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A non-linear fuzzy degradation model for estimating reliability of a polymeric coating

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ABSTRACT

Oftentimes, material components follow non-linear degradation because the material loss trough time is non-linear; the components present different levels of resistance during a degradation process. Constructing predictions of the component life span and performing reliability analyses regarding degradation is possible by non-linear regression. Generally, this method ignores the prediction error in the extrapolated time and it does not account measurement error in the observed sample paths. In this paper, it is proposed new means for predicting time to failure of the components, using a calibration regression method for measuring the error prediction in the extrapolation process. In order to consider the uncertainty, we proposed to perform the estimated times by a trapezoidal fuzzy numbers, providing a more reliable prediction without loss of information. Since the times to failure are shaped by fuzzy numbers, it was adapted the fuzzy probability theory to the classical reliability analysis for estimating the fuzzy reliability of a component. An accelerated test of a polymeric coating process was performed and also an application for a preventive maintenance frequency was proposed.

1. Introduction

During accelerated life testing the test units are subjected to more severe stresses than those of the normal operating conditions, thus shortening the testing times and provoking more failures. Estimating the normal stress levels of the process factors, based on the accelerated life testing data, is performed by an extrapolation process [29]. The process of wearing-off material is known as degradation process. Degradation is the reduction in the reliability of a component, until it experiences partial or total failure. Estimating a component remaining life is crucial for preservation and maintenance of concrete installations; modeling degradation behavior to predict component's life span is then of special interest. Material components feature non-linear degradation because the material loss trough the time is not proportional to elapsed time; following a natural process [34]. The mechanisms of the specific application must be fully understood, enabling the correct extrapolation model to be completely specified, otherwise results could be biased. Ramalho [35] mentioned that experimental results are usually characterized by big scatter and significant discrepancies for the same materials, tested by different research teams. This scatter in

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the data is frequently attributed to many variables involved in the experiments, namely: environment (especially humidity), contaminant layers, differences on test conditions and uncertainty on the results evaluation, considering this as the most important and difficult to monitor. Blau and Budinski [3] describe some of the main advantages of ASTM standard test methods, namely: the test methods have been rigorously evaluated by previous inter laboratory exercises and the procedures carefully documented.

Using non-linear models by themselves is possible; however, those include unhandled uncertainty because the information related to the failure of a component is obtained by means of extrapolation processes, thus estimated instead of observed, therefore requiring a method to measure the error prediction, for this purpose the calibration regression method is widely used. The calibration problem consists on using the observed data as well as the relationship between a dependent variable with an independent variable, for estimating other values of the independent variable from new observations of the dependent variable [15]. Therefore, since the times related to the failure of a component, obtained by means of extrapolation process are estimated by means of calibration model and are not observed, it is necessary to model the uncertainty as well as the way to degradation of the component. In this case, we could use other methods like fuzzy logic systems, fuzzy regression or fuzzy numbers to make the extrapolation process including the uncertainty. Namely, the times to failure estimated by the calibration model may be represented as trapezoidal fuzzy numbers; obtaining as a result fuzzy reliability.

I.e., fuzzy logic systems represent an attractive technique to aid the research, when the precise measurement of model is limited [18], it is because these kinds of systems let us to model the spatial variability. Regarding the application of fuzzy theory in engineering reliability, Bowles and Peláez [4] showed the applications of the main concepts of the fuzzy logic, fuzzy arithmetic and linguistic variables for the analysis of system structures, fault trees, the reliability of degradable systems and its probability of occurrence. Recently, Pereguda and Timashov [32] proposed a fuzzy reliability model for an automated complex system, which assumes that parameters of reliability model and reliability indices are fuzzy variables. Their approach allows taking into account the uncertainty of reliability model parameters and reliability indices. Dong et al. [11] realized a model for analyzing fuzzy reliability; they mentioned that the analytical equations for calculating fuzzy reliability indexes of machine part could not be obtained in most cases. Chadna and Ram [8] stated that given the fact that reliability parameters are often subjectively or ill-defined, the conventional measurement approaches cannot effectively handle the vagueness and ambiguity which exist within reliability parameters, hence, fuzzy theory is rather usefully. In this research the authors applied the fuzzy reliability evaluation approach to merit the input failure rates of a system; fuzzy reliability indexes were evaluated by means of linguistic variables assessed by experts. Conversely, although classical concepts of statistics such as estimators, confidence intervals and tests of hypotheses, which have their interpretations in terms of frequencies, were widely used in the past for analyzing reliability data, the continuous improvement of reliability of components and systems have rendered those classical methods insufficient for practical applications [16]. Likewise, Ni and Qiu [31] state that the experimental data is usually scant; therefore, the applicability conditions of the probabilistic model tend to be insufficiently. In that sense, they mentions that robust reliability uses the maximum degree of the uncertainty that allowed by the structural system to measure the structural reliability. Zhao and Liu [43] cite that for many systems such as space shuttle system, the estimations of probability distributions of lifetimes of systems and components are very difficult due to uncertainties and imprecision of data. Therefore, fuzzy theory can be employed to handle this problem. Hryniewicz [16] presents only main ideas and results that have been published in a few papers, related to the reliability analysis of systems with the usage of imprecise probabilities. Bearing in mind the previous work referenced, it is clear the need for a new method to analyze reliability data when ill-defined or subjective information is handled, so that, uncertainty is present.

Sudret [36] focused on the prediction of the initiation time for corrosion and/or the estimation of the residual strength of structures, pointing out the necessity of modeling the spatial variability of the model parameters in order to be able to characterize, not only the probability of degradation but also the extent of damage. Marano et al. [21], proposed a reliability of reinforced concrete structures where an efficient alternative approach was made by considering fuzzy time-dependent reliability analysis. Karbhari and Abanilla [19] used the Arrhenius method and the procedure developed by Phani and Bose [33] for modeling mechanisms and processes of deterioration, also for estimating their rates. Tanaka and Lee [37] made an exponential possibility regression analysis by an identification method.

In this paper, it is proposed a model to perform the degradation of a polymeric coating for predicting its reliability. The parameters of the probabilistic model are estimated by means of finite (predicted) times to failure, so there is some uncertainty in the sample values. This uncertainty is quantified by the standard error and confidence limits. Therefore, the prediction has an associated uncertainty (expressed as an interval). These intervals may be represented by trapezoidal fuzzy numbers due to the characteristics of the calibration regression estimations. As the times to failure are fuzzy numbers, the estimated parameters will also, so that, it was proposed to estimate the parameters jointly.

In general, we propose the use a non-linear regression (Section 3) to model the degradation behavior, and a calibration regression method (section 4) to perform the extrapolation process including the error prediction in the estimated times to failure of an analyzed component. Then, in order to estimate its reliability considering all uncertainty information in the model (Section 6), we proposed to perform the estimated times by a trapezoidal fuzzy numbers (Section 5), providing a more reliable prediction without loss of information. The method developed was tested (Section 6) on a coating process and its collected data. Moreover, an application for a preventive maintenance frequency was developed. The primary aim of this paper is showing the feasibility of an accelerated life test analysis using calibration method for including error prediction and uncertainty modeling by means of fuzzy numbers.