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SERVICE LIFE PREDICTION OF TIMBER-CONCRETE COMPOSITE FLOORS*

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Abstract. *Timber-concrete composite (TCC) systems have application for new floors and for upgrading and enhancing of existing timber floors in residential and office buildings. In order to develop the optimal maintenance programs of structures, it is essential to predict the performance of structures over their life-cycle. The long-term behavior of timber-concrete composite floors is influenced by a combination of various factors, including material properties, load distribution, moisture effects, temperature effects and durability considerations. Timber and concrete material in the composite system, exhibit different behaviors over time due to their inherent characteristics. Deterioration prediction models are used to estimate the future degradation and condition of various types of structures. The aim of this paper is to present two probabilistic models, random variable deterioration rate model and stochastic gamma process model, that will capture uncertainty and variability associated with the deterioration of TCC floor under the service load and to estimate its service life.*

Key words: *timber-concrete composite, service life, deterioration prediction, stochastic process model*

1. INTRODUCTION

Timber-concrete composite (TCC) floors combine the benefits of both timber and concrete to create a durable and efficient flooring system. These floors typically consist of parallel timber beams that are connected with a reinforced concrete slab using different kinds of connectors. The concrete slab is placed on top of the timber elements to provide additional strength and stiffness. Timber provides a natural aesthetic appeal and also acts

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as a thermal insulator, which can contribute to energy efficiency. The concrete slab in timber-concrete composite floors provides structural rigidity, fire resistance and enhanced load-carrying capacity. Timber-concrete composite floors offer good durability and can have a long service life when designed and maintained properly. Such floors are suitable for various applications, including residential, commercial and industrial buildings [1]. They are commonly used in floor systems where a balance between structural performance, thermal insulation and aesthetic appeal is desired.

Predicting the service life of timber-concrete composite floors involves assessing several factors that can affect their durability and performance over time. The choice of timber and concrete materials plays a significant role in determining the lifespan of the floor. Timber is susceptible to moisture damage, which can lead to rot, decay, and reduced structural integrity. Adequate moisture protection measures, such as moisture barriers, waterproof membranes and proper ventilation, should be implemented to prevent water infiltration and maintain the integrity of the timber. On the other hand, the concrete slab can benefit from protective finishes to enhance durability. Periodic inspections and regular maintenance are crucial for identifying and addressing potential issues before they become major problems. Environmental factors such as temperature, humidity and exposure to sunlight can impact the durability of TCC floors. Monitoring and controlling these conditions within acceptable ranges can help extend the service life of the floor. It is important to note that the service life of TCC floors can vary widely depending on the specific circumstances, including usage, maintenance and environmental conditions. While some TCC floors can last for several decades with proper care, others may require more frequent repairs or replacements.

2. Deterioration Modeling

Deterioration prediction models are used to estimate the future degradation and condition of various types of infrastructure such as buildings, bridges, roads, pipelines and more. These models can help in assessing maintenance and repair needs, optimizing resource allocation and making informed decisions about infrastructure management. We can distinguish deterministic and probabilistic deterioration prediction models. It is important to highlight that deterministic deterioration models rely on the assumption that all inputs and deterioration processes are known with certainty [2]. However, in practice, there is often uncertainty associated with deterioration mechanisms and environmental conditions. In such cases, probabilistic or stochastic models may be more appropriate to capture the variability and provide a more comprehensive prediction of structural deterioration [3].

2.1. Random Variable Deterioration Rate Model

A random variable (RV) deterioration rate model for structures is a probabilistic model that considers the variability and uncertainty associated with the deterioration process [4]. Instead of assuming a deterministic deterioration rate, this model incorporates random variables to represent the rate of deterioration, allowing for a more realistic representation of structural deterioration over time:

$$X(t) = \mathrm{f}(R,t) = R \cdot t^{b} \tag{1}$$

This model does not consider temporal uncertainties, but only a sample uncertainty of the deterioration process. It assumes that the deterioration of each sample follows a predictable pattern based on a known form and a constant deterioration rate over time. In our analysis, we have made the assumption that considered deterioration rate has gamma distribution. Therefore, probability density function of deterioration of X(t) could be presented by:

$$f_{X(t)}(x) = Ga(x\left|\eta, \delta t^b\right.) = \frac{x^{\eta-1}}{\Gamma(\eta)\cdot(\delta t^b)^{\eta}} \cdot e^{-\frac{x}{\delta t^b}} \tag{2}$$

Mean, variance and coefficient of variance of $X(t)$ are given respectively:

$$\begin{gathered} E\left[X(t)\right] = \eta \cdot \delta \cdot t^b, \\ Var\left[X(t)\right] = \eta \cdot \delta^2 \cdot t^{2b}, \\ Cov\left[X(t)\right] = \frac{\sqrt{Var\left[X(t)\right]}}{E\left[X(t)\right]} = \frac{1}{\sqrt{\eta}} = const. \end{gathered} \tag{3}$$

However, in reality, the most of deterioration processes exhibit temporal uncertainties. Deterioration rates may vary over time due to various factors such as environmental conditions, maintenance activities and other external influences. To account for temporal uncertainties, a more comprehensive model would need to consider stochastic deterioration processes that incorporate variability and uncertainty over time.

2.2. Stochastic Gamma Process Deterioration Model

The stochastic gamma process (GP) is a mathematical model that can be used to describe the deterioration process of structures over time [5]. This stochastic process has independent non-negative increments that are gamma distributed with an identical scale parameter. We observe the gamma process with shape function $k(t)>0$ and scale parameter $\theta>0$, as continuous-time stochastic process $\{X(t); t \geq 0\}$ with the following properties:

- $X(0) = 0$ with probability one
- $\Delta X(t) = X(t+\Delta t) - X(t) \sim \mathrm{Ga}(\Delta k(t), \theta)$; $\Delta k(t) = k(t+\Delta t) - k(t)$
- $\Delta X(t)$ are independent

where $k(t)$ is supposed to be a non-decreasing, right-continuous, real-valued function for $t \geq 0$, with $k(0) \equiv 0$. Probability density function of $X(t)$, according to the definition of the gamma process deterioration model could be given as:

$$f_{X(t)}(x) = Ga(x\left|ct^b, \theta\right.) = \frac{x^{ct^b-1}}{\Gamma(ct^b)\cdot\theta^{ct^b}} e^{-\frac{x}{\theta}} \tag{4}$$

with mean, variance and coefficient of variation:

$$E[X(t)] = ct^b \cdot \theta, \quad Var[X(t)] = ct^b \cdot \theta^2, \quad CoV[X(t)] = \frac{1}{\sqrt{ct^b}} \tag{5}$$

3. TIME-DEPENDENT TCC FLOOR DETERIORATION

The long-term behavior of timber-concrete composite floor is influenced by a combination of material properties, load distribution, moisture effects, temperature effects and durability considerations. Timber and concrete have different material properties and behavior over time. The differential shrinkage/swelling of the concrete slab and timber beam cannot freely occur due to the connection system which restrains the possibility of either part to move relative to the other [6]. When designing medium and long-span composite floors, one of the most critical criterion to consider is the limit state of maximum deflection. Consequently, it becomes necessary to analyze and model the mid-span deflection in TCC floors over time under service load. The aim of this paper is to demonstrate how two different probabilistic deterioration prediction models can be effectively applied to estimate the service life of the TCC floor using available inspection data. Gather data on the condition of TCC floors over a specified time period may include information on observed deterioration patterns, inspection records, maintenance activities, and environmental conditions.

We have observed the TCC floor with a span of 4.5 m in indoor conditions. The concrete slab of the TCC floor with a thickness of 60 mm is constructed using concrete of the strength class C25/30. The timber beams with dimensions 100 x 200 mm are made of sawn softwood timber with a structural strength class C27. The beams are located at a distance of 800 mm. The shear connectors are glued-in steel rods ϕ20/150 mm. These connectors are embedded in pre-drilled holes that are positioned perpendicular to the grain of the timber and coated with epoxy resin, at constant intervals of 240 mm. The steel rods used as connectors are manufactured from steel grade S235. The relative mid-span deflection of the floor over time under normal use conditions could be defined as follows:

$$X(t) = \frac{u(t) - u_{el}}{u_{el}} \tag{6}$$

where u(t) is mid-span deflection at time t and u_{el} is the elastic deflection measured immediately after applying the service load that is assumed to be an initial deflection, deflection at time t0. Based on the definition of relative mid-span deflection, it becomes possible to establish a maximum permissible value for this parameter:

$$\rho = \frac{u_L - u_{el}}{u_{el}} \tag{7}$$

This maximum permissible value serves as a threshold beyond which the deflection of the floor under normal use conditions should not exceed. According to Eurocode 5 [7], the serviceability limit value for long-term deflection uL could be defined as l/200, where l is the span length. When the maximum mid-span deflection exceeds the proposed serviceability limit value, the observed TCC floor will reach serviceability limit state as shown in Figure 1.

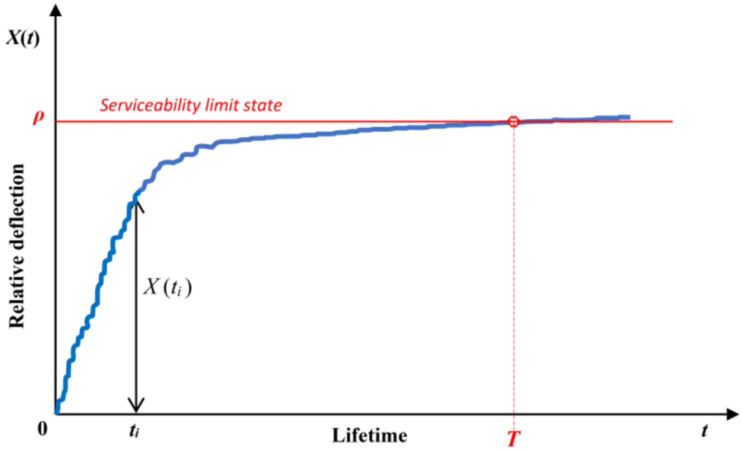

Fig. 1 Trend of the expected relative mid-span deflection increasing over time under service load

A probabilistic deterioration model for a timber-concrete composite floor would involve estimating the probability of failure of different components of the floor system over time. It is important to note that developing a comprehensive probabilistic deterioration model for a timber-concrete composite floor is a complex task that requires expertise in structural engineering, materials science and probabilistic analysis. In order to conduct a comprehensive time-dependent reliability analysis of TCC floors under normal use conditions, it is necessary to establish the limit state function. In this paper, the focus is on the serviceability limit state, specifically the maximum deflection of the TCC floor that could be expressed as:

$$g(\rho, X, t) = \rho - X(t) \tag{8}$$

According to this definition, probability of failure for considered TCC floor is given as follows:

$$P_f(t) = P[g(\rho, X, t) \leq 0] = P[X(t) \geq \rho] \tag{9}$$

Since there is a lack of deterioration measurement data under normal use conditions and conducting time-consuming experiments under normal operating conditions can be costly, an alternative approach was adopted. To obtain the necessary data for the study, an accelerated aging test was performed. To obtain accelerated deterioration data, we have employed an existing deterministic model. This model is based on conducted experimental tests, presented by Fragiacomo [8]. Variation in environmental conditions will cause dispersion of mid-span deflection within the population over time. To account for the uncertainties associated with the deterioration process in a large population of structural elements, we have employed the Monte Carlo simulation technique. This approach serves to simulate the condition of the set of identical specimens exposed to indoor conditions. The observed specimens are monitored through periodic inspections at year 10 and year 20. In that way inspections reveal the progress of the deterioration of each inspected specimen, as it presented in Figure 2.

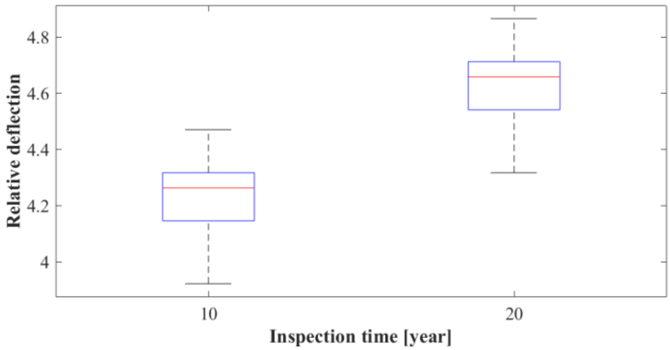

Fig. 2 Box plot of inspection data

In order to establish the relationship between the average deterioration level and time, we have utilized available inspection data and fitted it with a power function:

$$E[X(t)] = a \cdot t^b \propto t^b \tag{10}$$

where E[X(t)] presents the expected deterioration of relative mid-span deflection under indoor conditions at time t. This is performed based on the regression analysis using a least-squares fitting method, suggested by Nicolai et al. [9]. The regression analysis of the available data shows a strong fit with a power function, with a high coefficient of determination (R2 = 0.9175). Based on this analysis, the relevant value of parameter b was obtained as 0.1104. By determining the parameter estimate of the power b from the regression analysis, we are able to estimate the other two parameters of the proposed random variable deterioration rate model and gamma process deterioration model. Estimation of parameters was conducted using the method of maximum likelihood and presented in table 1.

Table 1 Estimated parameters of considered probabilistic models at year 20

RV deterioration rate model		Gamma process model	
Shape (η)	Scale (δ)	Shape (c)	Scale (θ)
834.069	0.0039	699.912	0.0047

4. SERVICE LIFE PREDICTION

Maintenance management is a critical aspect of ensuring the long-term performance and safety of structures and it primarily addresses the uncertainties associated with the service life of the structures. By estimating the time when a structure is expected to reach its serviceability limit state, we can make informed decisions regarding maintenance strategies as well as risk management. Considering that the RV deterioration rate model depends on only one random variable whose mean and standard deviation are constant over time, the coefficient of variation of this probabilistic deterioration model is constant over time as well. However, coefficient of variation of GP deterioration model is variable over time and presents the function of time with the negative exponent, $t^{-(b/2)}$. According to this fact, coefficient of variation of GP deterioration model has higher value within the first couple of years. Its value however is rapidly decreasing and quickly becomes lower than the coefficient of variation of the RV deterioration rate model, which is an indicator of quality and stability for long term predictions (Fig. 3).

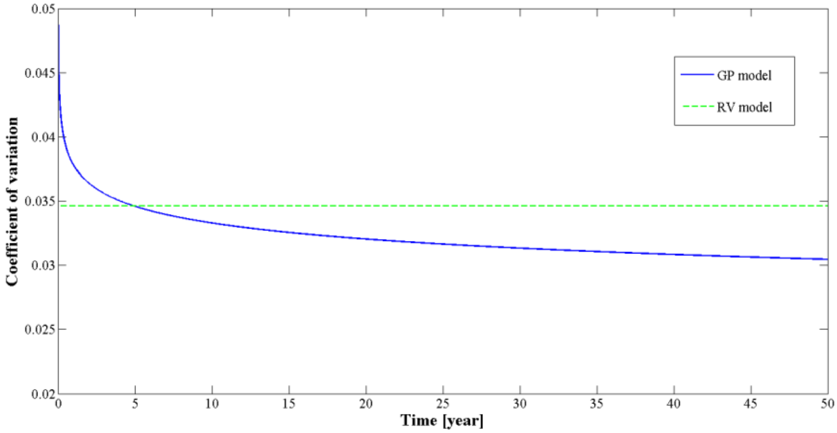

Fig. 3 Coefficient of variation of expected deterioration X(t)

Service life analysis plays a crucial role in this process by assessing the expected deterioration and determining the maximum time when the deterioration will pass the service life threshold. The service life of a structure, denoted as *T*, can be determined by identifying the first time when the sample path of deterioration *X*(*t*) exceeds the proposed serviceability limit value of relative mid-span deflection, represented by *ρ*.

$$F_T(t) = P[T \le t \,|\, X(t) \ge \rho] \tag{11}$$

When the deterioration is modelled using a random variable deterioration rate model, the cumulative distribution function of the service life can be presented as follows:

$$F_T(t) = 1 - GA(\rho; \eta, \delta t^b) = 1 - \frac{\Gamma\left(\eta, \dfrac{\rho}{\delta t^b}\right)}{\Gamma(\eta)} \tag{12}$$

where:

$$\Gamma(a, x) = \int_{t=x}^{\infty} t^{a-1} e^{-t} dt \tag{13}$$

is the incomplete gamma function for $x \ge 0$ and $a > 0$.

Considering the expected deterioration is represented by a gamma process deterioration model, the cumulative distribution function of the service life can be expressed as follows:

$$F_T(t) = 1 - GA(\rho; ct^b, \theta) = 1 - \frac{\Gamma\left(ct^b, \dfrac{\rho}{\theta}\right)}{\Gamma(ct^b)} \tag{14}$$

Based on Fig. 4, we can conclude that gamma process model gives a more stable prediction of expected service life than the RV deterioration rate model.

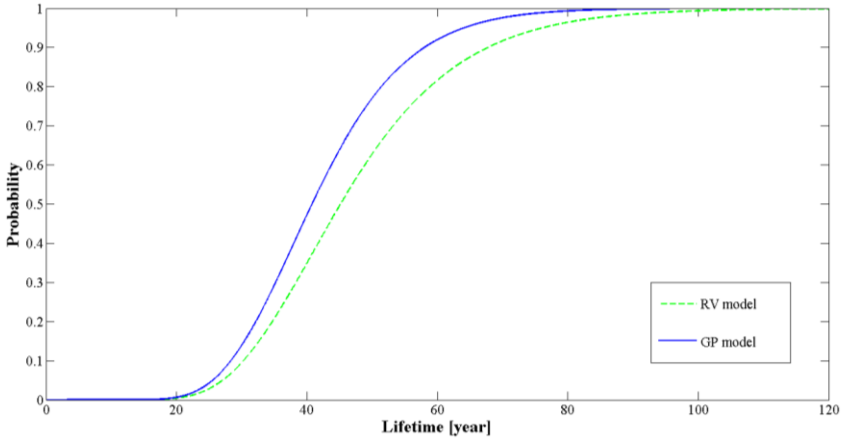

Fig. 4 Comparison of cumulative distribution function of service life, obtained from GP deterioration model and RV deterioration rate model

To effectively plan maintenance for a structure, it is crucial to determine the time at which the structure is likely to reach the serviceability limit state with specific probabilities, such as 5%, 50%, and 95%. This can be achieved by employing two presented approaches, as it shown in Figures 5 and 6.

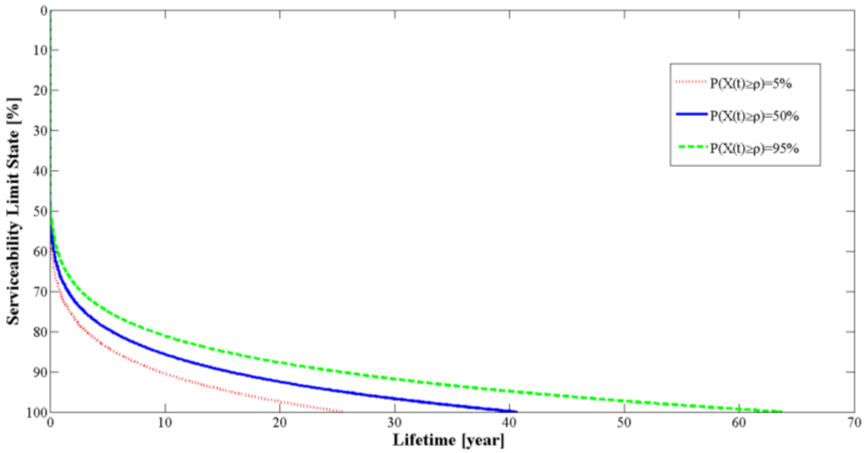

Fig. 5 Probability of achieving different levels of serviceability limit state condition during the lifetime applying GP model

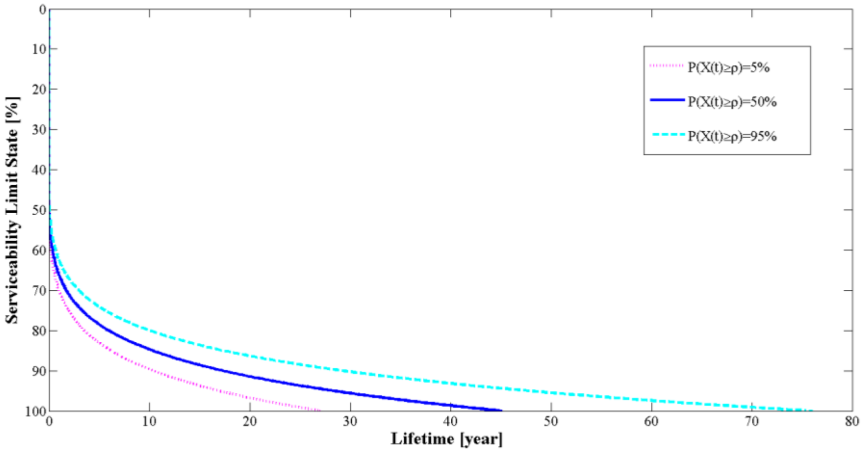

Fig. 6 Probability of achieving different levels of serviceability limit state condition during the lifetime applying RV model

5. CONCLUSION

Deterministic deterioration models are commonly employed in the maintenance management of structures. However, they have certain limitations when applied to real conditions, because the inputs and degradation mechanisms involved in structural deterioration are often uncertain and subject to variability. This work has presented the application of two probabilistic deterioration models, random variable (RV) deterioration rate model and stochastic gamma process deterioration model, to describe time-dependent timber-concrete composite floor deterioration. RV deterioration rate model does not consider temporal uncertainties, only sample uncertainty of the deterioration process. To account for temporal uncertainties, a more comprehensive model would need to consider stochastic deterioration processes that incorporate variability and uncertainty over time. The gamma process deterioration model considers deterioration increase as the sum of the series of non-negative random increments. In this model, deterioration rate in each time interval is not constant, rather it is random due to the uncertain influence of the environment over the life-cycle. Neglecting these temporal uncertainties can limit the model's ability to accurately predict the future state of the samples or make reliable projections. By considering temporal uncertainties, the stochastic gamma process model would provide a more realistic representation of the deterioration process, enabling better predictions and assessments of the samples future conditions.

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PREDVIĐANJE EKSPLOATACIONOG VEKA SPREGNUTIH MEĐUSPRATNIH KONSTRUKCIJA TIPA DRVO-BETON

Spregnuti sistemi tipa drvo-beton imaju primenu kod izgradnje novih međuspratnih konstrukcija kao i kod unapređenja i ojačanja postojećih drvenih međuspratnih konstrukcija u stambenim i poslovnim zgradama. U cilju razvijanja optimalnih planova održavanja konstrukcija, neophodno je predvideti karakteristike konstrukcija tokom njihovog eksploatacionog veka. Na dugotrajno ponašanje spregnutih međuspratnih konstrukcija tipa drvo-beton utiče kombinacija različitih faktora, uključujući svojstva materijala, raspodelu opterećenja, uticaj vlage, uticaj temperature i trajnosti. Drvo i beton kao materijali u okviru spregnutog sistema, pokazuju različito ponašanje tokom vremena. Modeli predviđanja deterioracije se koriste za procenu buduće degradacije i stanja različitih tipova konstrukcija. Cilj ovog rada je da predstavi dva probabilistička modela, model slučajne stope deterioracije i model stohastičkog gama procesa, koji će obuhvatiti varijabilnosti povezane sa deterioracijom spregnutih međuspratnih konstrukcija tipa drvo-beton pod korisnim opterećenjem i proceniti njegov eksploatacionki vek.

Ključne reči: *spregnuti sistem tipa drvo-beton, eksploatacioni vek, predviđanje deterioracije, model stohastičkog procesa*