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Reliability based Assessment of Structures in Marine Environment

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Abstract

The Atlantic Zone in Europe, like any coastal region, has many harbours, communication infrastructures and tourist buildings. These infrastructural elements are necessary for the economic life and sustainability of the region. The managers/owners of such structures in the region are therefore confronted with questions concerning the damage, maintenance, rehabilitation and the extent to which this maintenance or rehabilitation should be carried out. Since there are many parameters affecting the damage of a structure, it is of prime importance to know which of those parameters are guiding and what their relative importance are. Also, the effects of various critical limit states, possible conflicts between the engineer's and the owners criteria of failure and the mutual interrelationships among possible health assessment, monitoring techniques and repair options need to be assimilated within a single probabilistic framework accounting for the various epistemic and aleatory uncertainties accompanied with such decision making process. A central factor in this decision making process is the choice of damage model of a material and its evolution in time. In this paper, a general probabilistic format is proposed for structural assessment and maintenance. A questionnaire based survey has been carried out to procure information compatible with the proposed framework with special emphasis on damage of materials in the marine environment. Parameter importance based studies on steel and concrete have been subsequently performed in order to illustrate the impacts of the interrelationships of some critical components in the proposed framework. The study provides the owners/managers with a method of establishing a choice protocol for receiver operating characteristics (ROC) of non-destructive assessment techniques of structures based on its specific needs. This methodology, in association with reliable information regarding the choice of rehabilitation of a structure at an optimised cost can be helpful for any kind of decision making process in relation to a structure.

Keywords: Damage Modelling, Parameter Importance, Reliability, Probability

1. Introduction

The importance of structure and infrastructure assessment and the integration of such assessment information into a decision making framework has been emphasized in recent times (Neves *et al.* 2004). The collection and characterisation of this information is highly specific to the structure or a network of structures (Akgul and Frangopol, 2003) and is essentially probabilistic in nature due to the epistemic and aleatory uncertainties associated with the material, the degradation processes and the assessment techniques (Vu and Stewart, 2000). Non-destructive testing (NDT) based assessment of structures are extremely popular in this regard (Rouhan and Schoefs, 2003). Since resources are limited for nearly all infrastructure owners and managers, it is of critical interest to obtain case specific information on a structure or a network of structures, integrate the information within a general probabilistic format and determine the critical parameters to be measured for structural health monitoring or assessment through NDT. It is also possible to establish a protocol

for choosing an appropriate NDT technique based on how important a certain parameter is within the context of the structural performance on a case specific basis. This paper introduces a general hierarchical information system leading to decision making strategies for structure and infrastructure owners and managers. This system is compatible with probabilistic analysis. A questionnaire has been developed based on the proposed hierarchical information system and data related to degradation of marine structures in coastal region have been obtained. Information within the proposed framework can be dynamically updated if needed, without affecting the arrangement of the hierarchy of information. Updating of information can dynamically affect the decision making process. The relevance of parameter importance measures within such probabilistically compatible information framework has been emphasized and illustrated with examples on steel and reinforced concrete deterioration. The parameter importance measures guide the decision making processes for measurement and monitoring of significant variables from which information of the evolution of structure depending on its specific performance criteria can be obtained. The possibility of significant changes of these relative importance measures due to information update is also investigated.

2. Information based Case Specific Assessment

2.1 A Hierarchical Information Framework

A hierarchical information framework is presented in Figure 1. The framework is compatible with probabilistic treatments of the various components of information obtained from a structure. The format is also applicable to a network of structures.

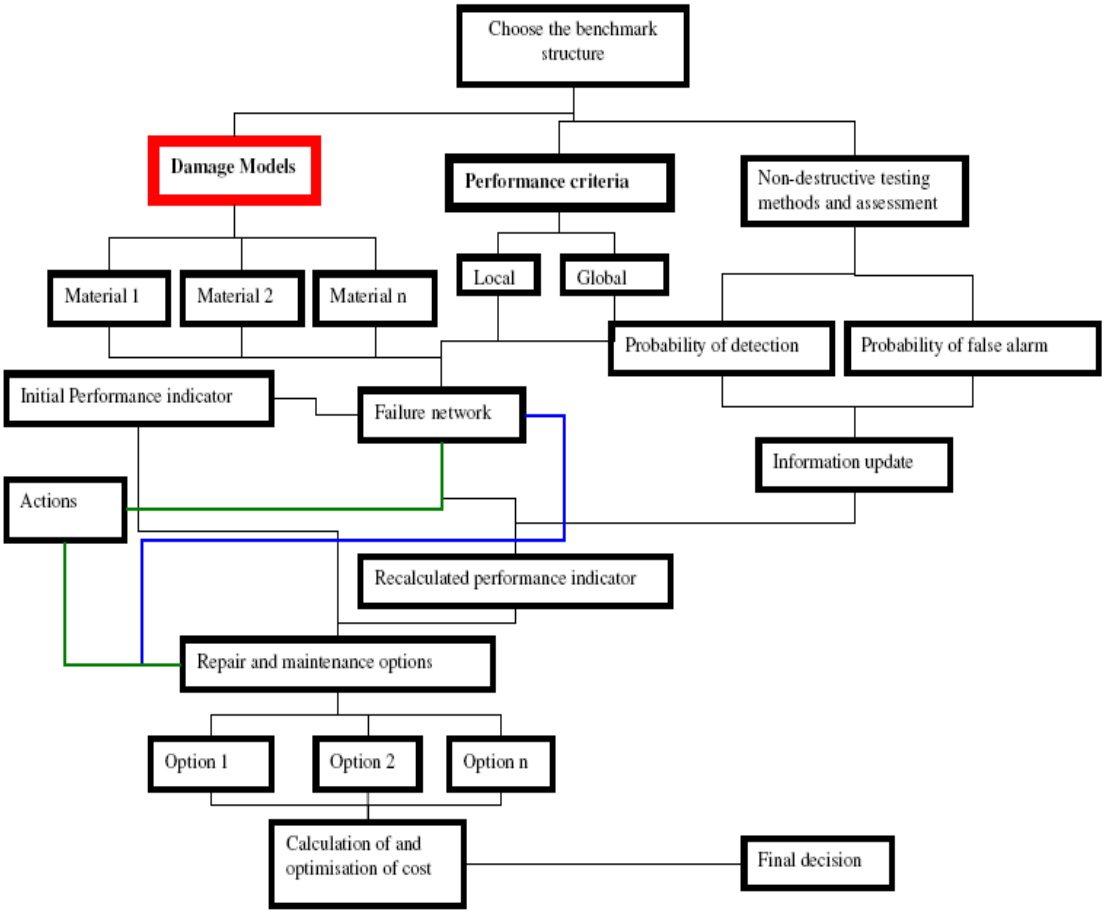

Figure 1. Hierarchical Information Framework.

A benchmark structure needs to be chosen and its performance criteria defined. It is important to point out that the performance criteria by the owner and that arising from a mechanical viewpoint need not necessarily be the same and there can be a possibility of conflict. The failure network can be obtained from these various local and global performance criteria. Since the degradation of a structure evolves in time, information on the damage evolution along with an idea about the uncertainties of the participating variables are also required. The choice of the damage model and the idea on uncertainties can be based on measurements, theory, empirical knowledge or expert's opinion and will affect the assessment of the structure based on how correct the choice is. Information of performance criteria coupled with that on damage models provide the evolution of performance indicators over time. However, appropriate NDT techniques can help update such performance indicator at any given time and this information can directly feed into an optimised repair, rehabilitation and maintenance strategy (Sheils *et al.* 2007). The information from NDT techniques can be characterised by uncertainties related with the probability of detection (PoD), which describes how correctly a method can identify a damage when there is one present and that related with the probability of false alarm (PFA) describing how often the method detects a damage when there is none present. The plot of PoD versus PFA is known as the receiver operating characteristic (ROC) (Schoefs and Clement, 2003) and these curves are indicative of the efficiency of the NDT technique they are associated with. It can be observed from Figure 2 that the updating of a performance indicator would be more severely affected if the ROC is inefficient for measuring a variable that significantly takes part in the evolution process. On the other hand, for a less important variable a comparatively inferior NDT can be safely used without affecting the decision making process (dependent of update of performance indicator/s) significantly. The relative parameter importance measures of the different participating variables thus play a critical role in the choice of an NDT technique.

2.2 Development of a Questionnaire

A questionnaire has been developed to obtain the hierarchical information framework introduced in the previous section for various materials (steel, concrete, stone and mortar, wood) related to the MEDACHS-Interreg IIIB Atlantic Space Project No 197. The interdisciplinary information framework has been developed from the assimilated responses to the questionnaire by the various participating experts. The questionnaire requested information on the damage and deterioration models of different materials along with as much information as possible related to the uncertainty of the parameters and the models involved in the deterioration process. The general governing parameters were identified by the experts and preliminary information on existing parametric and sensitivity studies were obtained. A brief summary of the possible testing regime/s on the materials and the options of NDT techniques for testing related to certain benchmark structures chosen by the participating groups were noted. The various limit state criteria and the possible conflicts from the engineer and the owner's points of view were summarized. Information on existing knowledge on the connection of the micro-scale modelling to the macro-scale counterpart for real structures, if any, was requested. Such information is deemed to be the starting point of a probabilistic analysis based on the framework presented in Figure 1 and the quality of information at any given point of time can significantly affect and alter the decisions of maintenance options related to the structure.

3. Illustrative Damage Models

For the purpose of illustration, two damage models, corresponding to the corrosion of steel and reinforced concrete respectively in a marine environment are considered from the responses to the questionnaire. The corrosion of reinforced concrete is a distinct two-stage process, comprising of the initiation and the propagation phase (Ferreira, 2004) unlike the chosen single stage steel corrosion model leading to interesting implications on the selection of NDT protocol. Coefficients

with absolute values in the various equations are representative and have been used as a simplified version of the reality for the purpose of illustration.

3.1 Steel Corrosion Model

The steel corrosion model used by Paik *et al.* (2007) has been considered. The model is given as

$$t_r = C_1(T - T_c - T_t)^{C_2} \quad (1)$$

where t_r is the loss of thickness due to corrosion, T is the age of the structure, T_c is the life of coating and T_t is the transition time to corrosion propagation. The coefficient C_1 is indicative of the annual corrosion rate while C_2 describes the trend of corrosion propagation. This is a special case where the initiation phase (related to T_c) and the propagation phases are assimilated within a single equation and uncertainties of these phases are available on a macro level.

3.2 Reinforced Concrete Corrosion Model

Sometimes the initiation and the propagation phases are modelled separately and the macro level models can be further linked to a more detailed model on a comparatively smaller level. A typical example of such a model can be given in terms of corrosion of reinforced concrete due to chloride ingress. The initiation phase is comprised of the time during which the chloride enters the structure and depassivates the steel layer and starts the corrosion. The propagation phase is related to the rust formation, sectional property loss and subsequent cracking and spalling of concrete (Imran Rafique *et al.* 2004). A simple two-stage detailed model is considered in this paper from the responses to the questionnaire for the purpose of illustration. The loss of steel diameter in the propagation phase due to chloride ingress is considered to be of importance in this regard. Thus, the propagation phase can be described as (Thoft-Christensen, 2001)

$$\frac{\Phi(t)}{\Phi_I} = 1 - \frac{\lambda i_{corr}}{\Phi_I}(t - T_{corr}) \quad (2)$$

where $\Phi(t)$ and Φ_I are the diameter at a given time 't ' and the initial diameter of reinforcement bar respectively. The parameter λ is a constant transforming the corrosion rate i_{corr} from $\mu A/cm^2$ to mm/year while T_{corr} is the time for corrosion initiation. However, this model can be resolved in a more detailed fashion, where the corrosion rate can be expressed as (Vu and Stewart, 2000)

$$i_{corr}(t_p) = i_{corr}(1).0.85.t_p^{-0.29}$$
$$i_{corr}(1) = \frac{37.8(1 - w/c)^{-1.64}}{d} \quad (3)$$

where t_p is the time of corrosion propagation, $i_{corr}(1)$ is an initial reference state, w/c is the water-cement ratio of the concrete and the term d is the concrete cover in centimetres. The corrosion initiation time can be further resolved as (Thoft-Christensen 2001, Zhang and Lounis 2006)

$$T_{corr} = \frac{d^2}{4D}(\text{erf}^{-1}(\frac{C_{cr} - C_0}{C_i - C_0}))^{-2} \quad (4)$$

where D is the diffusion coefficient and the terms C_{cr}, C_0 and C_i are the threshold, surface and initial chloride concentrations respectively. The diffusion coefficient can be further broken down as (Thoft-Christensen, 2001)

$$D = 11.146 - 31.025 w/c - 1.941\hat{t} + 38.212(w/c)^2 + 4.48(w/c)\hat{t} + 0.024\hat{t}^2 \quad (5)$$

where D is expressed in 10^{-12} m^2/s and $\hat{t}$ is the temperature in degree celcius.

3.3 Information on Uncertainty

Information on uncertainty of the different variables participating in steel and concrete corrosion is required for further probabilistic analyses. Values of uncertainty for steel are provided in Table 1 while that for reinforced concrete in provided in Table 2.

	Mean	Coefficient of Variation (COV)	Lower Bound	Distribution
C_1	$1.4x10^{-3}$	0.2	$0.5x10^{-3}$	Weibull
C_2	1	0.4	0.25	Lognormal
T (years)	Variable	0.03	0.1	Normal
T_c (years)	7.5	0.4	1.5	Normal
T_t (years)	0.5	0.1	0.0	Normal

Table 1. Information on Uncertainty for Steel Corrosion.

	Mean	Coefficient of Variation (COV)	Lower Bound	Distribution
C_0 (% wt of cement)	0.65	0.1	0.4	Lognormal
C_{cr} (% wt of cement)	0.3	0.17	0.1	Lognormal
C_i (% wt of cement)	0.01	0.05	0.005	Lognormal
d (m)	0.04	0.2	0.01	Lognormal
Φ_l (m)	0.02	0.05	0.016	Normal
D (m^2/s)	$3x10^{-11}$	0.17	$0.3x10^{-11}$	Lognormal
λ	$1.16x10^{-2}$	0	$1.16x10^{-2}$	Fixed
$\hat{t}$ (^oC)	20	0.6	1	Lognormal
t_p	Variable	0	0.1	Fixed
w/c	0.35	0.6	0.2	Lognormal

Table 2. Information on Uncertainty for Reinforced Concrete Corrosion.

4. Parameter Importance Measure

In the proposed probabilistic hierarchical information framework, it is easy to quantify the relative participation of various parameters in terms of reliability index. The reliability index, β can be defined as

$$p_f = \Phi(-\beta) \tag{6}$$

and

$$p_f = \iiint \ldots \int_{g(x_1,x_2,\ldots x_n)\le 0} f(x_1, x_2, \ldots x_n)\, dx_1 dx_2 \ldots dx_n \tag{7}$$

where $g(x_1,x_2,\ldots x_n)$ is the limit state, $f(x_1,x_2,\ldots,x_n)$ is the joint probability distribution of the participating variables x_i (i=1 to n), Φ is the standard normal distribution and p_f is the probability of failure defined as the probability of violation of the limit state. For details, (Ditlevsen and Madsen, 2003) can be consulted. The reliability index can be computed by first order reliability methods (FORM) or second order reliability methods (SORM). Parameter importance measures can be found as a by-product of reliability analysis (Haukaas, 2003). The importance measures are expressed as percentages, add up to hundred and are proportional to the partial derivatives of the reliability indices with respect to the mean or the variance of various parameters. For details, Haukaas (Haukaas, 2003) is referred. The measures help identifying the relative ranking of various parameters and provide indication related to the variables which are the most important from measurement.

It is clearly observed from Section 3 that the importance of a parameter can change over time due to the presence of a new regime of evolution of deterioration. Also, a relatively inefficient measurement of a variable of relatively low importance can be sufficient. This can be used as a basis for selecting NDT or any other measurement protocol. The efficiency of a measurement technique can be described by ROC and the comparison of the ROC curves of various techniques serve as a comparison for their relative efficiencies. Figure 2 describes three hypothetical ROC curves for three different measurement methods of different levels of efficiency. However, an improved efficiency usually comes with a higher price in terms of finance, availability, accessibility and expertise. As a result, the use of a measurement method with very high efficiency or precision is not recommended for the measurement of variables within a system that have significant, but relatively low impact. A comparatively inferior measurement technique would be cost effective, simple and more meaningful in those cases. Thus, the parameter importance measures directly affect the decision making process in terms of monitoring and assessment of structures.

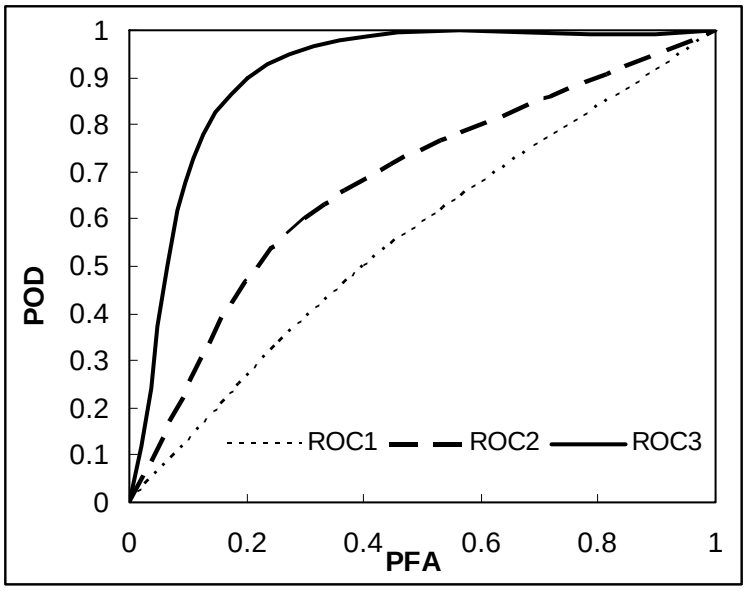

Figure 2. ROC Curves Corresponding to Different Levels of Efficiency of NDT Techniques. The Parameter Importance Measure Guides which NDT Technique to use under What Condition.

5. Results

An example of parameter importance measure values with respect to different reliability indices is shown considering the model of corrosion of steel. It is easy to observe that the age of the structure and the transition time affect the final value little and can thus be treated as a constant in the reliability analysis to reduce computational efforts. On the other hand, it is observed that the relative importance of the parameters change with the reliability index significantly. As a result, with the evolution of a structure the most important variable affecting the reliability index can change. As a result, the choice of an ROC curve for a certain NDT method related to the measurement can vary. For example, the importance factor for the life of coating sharply falls from 37.2 to 16.1 for a corresponding change in the reliability index from 3.4 to 2.6. As a result, a comparatively inferior method can be used to determine the variable at a lower reliability index since its contribution to the index is considerably low.

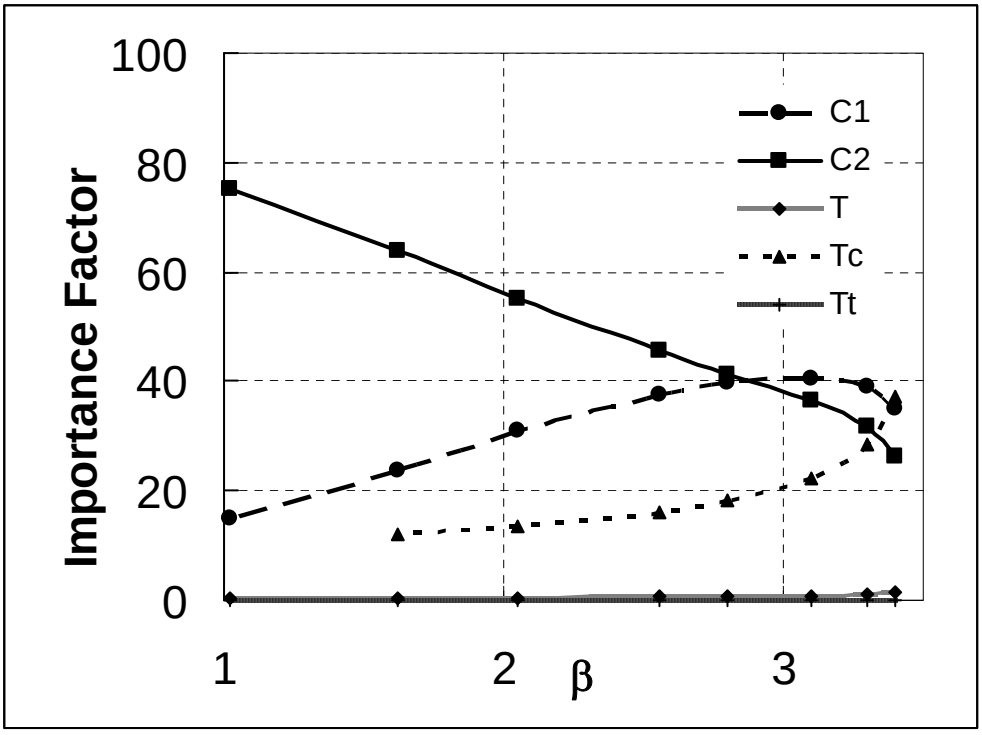

Figure 3. Significant Variation of Parameter Importance Measures for Different Reliability Indices.

Certain parameters can significantly affect the reliability index even with relatively low coefficient of variation. However, it is often the case that accurate measurements of such a parameter are relatively simple and does not require very expensive instrumentation. Under those circumstances, the uncertainty related to the variable can be greatly reduced without any attrition of resource and new and important governing variables emerge out which had been masked before. A typical case is considered in the case of chloride ingress and corrosion of reinforced concrete. When an uncertainty related to the cover depth exists, the cover depth governs the corrosion initiation time. However, if information on cover depth is precise, the importance of critical chloride concentration is felt more strongly. The importance of diffusion coefficient is also more. Table 3 provides a summary of the importance factors.

	d	C_{cr}	C_0	D	C_i	Comments
Parameter Importance	41.3	39.8	11.6	7.3	0	d as in Table 2
	-	69.5	19.3	11.2	0	d deterministic

Table 3. Variation of Parameter Importance Measures with Uncertainty of Measurable Variables.

Uncertainty reduction of measurable values alone does not affect the choice of the measurement technique to be adopted for other important parameters. Very often, a certain variable takes part in a number of physically distinct processes and are also layered within the hierarchy of information. In the example of chloride induced corrosion of reinforced concrete, the water-cement ratio is one such variable. As is observed in Section 3.2, the variable takes part both in the initiation and the propagation phase of corrosion and is layered within the diffusion coefficient in the initiation phase and within the corrosion rate in the propagation phase. Significant difference in the parameter importance measure for water-cement ratio exists in the two phases. Also, since temperature is a variable that can be comparatively easily measured a reduction of uncertainty for temperature would automatically mean that the importance of water-cement ratio would govern when considering the importance of diffusion coefficient. This kind of layered information is extremely important when the inspection, monitoring and assessment of a structure is layered as well. For example, on a global level a certain parameter can be less important. However, once the critical locations on the structure are identified, the less important variables start dominating due to the changed criteria of assessment on a local scale. Figure 4, in the form of a flow-chart, summarizes the discussion on the varying importance measure of the same variable at different phases of evolution of damage while being latent within the main participating parameters. The numbers in percentages show the respective parameter importance measures.

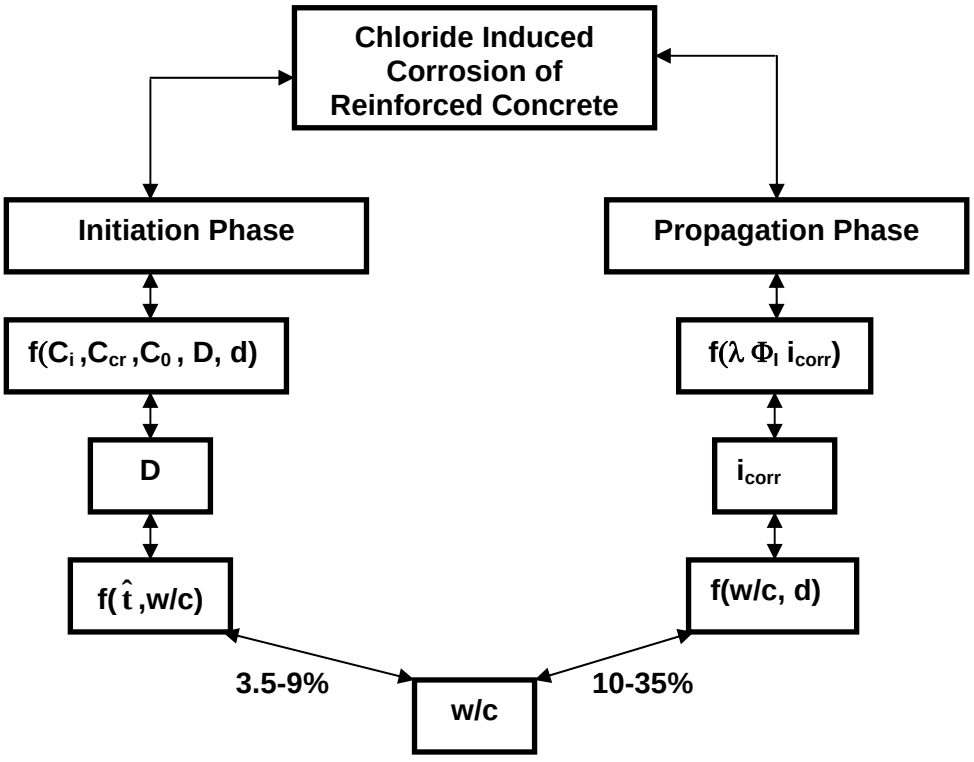

Figure 4. Importance Measures and Hierarchy for a Parameter in Multiple Phases of Evolution.

6. Conclusions

The relevance and application of parameter importance measure based relative ranking of governing factors for an evolving structure has been assessed in a proposed hierarchical information system based probabilistic framework. The impact of such measures on the choice of NDT techniques and measurements of variables for structural health monitoring, assessment, maintenance and subsequent rehabilitation decision has been pointed out. The variation of the importance measures with information update and temporal evolution of a structure has been investigated and discussed. It is observed, that under certain conditions, some governing parameters can clearly be measured with a technique with inferior receiver operating characteristics. The methodology is not limited to the discussed corrosion models and can also be applied to network of structures. The method is compatible for both simulated, measured and mixed data.

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