Limit States for Sustainable Reinforced Concrete Structures

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Abstract

Probability-based limit state design is a hallmark of modern civil engineering practice. Code requirements to meet both ultimate limit states (ULS) and serviceability limit states (SLS) have vastly improved the safety and usefulness of concrete structures. To meet increasing challenges of triple bottom line sustainability (covering social, environmental and economic aspects), a new class of design limit states are needed within code-based engineering design practice.

A framework for sustainable design and management considering environmental impacts was earlier developed, and a multi-physics and multi-scale deterioration model for reinforced concrete affected by chloride-induced corrosion was established. A simplified case study is presented in which a reinforced concrete panel is exposed to a marine environment. The multi-physics deterioration model is used to determine the time until an engineering limit state (cracking due to reinforcement corrosion) is reached, and a design and maintenance optimization is performed with regard to sustainability (global warming potential footprint).

Keywords: Sustainability, modeling (E), Durability (C), Concrete (E), Corrosion (C)

1 Introduction

Sustainability-focused innovation is required in the construction industry to meet future climate goals, *e.g.* [1-3]. To facilitate such innovation and allow for the sustainable design and management of concrete structures, both engineering (*i.e.* commonly used ultimate limit states (ULS) and serviceability limit states (SLS)) and sustainability limit states (*i.e.* maximum carbon footprint over a concrete structure's operational service life) need to be considered [4].

The European-funded DuraCrete project led to the formulation of a durability design framework resembling the probabilistic and factorial design approaches established for structural design [5]. This durability design framework was further developed and formalized in the *fib* Model Code for service life design [6] and the ISO standard 16204 [7].

In addition to including the durability design guidelines given in [6], the updated *fib* Model Code for concrete structures 2010 (MC2010) [8] also provides design principles for sustainability[1], including environmental impacts, social impacts, and aesthetics (see [8] Section 3.4), and suggests verification of sustainability metrics to be undertaken using rigorous life cycle assessment methods adhering to ISO 14040 [9] (see [8] Section 7.10). However, no specific guidelines or methodologies for undertaking the design are given in [8].

Complying with the intent of [8], a framework for sustainable design and management considering environmental impacts was, based on Lepech [10], proposed by Lepech *et al.* [11]. Using this framework for sustainability assessment and only considering engineering limit states at the materials level, Lepech *et al.* [12] illustrated the impact of the selected engineering limit state on the cumulative environmental impact of a single structure. Further exploring the role of material engineering limit states, Lepech [4] performed environmental impact minimization for 100,000 bridges over 100 years, which indicate a counter-intuitive sequence of different engineering SLS limit states to be optimal.

Both studies [4, 12] were undertaken using simplified deterioration models for reinforced concrete (*i.e.* Fickian transport models and uniform steel corrosion according to Faraday's Law). To allow for improved modeling of engineering limit states and thus improved assessment of sustainability, a multi-physics and multi-scale deterioration modeling framework for reinforced concrete affected by chloride-induced corrosion is being built [13].

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[1] "Ability of a structure or structural element to contribute positively to the fulfilment of the present needs of humankind with respect to nature, society, economy and well-being, without compromising the ability of future generations to meet their needs in a similar manner." [8]

This paper illustrates the need for considering both traditional engineering and newly-introduced sustainability limit states, and the importance of reliable and valid deterioration prediction models in support of sustainable design and maintenance of reinforced concrete structures. A simplified case study is presented in which a reinforced concrete panel is exposed to a marine environment. A multi-physics deterioration model is used to determine the time until an engineering limit state (cracking due to reinforcement corrosion) is reached, and a design and maintenance optimization is performed to select the best designs with regard to sustainability (global warming potential footprint).

2 Limit States

The concept of limit state design is applied in present codes like Eurocode [14], ISO 2394 [15], and MC2010 [8] for performance-based design (or re-design) for serviceability and structural safety. Within such design, the performance of the structure is assessed considering a set of limit states throughout the (design) service life (in CEN documents termed "(design) working life") [8]. A limit state separates a desired state from the adverse state (failure) [8]. Depending on the limit state chosen, a specific limit state can refer to the performance of the entire structure, one or more structural members, or local regions of a structure [8].

In practical design, most limit states are described using simplified models for the load, s, and the resistance, r, of the structure. The difference between load and resistance provides a limit state function, g, and the failure is determined by [8]

$$g = r - s \leq 0 \qquad (1)$$

An inherent part of selecting limit states is making a decision on the accepted failure probability, P_f, such that failure is increasingly rare for catastrophic or sudden failure modes;

$$P_f = \text{Prob}\,\{g \leq 0\} \qquad (2)$$

Thus, verification of design requires

- Definition of the limit states
- Identification of the required design service life and reliabilities
- Models describing the load and the resistance
- Model parameters and quantification of uncertainties.

For design of new structures, verification of performance requirements with regard to serviceability (SLS) and safety (ULS) is currently performed without considering possible changes of resistance over time, and in parallel service life verification is undertaken to check that no adverse states associated with time-dependent degradation are developed.

2.1 Engineering Limit States

As mentioned, according to [6] engineering limit states for reinforced concrete structures comprise Serviceability Limit States (SLS) and Ultimate Limit State (ULS). However, this binary classification of limit states is changing to better incorporate uncertainty in both the definition of the limit state, and our ability to observe whether it has been exceeded.

MC2010 [8] and coming *fib* reports are now grouping the limit states as ULS and SLS as they are traditionally used for structural design, while the limit states relevant for achieving a targeted service life are named "limit states associated to durability (or time dependent degradation)" (DLS) [16]. In some instances, this last group might overlap with SLS and ULS, but in the event “depassivation of the reinforcing steel” there is no obvious fit within either of the two traditional engineering limit state designations [16]. Moreover, ISO 2394 [15] introduces Condition Limit States (CLS) in addition to ULS and SLS. CLS covers: a) “an approximation to the real limit state that is either not well defined or difficult to calculate” (e.g. “use of depassivation as a limit state for durability)”, b) “local damage (including cracking) which can reduce the durability of the structure or affect the efficiency or appearance…”, or c) “additional limit state thresholds in case of continuous increasing loss of function”. DLS/CLS and SLS can be at the material and structural level as well as functional whereas ULS is at the structural level only.

As mentioned earlier, verification of design requires, among others, identification of acceptable reliabilities. According to [6] the suggested failure probabilities for depassivation is $P_f = 10^{-1}$ (corresponding to a reliability index, $\beta = 1.3$) and for ULS (collapse) $10^{-4} \geq P_f \geq 10^{-6}$, depending on the consequences of failure (corresponding to $3.7 \leq \beta \leq 4.4$). Reference is made to MC2010 [8] and ISO 2394 [15] for more detailed information on target failure probabilities.

2.2 Sustainability Limit States

Sustainability limit states in form of environmental impact targets or emission reduction goals have been proposed by numerous governments and policy-makers in order to achieve environmental sustainability on local, regional, and even global scales. These targets can take the form of reductions or absolute limits for each of 1 to dozens of environmental midpoint indicators, including global warming potential emissions, ozone depletion potential emissions, acidification potential emissions, particulate emissions, carcinogenic emissions, and many others.

An example of one of these environmental impact targets has been proposed by the United Nations Intergovernmental Panel on Climate Change (IPCC), which has suggested reduction targets for global greenhouse gas (CO_2-equivalent) emissions. Updated at the most recent climate summit in Paris (COP21), these emission reduction targets are based on a targeted global surface temperature rise of approximately 2°C [17], avoiding the greatest consequences of climate change and preventing irreparable damage to the biosphere. As shown by Russell-Smith *et al.* [18] these global emission reduction targets can be scaled-down to project-level reduction targets that form half of a sustainability limit state function;

the environmental “resistance”, *r*. Measuring the life cycle footprint of a project using rigorous life cycle assessment methods adhering to ISO 14040 [9] according to [8], the “load”, s, which is the second half of the sustainability limit state function, is calculated. As shown in Equation (1), the difference between resistance and load is the limit state function.

While accepted probabilities of failure for ultimate limit states (ULS) and serviceability limit states (SLS) are provided in standards and codes (e.g., [6]), there is no historical basis for selecting an appropriate probability of failure for a sustainability limit state. Based on a very simple model of accepted levels of annualized risk for deaths due to structural collapse by a major earthquake in Northern California and the annualized risk of deaths due to climate change (air pollution health impacts only), an acceptable probability of failure for not achieving sustainability targets (climate change goals) is approximately 12% [11]. While this number may seem high, it does not take into account a host of other health related impacts attributable to climate change, which would decrease the acceptable probability of failure. Among many other considerations, the increased uncertainty associated with climate change impacts in comparison to earthquake impacts is not accounted for. The impacts associated with earthquakes, while not predictable, are well known and can be estimated in aggregate. Very little is known about the true impact of climate change on human health, thus a greater level of uncertainty should be tied to such calculations.

Moreover, numerous researchers in the field of risk assessment and analysis have cautioned against assigning a specific risk associated with climate change or other global or regional scale environmental problems [19]. Such approaches allow designers to forego an understanding of the true consequences of their designs and focus on an uncertain design target. Such researchers suggest focusing on reductions associated with reducing the risk of global environmental disaster rather than assessing a “safe” level of risk and then designing within those levels [19].

Apart from environmental sustainability targets and limit states, social and economic targets and limit states should also be considered [20]. In many regards, economic limit states have long been considered explicitly or implicitly by trying to reduce the life cycle economic cost of a major structure. This concept of life cycle cost consideration was first formalized by the US Department of Defense in 1971 [20]. The social impact metrics, targets, and associated limit states are a recent introduction into the design process [21]. Such metrics and reduction targets have been proposed and calculated using the US Environmental Protection Agency’s “Social Cost of Carbon” methodology, which considers the broad, long-term social impacts of climate change [21]. More locally, social impacts resulting from reinforced concrete infrastructure construction, maintenance, and replacement include time lost on congested urban highway networks, *e.g.* [22, 23].

3 Design Approach

As mentioned before, MC2010 [8] states principles for sustainability design, but gives no detailed guidelines. Thus, we propose sustainable design and management of concrete structures to be undertaken using the multi-scale design and modeling framework within the “Sustainable Integrated Materials, Structures, Systems (SIMSS) Design Approach”, which was proposed by Lepech [10]. This design approach is valid for any product. The application to reinforced concrete structures was exemplified in *e.g.* [12]. The approach is in Figure 1 adopted to a single structure illustrating the impact of production, execution and operation (maintenance and loads).

As part of the assessment of potential design and maintenance strategies, both engineering and sustainability limit states need to be considered. For the determination of environmental emission reduction goals (e.g., global warming potential emission reductions as proposed by COP21), design for sustainability limit states may use a comparison of two potential design scenarios (a “*status quo*” and an “alternative”) as shown in Figure 2. Using ISO 14040 [9] life cycle assessment methods considering each design’s full design service life, the lifetime quantity of emissions, such as CO_2-eq, over the alternative design’s construction and repair can be probabilistically estimated for any time in the future. Similarly, cumulative emissions envelope can be computed for the *status quo* construction and repair timeline. From these, the difference between the alternative and *status quo* emissions envelopes can be associated with a given level of confidence for actually realizing the reduction target.

The probability of failing to meet a sustainability-focused goal by implementing the alternative design (viewed as the overlap between these two envelopes), $P_f(t)$, over the life cycle is shown at the bottom of Figure 2a. This probability of failure for meeting environmental sustainability midpoint indicator reductions is computed using Equation 3.

$$P_f = P\left(\frac{I_0(t_\gamma) - I_A(t_\gamma)}{I_0(t_\gamma)} - \gamma(t_\gamma) \le 0\right) \quad (3)$$

where, P_f is the probability of not achieving the environmental midpoint indicator reduction, $I_0(t_\gamma)$ is the cumulative impact of the status quo construction/repair strategy, $I_A(t_\gamma)$ is the cumulative impact of the alternative construction/repair strategy, γ is the recommended reduction in environmental midpoint indicators recommended by policy (*i.e.,* goal), and t_γ is the future time at which the recommended reduction should be achieved.

A “targeted” cumulative impact for the year a structure is functionally obsolete (t_{fo}) can be created by shifting the distribution mean by the targeted reduction percentage (see Figure 2b). If the shape and parameters of the cumulative impact of the alternate repair timeline in year t_{fo} and the cumulative impact of the reduction target repair timeline in year t_{fo} are known, this overlapped area can be computed analytically. Otherwise, this probability of failure can be determined through Monte Carlo methods knowing the underlying data that comprise the distributions. For the case treated in [12], the time-dependent probability of failure of not meeting the 38 % reduction target in greenhouse gases from Year 2011 to Year 2050 as set in the 2007 IPCC guidelines for greenhouse gas emissions [17] was calculated to be 31%.

4 Illustration of Concept; Impact Minimization of Façade Element

As a simple case study of integrating advanced service life modeling of a reinforced concrete element with sustainability assessment, a precast steel reinforced concrete façade panel positioned on the water-facing side of a waterfront office building was modeled. The objective of this model was to minimize the lifetime carbon footprint (CO2-equivalents) when considering the cost of fabrication, erection, maintenance (façade washing), and replacement of the façade panel. Here, we only consider the environmental sustainability metric of CO2-eq. since a) an absolute value for a sustainability target according to the Intergovernmental Panel on Climate Change (IPCC) [17] would require identification of a specific site for this case study, and b) a reduction target would require a reference to the impact of a conventional building. Thus, we aim at selecting the best design with regard to the environmental sustainability metric considered. Indirectly a variety of parameters are affected by varying the cover thickness, e.g. potential distribution, mass transport, etc..This is taken into account by applying a multi-scale and multi-physics modeling of reinforcement corrosion (see Section 4.1).

A software plug-in was coded that allows for geometric detailing of the steel-reinforced façade panel in Autodesk's Revit suite, and automatic porting of the geometry, material properties, and environmental exposures into other analysis software packages. Adapting the methodology used by Wu et al. [24] a concrete panel with dimensions 1.0 m x 1.0 m x 0.15 m was modeled. The panel is reinforced with steel reinforcing bars with a diameter of 13 mm spaced at 200 mm center-to-center. The reinforcement is modeled with a cover of 50 mm. The time-dependent exposure data in terms of relative humidity, temperature, and chloride concentration was applied.

4.1 Multi-Scale and Multi-Physics Modeling of Reinforcement Corrosion

To model the transport of heat and mass through the concrete, depassivation of reinforcing steel, and the corrosion of steel reinforcement over time, a multi-physics and multi-scale model is used as illustrated in Figure 4 [13]. The model includes coupled physical, chemical, electrochemical, and fracture mechanical phenomena at the material scale, which are further coupled with mechanical deterioration models at the structural/component scale [13]. Ongoing work includes extension to full 3D modeling of structural performance and modeling of the impact of the steel-concrete characteristics and electrochemical potential on chloride thresholds, see *e.g.* [25].

Coupled transport of heat and moisture, comprising both liquid and water vapor moisture transport, in porous media is modelled using Richard's equation, while multi-ion species transport and the interaction of predominant ions in the pore solution with solid phases of hydrated Portland cement is modelled by means of the Poison-Nernst-Planck equation and a thermodynamic model, respectively. Boundary conditions for the coupled heat and mass transport include varying climatic boundary conditions such as *e.g.* chloride content, relative humidity, and temperature, which, among others, affect the thermodynamics and kinetics of reinforcement corrosion. For more detailed information on the implemented heat and moisture transport model see *e.g.* [26, 27]

Depassivation of reinforcing steel and the corrosion of steel reinforcement over time is based on physical laws describing thermodynamics and kinetics of electrochemical processes at the reinforcement surface. These processes include various reinforcement corrosion phenomena, such as activation, resistance, and concentration polarization, as well as the impact of temperature, relative humidity, and oxygen. Within the modelling approach, Laplace’s equation is used to describe the potential distribution in concrete assuming electrical charge conservation and isotropic conductivity, while Ohm’s law is used to determine the corrosion current density from the potential distribution and resistivity of the electrolyte. Kinetics of electrochemical processes are described by anodic and cathodic polarization curves, which comprise activation and concentration polarization. The electrochemical processes are thereby coupled with heat and mass transport mechanisms to account for the impact of temperature, relative humidity, and oxygen on the reinforcement corrosion process. To link initiation (*i.e.* the formation of anodic regions) and propagation of reinforcement corrosion, a conditional statement is defined for the critical chloride threshold along the reinforcement surface. For more detailed information on the applied modelling techniques reference is made to *e.g.* [13, 28]

Corrosion-induced damage, such as deformations and cracking, are described by means of a thermal analogy to model the expansive nature of solid corrosion products. The developed fracture mechanics model accounts for the penetration of solid corrosion products into the available pore space of the surrounding cementitious material, as well as non-uniform distribution of corrosion products around the circumference of the reinforcement. Faraday´s law is used to relate the cross sectional reduction per time unit to the corrosion current density obtained by modelling thermodynamics and kinetics of electrochemical processes at the reinforcement surface. For more detailed information reference is made to *e.g.* [29-31].

4.2 Results of Façade Element Impact Minimization

To demonstrate how this type of modelling would be included in a sustainability assessment, performance of the panel was evaluated using the midpoint indicator CO_2 equivalents ($kgCO_2$-eq); *i.e.* neither social (e.g. accessibility) nor economic aspects of sustainability are included. The case is only used for illustration purposes; the actual applicability of façade washing as a mitigating measure should be verified.

Given that a cover of 50 mm meets design code requirements on minimum cover thicknesses, it is assumed that all engineering limit states considered by the design code (ULS and SLS) are inherently met. With cover thicknesses less than 50 mm, however, preventive maintenance will be required to prevent premature chloride-induced corrosion leading to structural degradation. In this case the impact of removal of surface chlorides through surface washing from time to time on all the considered engineering limit states is assessed. While thinner concrete cover will reduce the material intensity of the panel by consuming less concrete, increasingly thinner cover will also lead to more often required recurrence of façade washing. Following Lepech et al. [11], the average carbon footprint for production of 1 m^3 of concrete in the case study is 185 $kgCO_2$-eq. Also following Lepech et al. [11], the average carbon footprint of the assumed 150 L of water needed for each panel façade washing is 0.15 $kgCO_2$-eq. As shown in Figure 4, an optimal range of designed cover thicknesses to minimize life cycle global warming potential emissions from this one panel can be calculated, *r*(*t*). When combined with a project-specific sustainability limit state for global warming potential, *s*(*t*), a range of acceptable façade cover thicknesses, and their associated life cycle washing timeline, can be calculated.

Following Russell-Smith et al. [18], project-specific targets for sustainability can be set based on local, regional, or global sustainability goals that are absolute or relative in nature. Such project specific targets serve as sustainability limit states, *g*, in Equation (1). A life cycle target of 40 kg CO_2-eq for each panel on the building façade would, for example, suggest a cover thickness between approximately 27 mm and 40 mm, with occasional façade washing to remove accumulated surface chloride. This would result in a sustainability load, *s,* in Equation (1), lower than the resistance, *r*. In this way, designers can use advanced deterioration modelling, life cycle assessment techniques, and science-based sustainability limit states to inform the design and life cycle management of sustainable reinforced concrete structures.

5 Discussion

As stated in the introduction, innovation supporting sustainability-focused design and management of structures is required of the construction industry*, e.g.* [1], [3]. In line with Hamming's statement of the purpose of computing being insight, not merely numbers [32], W.F. Baker, Structural and Civil Engineering Partner at Skidmore, Owings & Merrill (SOM), and structural engineer for the Burj Kalifa, recently stressed that we need tools for exploring, inspiration and understanding possible design solutions; and that new tools lead to new solutions [33]. Led by P. MacLeamy, former chairman and CEO of HOK, a global design, architecture, engineering and planning firm, in 2004 at the Construction Users Round Table first stressed the need for placing more effort into developing and testing design alternatives, and the cost benefits that can be derived from this shift in effort [34]. By shifting efforts forward in time the ability to optimize design and control costs increases rapidly, as earlier pointed out by De Sitter [35] in his “Law of Fives”. MacLeamy [34] advocates the use of a combination of Building Information Modeling (BIM), Building Assembly Modelling (BAM) and Building Operation Optimization Modeling (BOOM) to change the traditional effort curve. We see a large potential in combining BIM-BAM-BOOM with multi-physics and multi-scale deterioration models.

This paper stresses the importance of reliable and valid multi-scale and multi-physics prediction models in support of sustainable design and management of reinforced concrete structures, the need for considering the whole life cycle of an engineered structure, and the increasing need to consider both engineering and sustainability limit states in practice. Efficient structures consume fewer resources in the design and construction phase; however, we also need to demonstrate that the design solution identified is indeed efficient and sustainable during the entire design service life. The iterative process used to accomplish this need is illustrated in Figure 1.

Besides reliable and valid performance prediction models providing information on structural safety and a timeline for activities, the construction industry requires a decision support system providing sustainability assessment and cost estimates.

As illustrated in *e.g.* [12] the proposed framework can be used for assessment of whether or not a given alternative design and maintenance (here repair) complies with a sustainability limit state (here a CO_2-equivalent emission reduction target).

To quantify the sustainability of potential design and management solutions the construction industry needs reliable and valid time-dependent performance prediction models. Such models must be a) mechanism based (*i.e.* multi-physics) and generic to capture the actual degradation mechanism of a suite of concrete compositions and exposure conditions, as well as b) multi-scale to allow for assessment of the time dependent structural performance considering variations in load, *s*, and the resistance, *r*, of the structure at both materials and structural scale.

Models for predicting structural degradation due to reinforcement corrosion have received most attention. However, reliable and valid models for structural assessment of corroding structures are still lacking and the understanding of several topics is limited. At the materials scale, models and quantified model parameters are needed for *e.g.* the long-term impact of crack, chloride thresholds for corrosion initiation, and the properties and distribution of corrosion products [25]. At the material and structural scale, models and data for changes due to sequential maintenance and repair, and the environmental exposure are required.

Models of other deterioration mechanisms *e.g.* freeze thaw action and alkali silica reaction and especially combined models for multiple deterioration mechanisms acting simultaneously requires additional attention.

As mentioned in Section 2, verification of design requires not only models (and quantified model parameters for loads and resistance) and identification of limit states (and identification of required service life and reliabilities), but also quantification of uncertainties. Uncertainties to be considered are *e.g.* statistical, measurement, and model uncertainties, and uncertainties related to natural variability and new information [15]. We see a need for increased awareness of the various types of uncertainties and further quantification of their impact on the reliability of performance predictions. Also, to ensure that prediction models are not excessively conservative, these models must be validated against field performance data and we see the significance of collaboration of academia with consultants and owners.

Considering these limitations and the limited validation of the prediction models, it is proposed to use sensor technology to support verification and updating of the models and to facilitate optimized management of the actual structures.

Regarding sustainability quantification, future needs for model improvement include, among others, modeling of the economic and social components of sustainability. As discussed earlier, these can take the form of direct impacts such as project life cycle cost considerations, or indirect impacts such as the impact of climate change on our global society. By necessity, the creation of these models will require collaborative research involving engineers, economists, sociologists, political scientists, biologists, and climatologists, among many others.

6 Conclusions

This paper links sustainability to service life modelling and stresses the importance of reliable and valid time-dependent performance prediction models in support of sustainable design and management of reinforced concrete structures and the need for considering the whole life cycle, and both engineering and sustainability limit states.

Performance models must be a) mechanism based (*i.e.* multi-physics) and generic to capture the actual degradation mechanism of a suite of concrete compositions and exposure conditions, as well as b) multi-scale to allow for assessment of the time-dependent structural performance considering variations in load and the resistance of the structure at both materials and structural scale.

Reliable and valid models for structural assessment are still lacking and we see the need for improved models for both the load and resistance at the materials and structural scale and increased awareness of the various types of uncertainties and further quantification of their impact on the reliability of performance predictions. To ensure that prediction models are not excessively conservative, prediction models must be validated against field performance data and we see the significance of collaboration of academia with consultants and owners.

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Figures

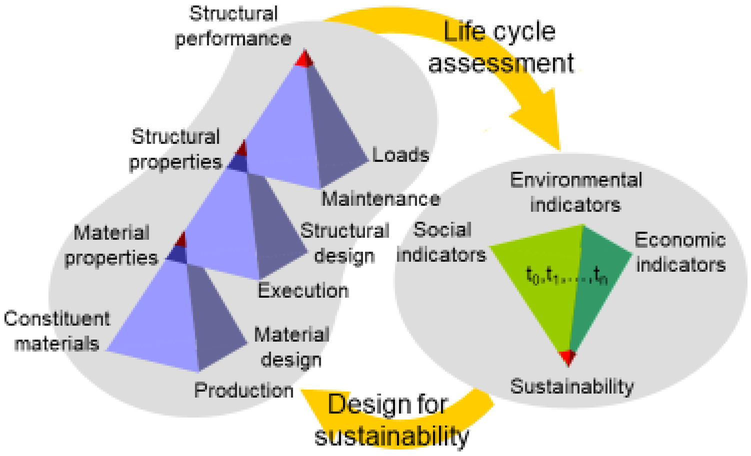
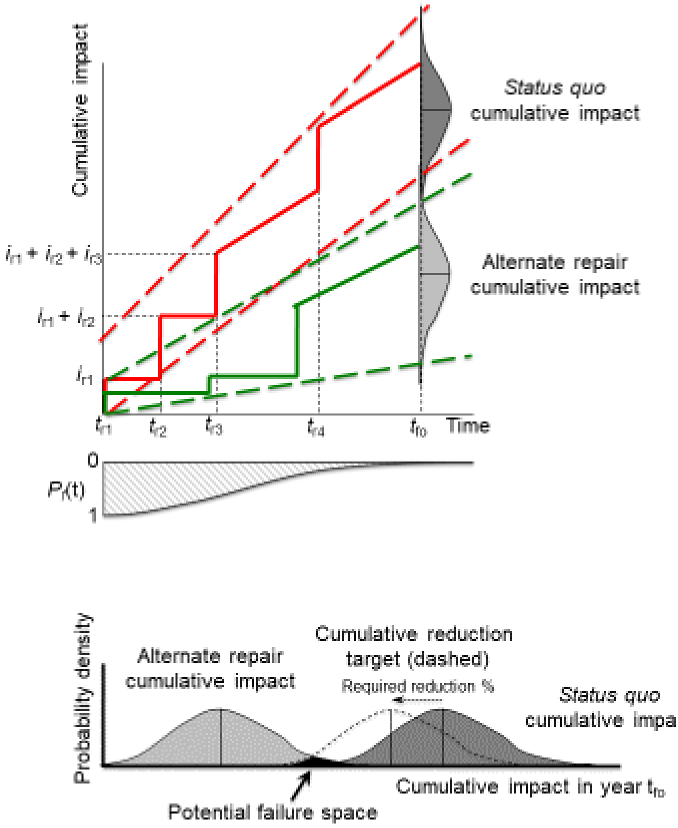


Figure 1 – Multi-scale design framework for “Sustainable Integrated Materials, Structures, Systems (SIMSS) Design Approach” adopted to a single structure. After [10]



a)

b)

Figure 2 – a) Probabilistic distributions of cumulative sustainability impact from construction (t_0) to functional obsolescence (t_{fo}) for status quo (higher envelope) and alternative repair strategy (lower envelope). Failure probability of not meeting reduction targets (P_f) is shown as a function of time. b) Cumulative impact distribution probability density functions in year t_{fo} for the status quo repair strategy, the alternative repair strategy, and required reduction target. The probability that the cumulative impact of the alternate repair in year t_{fo} is greater than the cumulative impact of the reduction target repair timeline in year t_{fo} is marked black. After [4, 12]

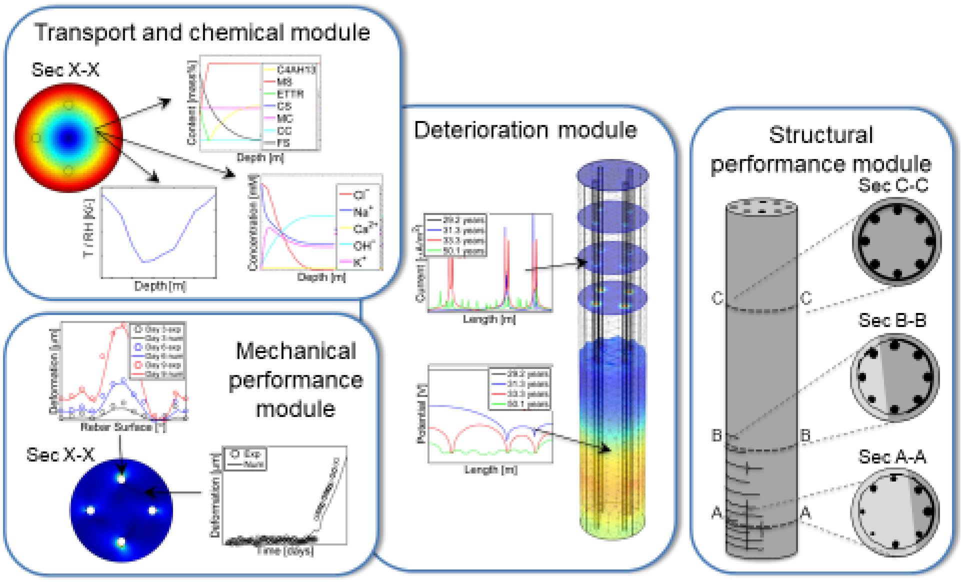


Figure 3 - Multi-physics and multi-scale modeling model for deterioration of reinforced concrete, including coupled physical, chemical, electrochemical, and fracture mechanical phenomena models at the material scale, which are further coupled with mechanical deterioration models at the structural/component scale. After [13]

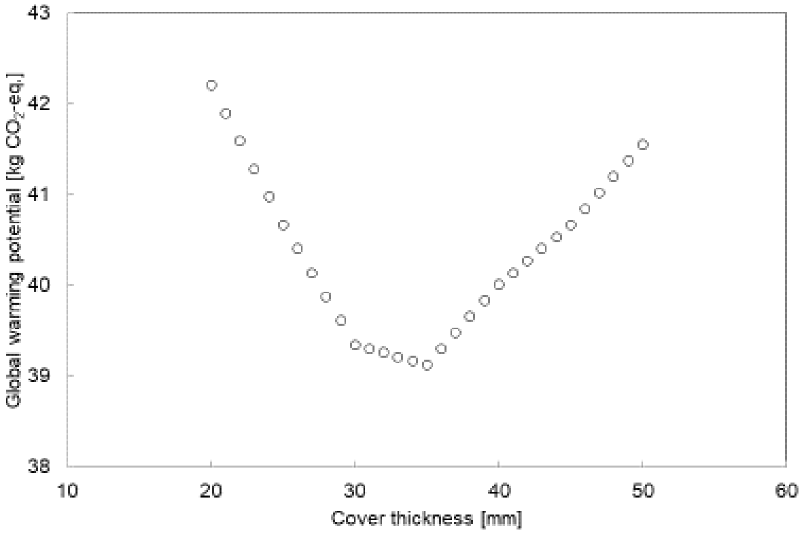


Figure 4 – Total global warming potential emissions for concrete façade panel case study as a function of concrete cover thickness considering both panel material production and lifecycle maintenance (façade washing). Note the limited scale on the abscissa.

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