YCRETS 2023
YOUNG CONCRETE RESEARCHERS, ENGINEERS & TECHNOLOGISTS
SYMPOSIUM

CEMENT & CONCRETE SA

The role of sustainability in target reliability assessment

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Abstract

Reliability is a measure of structural performance and is central to modern structural design. Current structural standards incorporate reliability to minimise risk and optimise the design of a structure using probabilistic methods, with target reliability as a measure of structural performance. However, the need to preserve the planet and combat climate change requires the design of structures to contribute to curbing harmful environmental effects. Most design standards mention the need for sustainability, but do not give comprehensive guidelines on its incorporation in the determination of reliability, which is the basis of structural design. This paper provides a framework for future research which aims to incorporate sustainability in the determination of target reliabilities. Structural deterioration models will be integrated with a sustainable framework design model. The sustainable design framework will be derived from a Life Cycle Analysis, which includes quantified and weighted sustainability indicators. Due to the vagueness of the term sustainability, the No Effect Level and Expert Panel methods are recommended for quantifying sustainability indicators. This will enable target reliabilities covering all aspects of sustainability to be determined and recommended.

Keywords: target reliability, serviceability, sustainability, framework

1. INTRODUCTION

This paper provides a framework for future research focussing on the role and effects of including sustainability factors in assessing and determining the target reliability of structures. Reliability is the basis of current structural design methods and is a measure of structural performance [1]. Structural design standards such as Eurocode (EN1990, 2002), (ISO 2394, 2015), SANS 2394, SANS 10160-1 (SANS 2018), ANSI ASCE 7-10 [2], and the *fib* Model Code 2010 [3] employ reliability methods in the design of new and the assessment of existing structures. Probabilistic methods are used to analyse risk and safety of the structure's occupants, maintenance workers and the public within the vicinity [4]. A structure's performance in relation to a minimum or acceptable required performance is governed by limit states. Consideration of limit states ensures optimal behaviour of the structure or structural component with focus on human safety, functionality, aesthetics, and comfort to users [2]. This must include sustainability aspects which consider economic, social, and environmental impacts during the life cycle of a structure.

The advent of climate change has prompted the world to move towards saving the planet by curbing greenhouse gas emissions, lessening resource usage, and reducing waste production. Structural designs are now required to contribute positively to climate change, as their construction has significant negative environmental impacts. Reinforced concrete infrastructure poses two major challenges in the attainment of global sustainability. The first challenge is the emissions from the manufacturing of construction materials such as Portland cement, which accounts for 5% of global CO_2 emissions. The second challenge is in the sustainability of transportation methods for construction materials and structural components [5]. Despite all these challenges, of which structural design is a major contributor, most design standards have received minor to no updates on considering sustainability in structural reliability analysis. The *fib* Model Code 2010 (MC 2010) outlined the basic principles and performance requirements of concrete, concrete elements, and structures in relation to the environment, the society, and the economy [3]. This is currently being updated so that the Model Code 2020 Draft includes the sustainability performance of a structure by combining economic, social and environmental aspects in the life cycle of a structure [6].

SANS, like most current design standards, have received minor updates with regards to sustainability and more so, the effects of sustainability on the target reliability of a structure. SANS 2394, adopted from ISO 2394, focusses on general principles on the reliability of structures, and highlights the fact that sustainability in relation to reliability is still a concept under development [7]. Structural design must include the sustainability concept in line with Sustainability Development Goals. Currently, SANS 10400-XA [8] outlines energy usage in buildings by considering thermal properties of materials, and water supply systems in different climatic conditions. It is imperative that structural design standards incorporate sustainability performance to complement structural performance in the life cycle of the structure.

2. STRUCTURAL PERFORMANCE AND RELIABILITY

Structural performance depicts the behaviour of a structure/structural component when it is subjected to an action or a combination of actions. MC 2010 [3] outlines three major categories namely structural safety, serviceability, and sustainability. These requirements stem from stakeholder demands which influence how the structure functions to meet their essential needs. Structural safety and sustainability cater for social needs while serviceability focusses on the requirements of clients and users. Durability and robustness are other critical aspects to structural performance. Durability refers to the ability of a structure to meet safety and serviceability targets throughout its life with crack width, carbonation depth and chloride content as performance indicators for concrete structures in particular. Robustness is a structural safety aspect, which is defined as the ability of a structure to withstand accidental or exceptional actions without being disproportionately damaged, or the ability of a structure to revert to its original function after undergoing repairs. Performance indicators for robustness consist of redundancy and the resistance of a damaged structure [1].

Limit States are conditions under which structural performance is below an acceptable level, whose exceedance of adverse conditions results in failure or impaired function of a structure. The state of material degradation is a measure of durability associated with limit states. However, limit states associated with durability should be clarified on whether they are applicable to either serviceability limit states or ultimate limit states [9]. This is important in reliability management to ensure that the performance requirements are satisfied in a well-balanced manner throughout the life cycle of the structure. The assurance of structural performance to an acceptable level of probability of failure corresponding to a reference period is known as target reliability [2].

2.1 Target Reliability

Target reliability is differentiated based on the use of the structure, type of structure and situations considered in the design [1]. The reliability index, β, is a standard of measure of reliability, which is related to the probability of failure through the following function:

$$\beta = -\Phi^{-1} (P_F) \tag{1}$$

where Φ( ) is the Gaussian distribution, and P_F is the probability of failure. Reliability indices are scattered as they are dependent on various factors such as the type of structural component, loading conditions and structural materials together with theoretical models used to describe the basic variables [10]. Target reliability values for generic structures in South Africa are well defined in SANS 10160-1 [11] and are generally dependent on the costs of increasing safety together with economic, societal, and environmental consequences of structural failure. Cost optimisation is the main factor in determining target reliability except where human safety is a higher risk in the event of failure. This requires additional constraints which determine minimum reliability levels to minimise risk from a societal perspective [12]. Target reliability through cost optimisation is represented by the following function:

$$Z(d) = C_0 + C_1.d + A(d) + D(d) \tag{2}$$

where C_0 are the initial construction costs without the decision parameter, C_1 are the costs related to changes in the decision parameter *d*, A(*d*) represents obsolescence costs, and D(*d*) represents the costs related to failure. Societal limits on target reliability are determined by considering individual and group risk requirements through the Life Quality Index (LQI). The determination of LQI constitutes mainly of the Gross Domestic Product per capita to reduce risk, ratio of work to leisure time, demography, societal willingness to pay, and the number of fatalities expected in the case of failure [12]. (ISO 2394, 2015) [7] specifies an acceptable fatality of 10^{-6} per year, with a corresponding annual Ultimate Limit State (ULS) reliability index of 4,7 [10]. Target reliability optimisation currently includes economic aspects with regards to structural and societal safety, with focus on the Ultimate Limit State. Way *et al,* 2022 [12, 13] indicated that the proper determination of target reliability with regards to the Serviceability Limit State (SLS) has not been considered in design standards. Current design standards also do not incorporate sustainability with the exception of including costs of environmental consequences from an economic perspective. There is a need for a sustainable design framework to be integrated with structural design models.

3. SUSTAINABILITY

Sustainability is defined as the ability to fulfil current needs of humankind with respect to nature, society, and humans without compromising the needs of future generations [6]. This concept was introduced with the intention of curbing climate change by stabilising the concentration of greenhouse gases in the atmosphere. Sustainability also applies to urban development, which relies on the construction of infrastructure, with concrete as the most widely used material [6]. Reinforced concrete structures pose a major sustainability challenge due to cement production. Regional, local and project specific frameworks have been devised to aid in making designs and infrastructure management more sustainable. These frameworks consist of three subsets which are knowledge based, rating based, and performance based. Knowledge based methods are defined by the criteria under which sustainability was defined and consists of manuals, guidelines, and design recommendations. Rating based frameworks consist of discrete allocation of conditions under which a structure is deemed sustainable. This includes design checklists and sustainability calculators. Performance based tools include continuous impact variables which consist of Life Cycle Assessment methods and the analysis of material flow. This includes simulation tools for assessing environmental impacts and can incorporate economic, social, and environmental aspects. The continuity of performance tools makes them preferrable to knowledge and rating methods as probabilistic analysis can be incorporated [5]. This allows the use of limit states to define the sustainability performance of a structure.

3.1 Sustainability Performance

Structural performance with regards to safety must be complemented by appropriate levels of sustainability [1]. This entails meeting stakeholder demands while striking a balance between economic efficiency, social responsibility, and improving environmental quality. The performance criteria of sustainability must be determined by skilled stakeholders to avoid conflict, ambiguity, and incompleteness of these criteria. The desired level of satisfaction must be achieved in compliance with statutory responsibilities and requirements [6].

3.1.1 Economic performance

The economic performance of a structure is normally conducted through a Life Cycle Cost Analysis (LCCA) to assess the financial feasibility of projects. This is based on discounted cash flow analysis which is tied to the net present value of a structure, and is useful when different economic alternatives of a project are required [6]. Economics highlight the interdependence between risk and cost of safety. There are two main categories in the economics of a project, which are direct and indirect costs. Direct costs are carried by the owner, and these are related to design and construction, overheads, operation and inspection, maintenance, and end of life costs. Indirect costs are those borne by society as a result of the project. To the user, these costs may be time lost due to maintenance and rehabilitation. Societal costs can be associated with the preservation of cultural values, heritage, beliefs, etc. However, these costs are not easy to quantify in monetary terms. Target reliabilities can be determined based on economic optimisation unless the structure poses a major risk to human life in the event of failure [2].

3.1.2 Social performance

Social performance focusses on stakeholder satisfaction during the structure's life cycle, forming a connection between structural engineering and the society. The first aspect outlines the impacts of how users perceive and behave in relation to a structure's function. The second aspect focusses on safety and security, which is based on risk analysis that includes threats, vulnerabilities, expected loss and potential impact, particularly on the environment [6]. Life-saving costs are generally applied when societal or individual risk is the basis for determining target reliability. This gives rise to consequence classes which outline the risks to human life. The Life Quality Index shows societal preference for life safety and is expressed in terms of the willingness to save one's life. LQI depends on GDP, leisure-work ratio and life expectancy [2].

3.1.3 Environmental performance

Environmental performance is based on either Life Cycle Assessment (LCA) or the evaluation of Environmental Impact. The Environmental Impact is further subdivided into the Life Cycle Concept [5]. The Life Cycle Concept considers the total environmental effect of a product, from the acquisition of raw materials through to disposal. The environmental impact of the entire structure can be expressed as a profile composed of values of different criteria, or as a single characteristic value impact. The Environmental Impact value can be expressed as an eco-cost or a normalised system of points [6]. It can also be depicted in terms of a limit state of sustainability, which relates the performance requirement and structural performance over the life cycle. However, this method has not been fully developed [5]. The impact related to a particular step of the life cycle incorporates all environmental damages which combine the weighting and the number of essential environmental criteria. The determination of weighting factors is complex and subjective due to different criteria with a variety of characteristic features. It is a sensitive approach which requires a decision based on a panel of experts on local, regional, and national levels. Three weighting approaches are currently available. The first approach entails Environmental Priority Strategies which constitute of the price to be paid by society to prevent harmful environmental impact. The second approach entails the Panel Method, which is an expert-based determination of weighting factors. The third approach is the No Effect Level (NEL), which provides the relation between zero effect and the current level of a particular environmental aspect. The difference between the zero effect and environmental impact is called a sustainability indicator. A combined Panel-NEL method is also feasible, where experts determine the impact/weighting of a sustainability indicator. Either basic costs or an Environmental Impact evaluation should be an assessment condition for the entire structure or structural elements where the performance of a structure, deterioration, extent and future degradation are determined [6].

4. ASSESSMENT OF THE EFFECTS OF SUSTAINABILITY ON TARGET RELIABILITY

The methodology to determine the effects of sustainability on target reliability will entail the integration of a structural deterioration model with a sustainable design framework. A representative structure, whose performance failure is governed by serviceability, will be chosen to determine the associated risks and consequences. The structural model will be analysed iteratively until it fails to meet the minimum performance criteria. Annual target reliabilities to restore performance to acceptable levels will be determined from the economic, social, and environmental perspectives. Cost optimisation will be conducted to determine the target reliability from an economic perspective, while the Life Quality Index will be used to calculate the target reliability from a social perspective, considering the requirements on human safety and individual risk. This is a combination of human safety and economic aspects.

Target reliability from an environmental perspective will be determined by quantifying the anticipated environmental impacts. This will entail the derivation of environmental indicators in line with the work to be carried out. Some of the indicators outlined in the *fib* Model Code 2010 include CO_2, SO_x, and NO_x emissions, non-renewable resource usage and waste production [3]. However, more precise sustainability indicators will be derived to quantify the environmental impacts, from design to construction [6]. The significance of the indicators will be determined by weighting factors. Two methods, which are the Panel Method and the No Effect Level Method, will be assessed and compared. The impact due to the indicators will be normalised into costs of reducing environmental damage to determine target reliability. The target reliabilities obtained from the economic, social, and environmental aspects will be compared to determine the final target reliability. The target reliabilities will also be assessed to determine their suitability, upon which a decision can be made to either demolish the structure or conduct the necessary construction/repair methods. The methodological approach is shown in Fig 1.

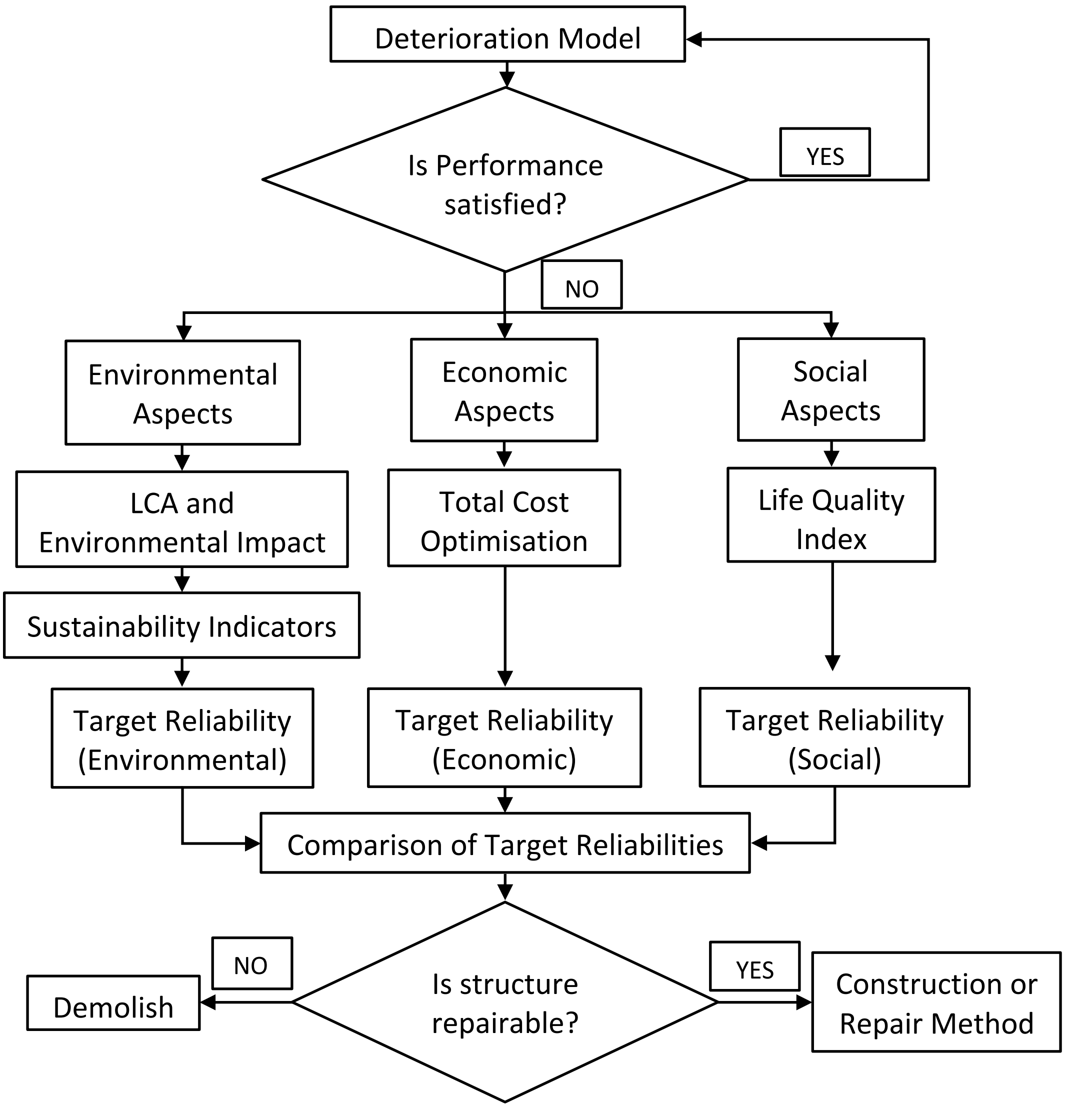

Figure 1. Flowchart of Methodological Approach

5. EXPECTED RESULTS & DISCUSSION

Expected results will entail an integrated structural deterioration model which incorporates sustainability aspects in the assessment and determination of annual target reliability. The model will help to evaluate the impact of environmental factors on target reliability. Inclusion of all aspects means that overall sustainability performance can be determined during the life cycle of the structure. Comparison of target reliabilities allows the consideration of alternative and environmentally friendly methods in construction activities. However, the concept of sustainability needs to be clearly defined in line with structural design standards. The vagueness of the current definition complicates the derivation and quantification of indicators. Currently, the Model Code 2020 [6] recommends using a panel of experts to determine the weighting of sustainability indicators. This is still a subjective and complex undertaking, therefore a clear definition is needed beforehand. The inclusion of quantified environmental indicators would define a sustainability limit state, which is lacking in structural design standards. Environmental impact assessment allows alternative methods of repair and maintenance in place of conventional methods. Uncertainties in the environmental model will result from variations in material quantities used, different types of construction processes and waste generated.

6. CONCLUSION

Target reliability is a major aspect of structural design. It is well defined by design standards considering the Ultimate Limit State. This paper highlights the need for target reliability to be derived from a serviceability perspective while including sustainability. The research is expected to determine a link between sustainability and structural design using reliability as a basis. This will ensure that a sustainability evaluation is conducted from the design to the construction of a structure. Sustainability will first be considered from an SLS perspective, and any evaluations will be on an existing structure. Further research will enable the incorporation of sustainable factors in the assessment of existing structures also considering the Ultimate Limit State.

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