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Review of the evolution of conceptual service life models for reinforced concrete.

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ABSTRACT
The objective of this work is to review, according to the available literature, some of the conceptual service life models for reinforced concrete in terms of durability, highlighting their contributions and the aspects in which they evolved with respect to their predecessors. The journey is made chronologically to the present time, beginning with the pioneering work of Tuutti in 1982. The transition from phenomenological to temporal models is addressed, as well as from the prescriptive to the performance point of view, and from the general vision to the specialized vision. One of the main conclusions is that each model must adjust its validity to an age range through which the structure transits, warning about the certainty of the predictions depending on the stage of service life to which it is confined. The review ends with reflections on the present and future use of these conceptual models.
Keywords: conceptual model; service life; durability; performance; evolution.

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Revisión de la evolución de modelos conceptuales de vida de servicio para el concreto reforzado.

RESUMEN

El objetivo de este trabajo es revisar, de acuerdo con la literatura disponible, algunos de los modelos conceptuales de vida de servicio del concreto reforzado en términos de durabilidad, resaltando sus contribuciones y los aspectos en los que evolucionaron con respecto a sus antecesores. El recorrido se hace en forma cronológica hasta tiempos actuales iniciando con el trabajo pionero de Tuutti de 1982. Se aborda la transición de modelos fenomenológicos a temporales, de lo prescriptivo al desempeño, y de la visión general a la visión especializada. Una de las principales conclusiones es que cada modelo debe ajustar su validez a un rango de edad por la que la estructura transite, advirtiendo sobre la certidumbre de las predicciones en función de la etapa de vida de servicio a la que se acote. La revisión finaliza con reflexiones sobre el uso presente y futuro de estos modelos conceptuales.

Palabras clave: modelo conceptual; vida de servicio; durabilidad; desempeño; evolución.

Revisão da evolução dos modelos conceituais de vida útil para concreto armado.

RESUMO

O objetivo deste trabalho é revisar, de acordo com a literatura disponível, vários dos modelos conceituais de vida útil do concreto armado em termos de durabilidade, destacando suas contribuições e os aspectos em que evoluíram em relação aos seus predecessores. A jornada é feita cronologicamente até o presente, começando com o trabalho pioneiro de Tuutti em 1982. A transição dos modelos fenomenológicos para temporais é abordada, do prescritivo para a performance, e da visão geral para a visão especializada. Uma das principais conclusões é que cada modelo deve ajustar sua validade para uma faixa etária pela qual a estrutura transita, alertando sobre a certeza das previsões dependendo do estágio de vida útil ao qual está confinada. A revisão termina com reflexões sobre o uso presente e futuro desses modelos conceituais.

Palavras-chave: modelo conceitual; vida útil; durabilidade; performance; evolução.

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1. INTRODUCTION

Service life models are important because they allow us to understand the behavior of a structure and at the same time monitor it over time through preventive and/or corrective maintenance. Various authors, committees and organizations define the types of models that have been used for several decades, to mention a few: ICA, 2000, 2017; Alconpat, 2020; CEB, 1982, 1983, 1987, 1997; CIB, 1991, 1996, 2004; DURACRETE, 1999, 2000; ISO, 2000, 2001, 2008, 2012; LIFE-365, 2005; NMX, 2018, 2020; FIB, 2006, 2010, 2013; etc. Initially, when the designer conceives the structure, he or she must build on or create a conceptual model. The conceptual model is based on drawings and strokes that obey what is to be represented. What one wants to represent can be presented in a qualitative or quantitative way. Hence, conceptual models allow empirical and analytical models to be represented in an illustrated way.

An empirical model is one that is based on experience and test results, usually from field and laboratory tests, to which correlation methods are applied, and of which it is not known if they will be reproducible under circumstances different from those in which they were obtained. On the other hand, an analytical model is one that represents situations in which so many results have been obtained that they have been correlated under the action of certain variables, which already become laws for construction materials or the durability of structures. In the jargon of the construction industry, empirical models represent engineers and analytical models represent scientists (Rilem Report 14, 1996). When it is necessary to build a durability model, both options must always be considered, the empirical and the analytical.

The conceptual model, on the other hand, is not only a representation of what would be expected in real life, in this case the service life of the structure, but also of the way in which some parameters can be addressed as a function of time, for example: degradation, performance, corrosion, etc. This approach can correspond to a deterministic, semi-probabilistic or probabilistic (stochastic) model, that is, mathematical models.

The difference between a deterministic model and a stochastic model is the way they handle uncertainty and randomness.

A deterministic model assumes that the outcome is completely predictable, with no uncertainty, uses equations to predict the outcome, and gives us a single answer. Whereas, a probabilistic model assumes from the beginning that there is randomness and uncertainty. Therefore, in a conceptual model, they are shown as probability distributions.

In summary, a conceptual model shows in schematic form what can happen with variables such as corrosion, degree of deterioration, performance, etc., through empirical (deterministic) and analytical (stochastic) mathematical models. With them, predictions can be made, whose verification, over time, allows the conceptual model to be refined.

A conceptual model can evolve depending on a wide variety of factors, and this is what has happened since Tuutti, 1982, in the case of corrosion, degree of deterioration or performance of a structure, depending on what you want to represent.

This paper reviews the evolution of conceptual models for service life of reinforced concrete based on the model of Tuutti, 1982, discussing the contributions of each one with respect to their predecessors and exposing the trend that they will follow in the coming years.

2. EVOLUTION OF CONCEPTUAL MODELS.

The model of Tuutti, 1982, reproduced in Figure 1, was a watershed that allowed us to see the deterioration of the infrastructure in terms of durability, and more specifically of corrosion. Tuutti presented it through his doctoral thesis in 1982. For the first time, two periods were considered: the initiation period, which includes the time it takes for aggressive agents to reach reinforcement, and the propagation period, which considers the onset of corrosion, catalyzed by ideal temperature and humidity conditions associated with the presence of aggressive agents, such as chlorides or CO_2. This was a conceptual model focused on corrosion deterioration.

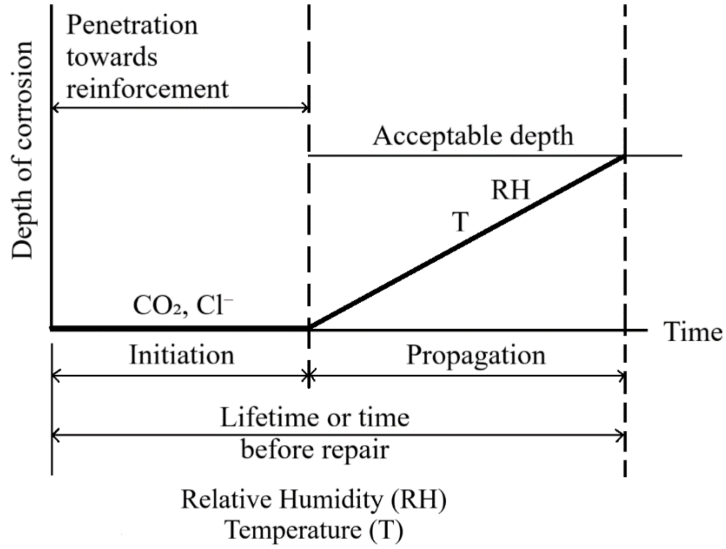

Figure 1. Tuutti's conceptual model (reproduced from Tuutti, 1982).

Several years passed and the conceptual model of Tuutti, 1982, served as the basis for refining new inclusions such as the limit state or the performance one, both discussed by Rilem's 130 CSL Committee in 1994 (Sarja and Vesikari Eds., 1996). Figure 2, reproduced from the 130 CSL Committee document, replaces the corrosion depth of the Tuutti model with the progress of corrosion in the Y-axis. This new model considers that the propagation period can be accelerated as a function of the angle "r" in the propagation stage. In the same way, it adds a limit state that is reached when there is a maximum loss of section, or loss of section or width of admissible crack. Beyond the borderline state, this model illustrates a dotted line that implies unknown behavior. This model was conceived and specified by this committee for cases of generalized carbonation corrosion

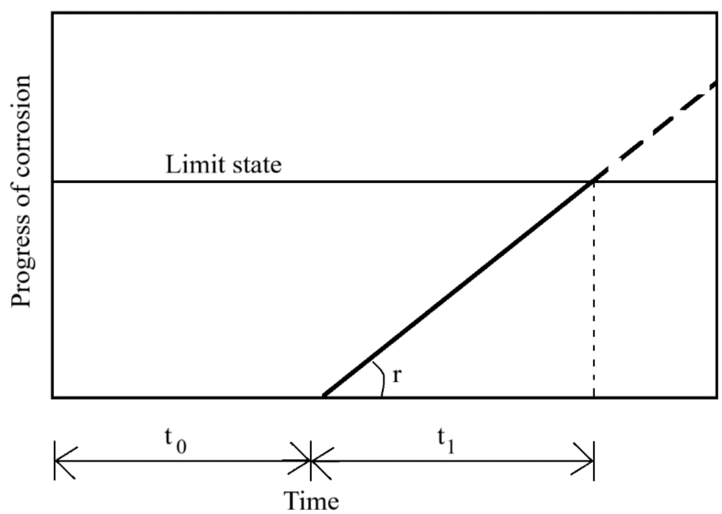

Figure 2. RILEM 130 CSL Committee, Boundary State Model (reproduced from Sarja and Vesikari Eds, 1996).

The same 130 CSL committee, at that time, considered it important that conceptual, or empirical, models could be sustained through the necessary investigations. This would make it possible to incorporate environmental parameters and develop other types of models, especially quantitative ones. The model in Figure 3 shows this by showing that the X and Y coordinates of the model follow a probabilistic distribution, i.e., that the model also has probabilistic criteria. This is one of the main contributions of that report. However, at that time there was not yet the boom of so many varieties of cement and concrete that could well have, and did, a transcendental importance in their behavior in the short term. Hence the importance of models continuing to evolve in order to preserve the latter.

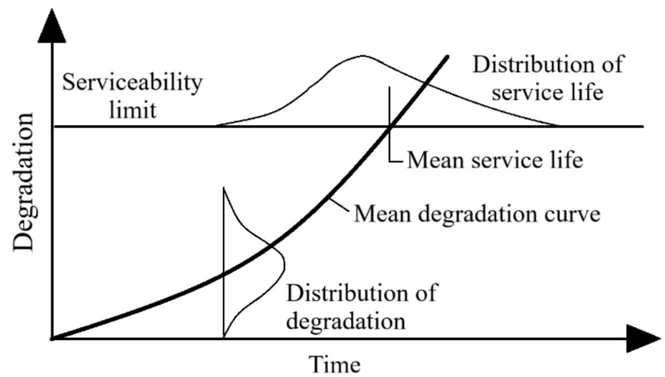

Figure 3. RILEM 130 CSL Committee, Degradation or Performance Model (reproduced from Sarja and Vesikari Eds., 1996).

Although the 130 CSL report was published in 1996, the various co-authors of this report had previously published explanations of the validity of these two models and others in: Alonso and Andrade, 1993; Andrade et al, 1989, 1994; Bakker 1994; Fagerlund et al 1994; Kasami et al, 1986; Parrot 1992; Philajavaara 1984, 1994; Siemes et al 1985; Tuutti 1982; Vesikari 1981, 1988.
One of the conceptual models of that time was that of Sommerville 1986a, 1986b, 1992, 1997, shown in Figure 4. This was a very interesting evolution of the previous models because it began to define what, in the previous model in Figure 2, was anticipated with a dotted line. In this model, the Y-axis is now called "structural performance", which starts optimally up to point A, which is called "present performance", and over time continues to decrease to point B, which is called "minimum acceptable performance". The difference between A and B is now called the "residual life." This type of model no longer specifically shows the initiation and propagation stages, but attempts to translate the previous models into the language of structural engineering. This, to achieve, perhaps and especially, a better understanding in the civil engineering sector, and particularly that of structural engineers. The model not only attracted attention, but quickly began to be complemented. One of these models that complement the structural part is that of Andrade in 1994, which adds point C, with the difference C-B being the "safety factor", as can be seen in Figure 5.

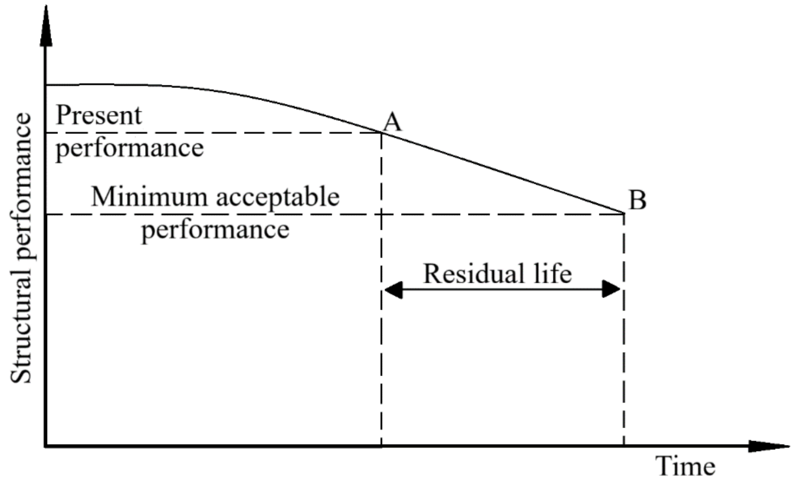

Figure 4. Somerville Model, 1986a, 1986b, 1992, 1997 (reproduced from Somerville, 1997).

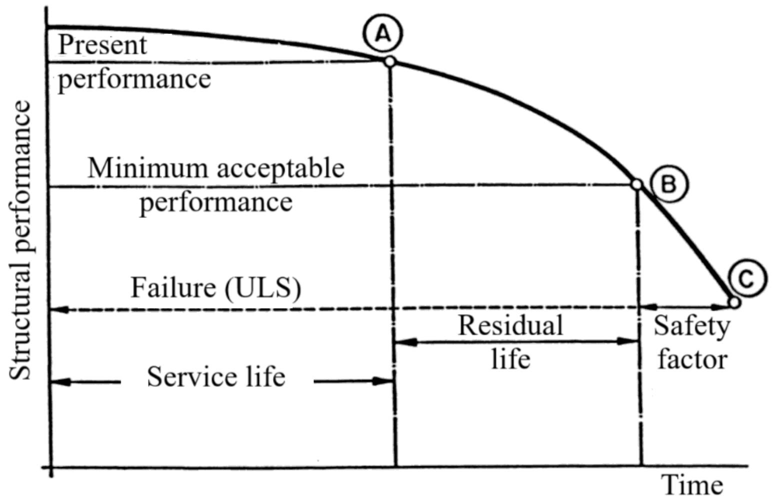

Figure 5. Andrade's Model, 1994 (reproduced from Andrade, 1994).

The interpretation that reinforced concrete has several "lives" was gaining strength and Paulo Helene in 1993, 2003 published his conceptual model that relates the "lives" through which concrete passes with its manifestations of damage, figure 6. That is, evidence of damage appears in different "lives", but it is attributed to different causes. Helene's model considers at least service life, service life, total service life, residual service life, etc. Until then, there was a need to place in context, in empirical models, the existence of various types of life and their relationship with phenomenological manifestations, or physical evidence. Paulo Helene (1993, 1997, 2003) is also one of the first to consider performance in the Y axis.

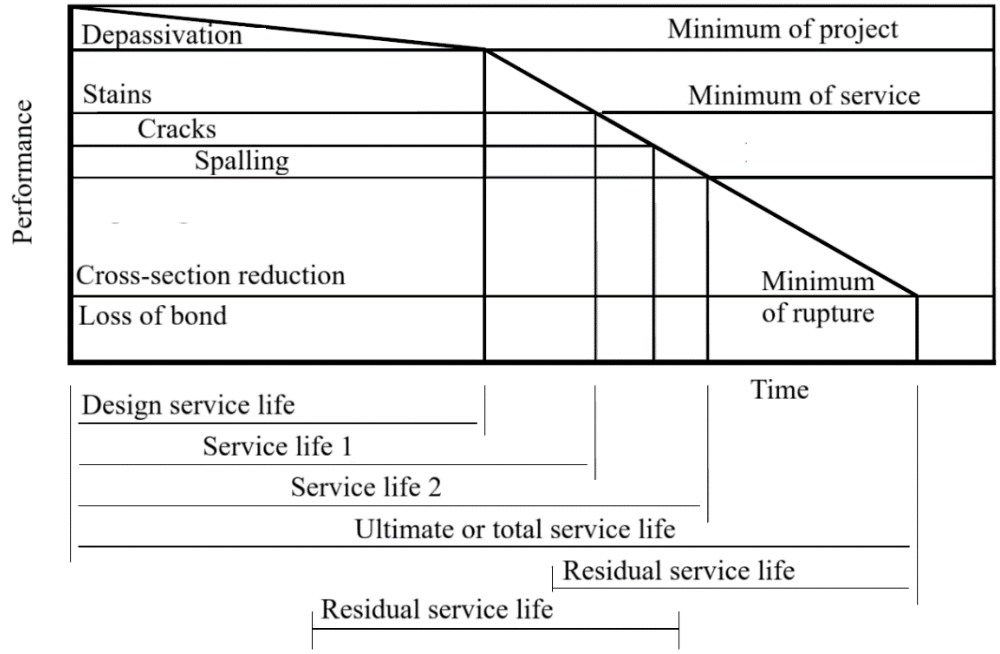

Figure 6. Model by Paulo Helene, 1993, 1997, 2003 (Reproduced and translated from Helene, 1993).

Although there will surely be more previous contributions, it was not until 2002 that Siemes and de Vries, 2002, published what was arguably one of the first phenomenological models. In practical terms, the one that refers to the evidence. Siemes and de Vries 2002 again show the periods of initiation and propagation and refine the Y-axis by calling it "amount of damage". This model simplifies, in part, what Paulo Helene had shown a few years earlier, 1993, 1997. The main contribution of Siemes and de Vries, 2002, is in the propagation period where they show what could well be called "behavioral slopes" and denote the amount of damage to be taken into account from the beginning of corrosion to then give rise to cracking, loss of bond, spalling and collapse.

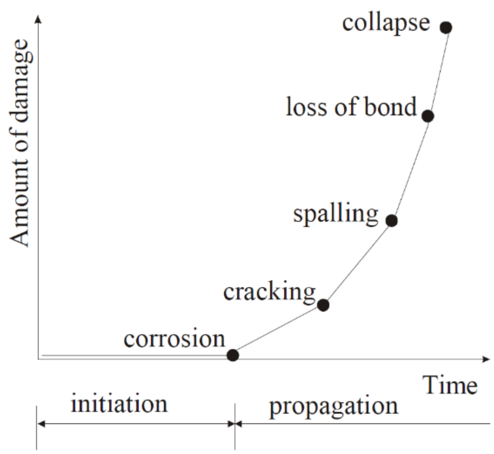

Figure 7. Siemes-de Vries model, 2002 (reproduced from Siemes-de Vries, 2002).

In this twenty-first century, the different existing models have already evolved, especially when referring to specific situations. One of them was the case of Melchers, 2006, who has published several models, 2003a, 2003b, 2004, applied to specific situations of marine corrosion. One of his models, which draws attention, is the one published in 2006 and which is reproduced in Figure 8. He considers it as a phenomenological model, based on the corrosion of the reinforcement (in mm). This model specifies what happens in the initiation stage focused on the diffusion of chlorides and hydroxides. Its propagation stage considers evidence such as the reduction of pH and the occurrence of corrosion in aerobic and anaerobic environments, typical of marine corrosion, but referring exclusively to bare metal. In his work, Melchers discusses the models of Tuutti 1982; Weyers et al. 1994; Bentur et al. 1997; François and Arliguie 1999; and differs from them in that some, Weyers/Bentur, apparently confuse the accumulation of corrosion products (usually not visible) with cracks (visible). For this reason, Melchers 2006, in his model, figure 8, only represents the behavior of steel

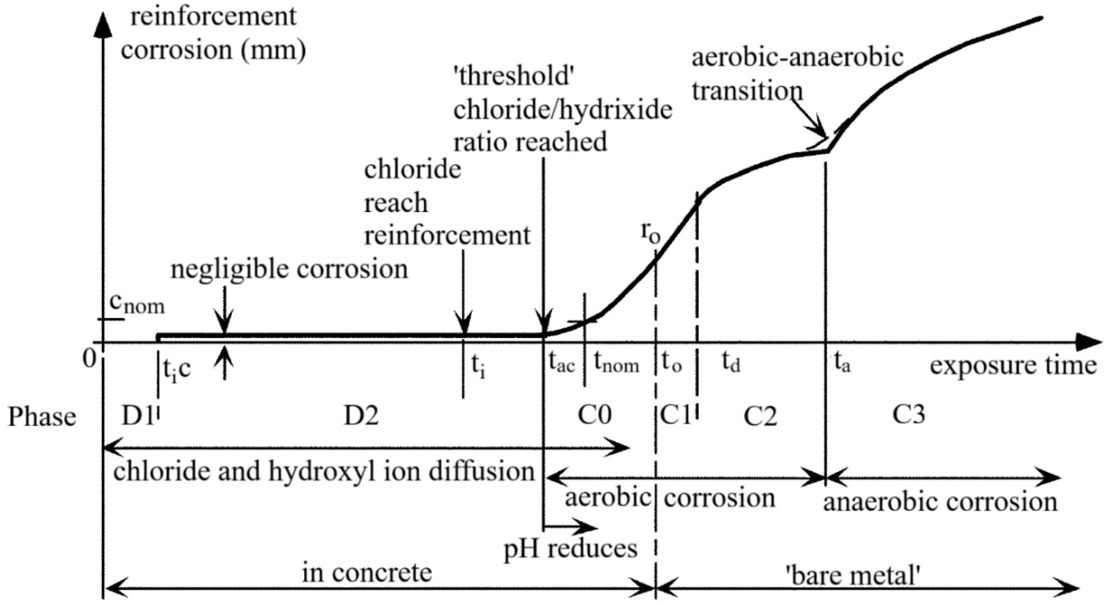

Figure 8. Model of Melchers and Li, 2006 (reproduced from Melchers and Li, 2006).

Until that moment, 2006, the different models had focused, at different times, on contributing with the following:

- Existence of the initiation and propagation period.
- Evolution of corrosion depth to degradation, then to amount of damage and finally to performance.
- Appearance of limit states and different "lives" of service, useful life, etc.
- Consideration of a statistical behavior in both axes.
- Existence of several "lives" considered within the stages of initiation and propagation of Tuutti 1982.
- Consider all or part of the above in conceptual models expressly for particular situations

However, in all cases, there was a need to limit the validity of the prediction of each conceptual model to the age range to which it was reliable. It was in 2007 when Castro and Helene 2007, 2018, presented a conceptual model that divided service life into 7 stages, starting from the conception of the structure and ending with its final disposition after its collapse. In each of the stages of the service life of this model, such as stages 4 to 7, the different types of damage that the initial and phenomenological models have contemplated occur. In the wording of the characteristics of this model, it is specified that the same type of damage, say a crack, can have different origins and at different stages of life of the structure. This model has been in force in Mexico (NMX 530, 2018; NMX 569, 2020) and Latin America (Alconpat, 2020). One of the aspects that the model of Castro and Helene 2007, 2018 highlights the most is that the predictions of mathematical models must be limited to the stage of service life in which they are. Since trying to extrapolate the prediction to different life stages can significantly affect its validity and certainty. To achieve this, Castro and Helene describe in detail each stage and what happens in it at all levels, from the administrative and conceptual to the limits of each stage of life, Figure 9.

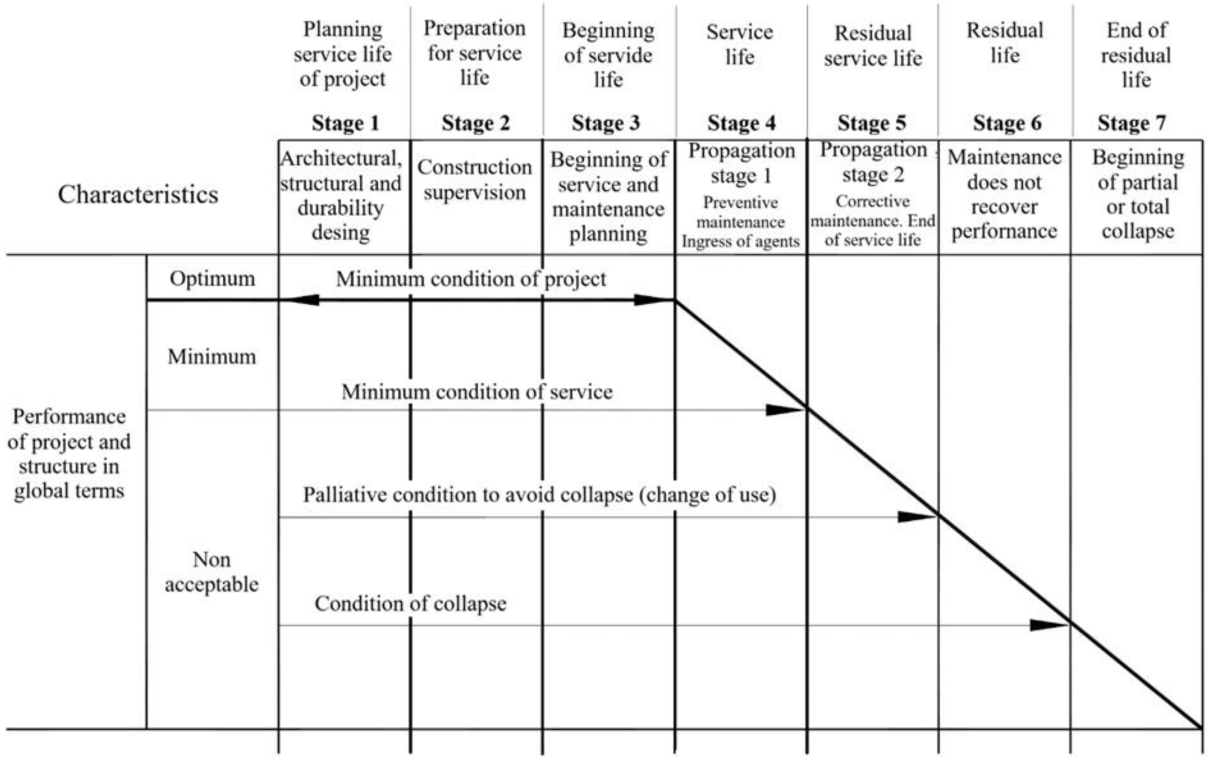

Figure 9. Conceptual model of P. Castro and P. Helene (Reproduced from Castro and Helene, 2007, 2018).

A need of the moment was to clarify what the different "lives" of concrete meant, as well as what the definitions of durability, commonly published in different media, meant. In this sense, Mendoza-Rangel and Castro-Borges, 2007, published a critical review in this regard, where they also classified the different types of conceptual models published up to that time according to their deterministic, semi-probabilistic or probabilistic character. At that time, key pieces for this review were the definitions published by DURAR, 1997; CPD, 1998; NMX 403, 1999; REHABILITATE, 2003; LIFECON, 2003; and CIB, 2004. The new definition proposals already indicated that both, new materials and climate change, would have to be taken into account.

This work sought to guide, critically but implicitly, where the evolution of conceptual models could be directed. They themselves Mendoza-Rangel and Castro-Borges, 2009 published, but in an expanded form, the risks faced by the use of these models in the face of the threats of climate change.

Conceptual models continued to evolve for specific situations, and in some ways including the contributions of previous models, Figure 10. In Figure 10, the reference year corresponds to the work being cited, but citations are also included from when each author or authors began the publication of their models. That is, the evolution is seen chronologically, although in practice some article was published before or after it occurred.

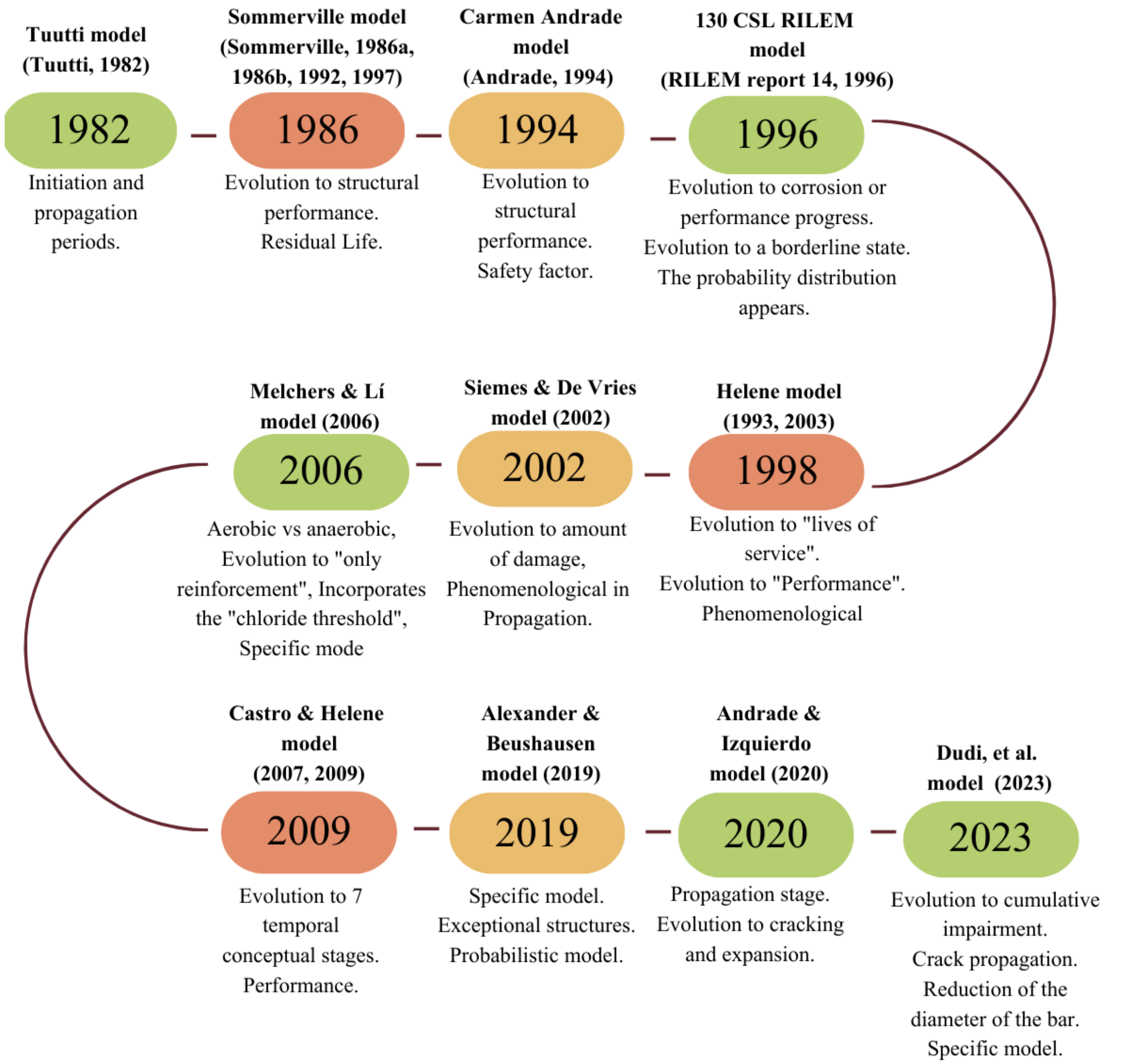

Figure 10. Timeline illustrating the contributions of conceptual models in the last 43 years.

In the last decade (2015-2025), models have appeared that build on the previous ones, but focus on specific needs such as considering rehabilitation and repairs, and the behavior in the propagation stage of structures that have not yet been repaired, as in the following cases.

Alexander and Beushausen, 2019, published a very complete review in which they discuss the modifications to the conceptual models to include parts that consider the rehabilitation of the structures. They also insist that the design of service life, model, and prediction must be clearly related to each other. In the literature reviewed, Alexander and Beushausen discuss various topics related to service life, one of the most interesting being where they state that there are models that are made for exceptional structures, such as the one in Figure 11, which is a probabilistic conceptual model that they work on based on the contributions of ISO 13823:2008, Siemes and Visser 2000, and DuraCreteR17, 2000. In ISO, every conceptual model has been important since the beginning of this century, ISO 2000, 2001, 2008, 2012. Considering that this type of conceptual model, with a probabilistic tinge, must be calibrated vs a completely probabilistic model, based on clear rules of design for durability, is something that Alexander and Beushausen insist on and that has allowed conceptual, semi-probabilistic and probabilistic models to advance, as has been discussed in recent decades in large working groups that have given rise to well-known models such as those of DuraCrete. 2017; Life 365, 2005; LIFEPRED, Andrade, & Tavares, 2012; fib ModelCode, 2006, 2013, etc.

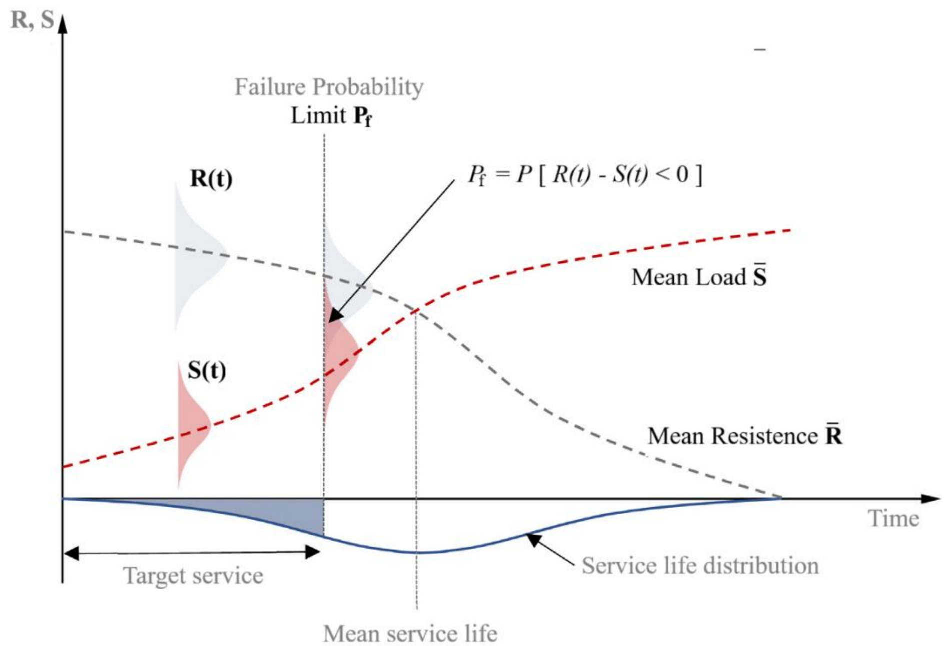

Figure 11. Alexander and Beushausen Model (Reproduced from Alexander and Beushausen, 2019).

In 2020, Andrade and Izquierdo focus in depth on what happens in the Tuutti propagation stage and how to represent it in a conceptual model, figure 12. This work has several contributions, being that of its conceptual model the one that contributes to a better understanding of the behavior of expansion and cracking over time, specifically by the action of sulfates.

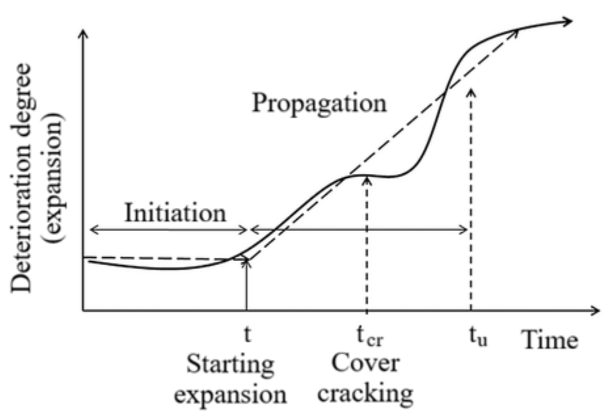

Figure 12. Andrade and Izquierdo's model (Reproduced from Andrade and Izquierdo, 2020).

Dudi et al, 2023, Figure 13, focus at a theoretical level on what happens in the propagation stage. Like Andrade and Izquierdo, 2020, they consider cracking and its evolution, but previously include in the propagation stage the behavior associated with the accumulation of corrosion products and the clogging of pores that ends up affecting the corrosion rate. Also in 2023, Lai et al proposed a theoretical model to incorporate the convection-diffusion effect of chlorides, although they do not analyze it from a conceptual model.

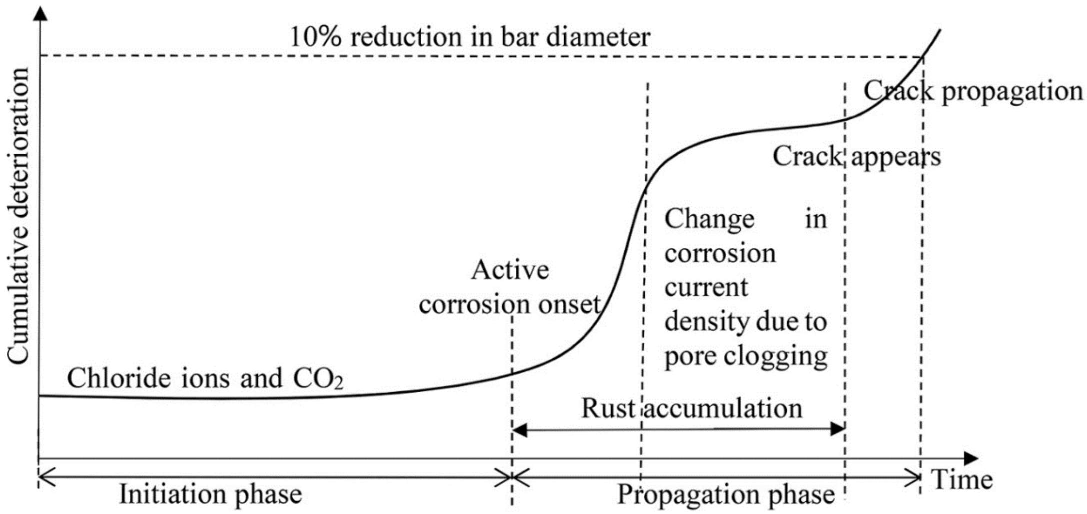

Figure 13. Dudi et al's model (reproduced from Dudi et al, 2023).

3. FUTURE PROSPECTS

It will be common to see in the near future more models that focus on the propagation stage, especially because this depends on many factors that are associated with the materials, the climate and the quality of the structure.

Despite the evolution up to these times, each group, each organization and each author follows its own convictions, adapted to its needs and projects. The important thing is to take into account what various concepts and models mean and what they are looking for, while at the same time adapting to materials, structures and customs from different regions.

It is important to highlight the role that various international organizations have played over the years in the development of models, not only conceptual, but also deterministic, semi-probabilistic and probabilistic, whose benefits are widely known (ACI, RILEM, ALCONPAT, CIB, fib, etc.). Figure 10 shows the line of evolution, which of course can still be perfected because surely other valuable models are not yet there. In this line of evolution, from this twenty-first century, the following stands out:

- Prescription vs. Performance.
- Compromise among service life designs, modeling, and prediction.
- Differentiate between conceptual, empirical (deterministic) or analytical (semi-probabilistic or probabilistic) models.
- Differentiate the stages of service life well.
- What happens in the propagation stage (expansion, cracking, etc.).
- Inclusion of rehabilitation or repair in models.

The advent of new variables such as new construction materials, climate change, new cements, among others, will pose new challenges in terms of the service life of concrete structures. Conceptual models will continue to evolve according to these new variables for both the initiation and propagation periods.

4. CONCLUSIONS

A review was made of the contributions of some of the conceptual models of service life that have been generated and published from 1982 to 2023, 41 years. The evolution has been very productive and has clearly taken into account the advances in the construction industry, as well as the research carried out during this time. The contributions of each one were discussed, linking the new of each version to the present time. The timeline provided contains the major contributions and the dates

on which they occurred. It was emphasized that the validity of the models, in general, is a function of limiting their predictions to temporal stages of "lives" of service. The revised models can easily be placed in one of the stages of the seven-stage conceptual model. The models have moved, in these four decades, from the prescriptive to the performance, from the phenomenological to the temporal, and from the general to the specific, where they will continue.
It was concluded that conceptual models will continue to evolve based on variables that have gained strength in recent years and that have to do with new materials, new cements and climate change.

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