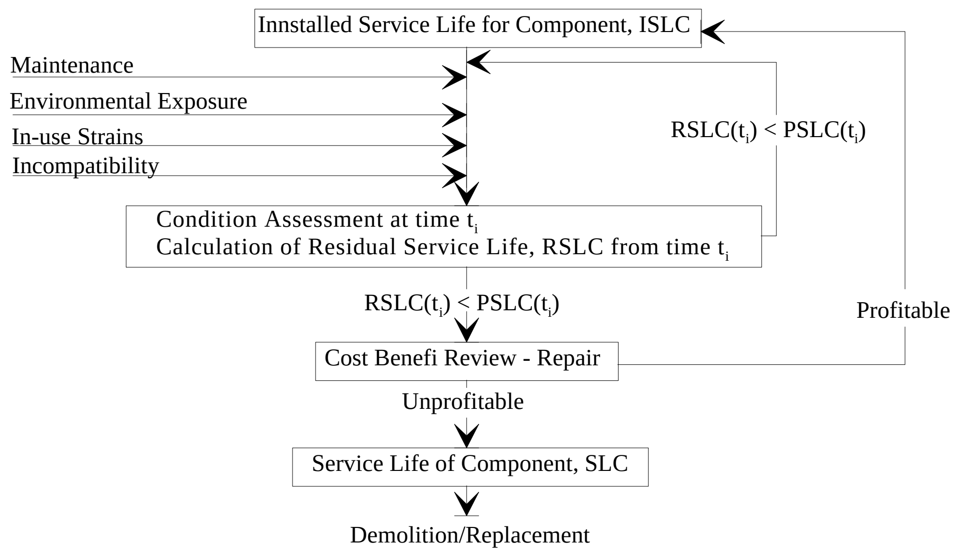

Fig. 6: Schematic illustration of service life management in the in-service period

7 Conclusions

Building materials and components have finite service lives due to gradually chemical, physical or biological degradation, which reduce the ability to perform as required. This gradual deterioration can be modelled and a quantitative service life predicted. The service life modelling covers only gradual deterioration, not obvious deficiencies in engineering and execution, nor suddenly destruction. Service life modelling allows technical and economic optimisation in durability design and permits life cycle assessment. In this paper the rudiments of an integrated design-, construction and management strategy to control service life for building component and assemblies has been suggested. The methodology implies that all factors affecting service life in programming, design, construction and maintenance phases are systematically considered. In an early design stage the service life target for each component is set as a basis for durability design. Reduction in performance is predicted through mathematical modelling of the deterioration processes. In the service life period the real functional level at the time of inspection is to be compared with the predicted level. The service life can then be controlled by adequate maintenance to exceed the design life. The new quantitative durability design approach is complex and information intensive as it requires detailed knowledge of all factors affecting service life. Despite imperfections in methodologies and available data it is today in many cases possible to predict service life with reasonable accuracy. If the building industry starts to use a systematic methodology for service life estimations best practice in optimising performance criteria will be developed further together with necessary input data.

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