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Effects of Damage Models in Probabilistic Assessment of Structures: An Illustrative Example

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Abstract

Deterioration modelling of structures has gained significant importance in recent times in relation with structural health monitoring, rehabilitation, maintenance and decision making process. The behaviour of any deteriorating structure (or a network of structures) is extremely important while considering failure as defined from the viewpoint of both the owner/manager and the engineer. Since there are epistemic and aleatory uncertainties associated with any such process, the ideas of failure and the damage model require a probabilistic treatment. The time dependence of damage propagation very often depends on the climate conditions. On the other hand, the definition of failure by the owner and by the engineer may have different focus. These uncertainties and conflicts directly affect the assessment, optimal assessment time, repair and maintenance strategies, associated cost and the final decision regarding a structure at any given point or period of time. The paper discusses how the choice of a deterioration model (even non-functional) of a structure can affect the decision making options regarding a structure based on a probabilistic material and structure independent general framework through a simple and illustrative example. A wooden beam damaged by the growth of fungus is considered to be the benchmark problem in this regard. The damage is modelled to be comprised of two stages – the initiation and the propagation period. A Monte Carlo simulation investigates the effects of environmental parameters, active regions in time, conflicts of owner's and engineer's criteria and the critical location in a structure in terms of possible destructive or non destructive instrumentation.

Keywords: Damage Model, Probabilistic Assessment, Probability of Failure, Wood.

1. Introduction

Deterioration modelling of structures has gained significant importance in the recent times in relation with structural health monitoring and the consequent decision making process (Basheer *et al* 1996). The behaviour of any deteriorating structure or a network of structures is extremely important while considering failure as defined from the viewpoint of the structure and infrastructure owners, the managers and the engineers. Since there are epistemic and aleatory uncertainties associated with any such process of structural assessment, the idea of failure and the damage model require a probabilistic treatment (Lounis 2003).

Damage in a structure evolves over time and very often this evolution is associated with significant uncertainty (Mahadevan 2004). Also, the time dependence of damage propagation usually depends on the climate conditions (Andrade and Alonso 2001). As a result, the study of performance of structures under uncertainly evolving damage is deemed extremely important. On the other hand, the definition of failure by the owner and by the engineer may have different focus. These uncertainties and conflicts directly affect the assessment, optimal assessment time, repair and maintenance strategies, associated cost and the final decision regarding a structure at any given point or period of time (Guillaumot *et al.* 2001)

This paper illustrates the importance of probabilistic deterioration modelling of structures for structural decision making process through an example. The illustrative example comprises of a simply supported wooden beam deteriorated by the growth of fungus.

2. Damage Model

2.1 Description of the Problem

To illustrate the concepts present in the introduction, an example numerical problem is chosen. A 6m long simply supported single span wooden (Spruce) beam hypothecially assumed to be situated in Bordeaux, France is considered for the purposes of simulation. The cross section of the beam is rectangular and of dimensions 400mm (depth) x220mm (width). The beam is subjected to Uniformly Distributed Load (UDL). It is assumed that the deterioration process in the beam is brought about by the action of fungi. The rate of degradation is related to the temperature and the humidity of the ambient environment. The activity of the fungi is thus directly related to the temperature and humidity. It is also acknowledged that the activity rates for a given set of temperature and humidity are not unique, but have uncertainties associated with them.

2.2 Criteria of Failure

The owner's criteria for failure are considered on the basis of aesthetics, while the Engineers' criteria are based on mechanical failure. Thus, both serviceability and safety aspects have been taken into consideration and a conflict in the definition of failure is present. Also, this allows studying the effects of conflicts of interest between the owner and the engineer in terms of limit states. The structure is deemed to have failed by the owner if the length affected by fungi exceeds 10% of the length of the beam irrespective of its position. Whether the affected length has resulted in a mechanical deterioration or not is inconsequential to the owner and a fungi growth resulting in loss of strength of the beam is not distinguished from a benign growth. The engineer considers a failure if the moment or shear stress at any section exceeds the resisting strength (Ultimate Limit State or ULS) or if the deflection at any point exceeds a predefined limiting value (Serviceability Limit State or SLS). Any fungal growth not affecting the strength of the beam is not recognised.

2.3 Damage Initiation and Propagation

The evolution of damage can be characterized by the damage initiation and the consequent damage propagation due to the activity of fungus. The damage initiation or the germination of fungus for a beam in a given environment is modeled as a random event. The damage propagation phase or the activity rate of fungus (in mm/month) is considered to be a function of the temperature and the humidity of the ambient environment. The propagation phase cannot start unless the germination process has taken places.

2.4 Activity Rate

The monthly variation of temperature and relative humidity for Bordeaux (*bbc.co.uk, accessed 2007*) is shown in Figure 1. The activity rate of a fungus for such environment can be found from the activity contour plots provided by Krus *et al*. (2001). The activity rate of a fungus is defined to be the rate at which the fungus grows under a given temperature and humidity condition. This rate can be expressed as the equivalent distance per unit time and directly used for engineering calculations. Due to the seasonal nature of the temperature and humidity at any location, the activity rate approximately repeats itself every year. As a result, an activity profile for a certain location can be constructed by considering the average monthly activity profiles over an entire year. Since the environmental conditions vary randomly about the average cycle every year, a random noise has been added to the yearly activity profiles to obtain a more realistic fluctuating series of activities. This enables to identify the effects of random fluctuations on the damage evolution process. Uniform profile (activity 1), profile obtained from Krus et al. (2001) (activity 2) and a triangular profile (activity 3) are considered for activity rates over a year. The unit of the activity rates is taken as m/month.

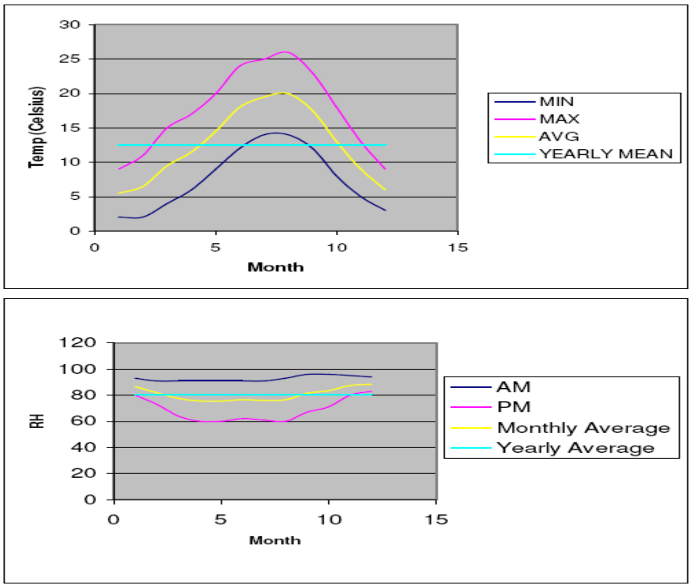

Figure 1. Temperature and Relative Humidity in Bordeaux.

2.5 Mechanical Model

The damaged beam is considered to be divided into a preselected finite number of divisions with one of such division being assumed to be damaged. The sectional loss, leading to subsequent loss of moment of inertia increases the stress in the damaged section and a failure condition is met when the stresses (shear or moment) surpass the allowable values. Figure 2 shows such a smeared damage model for the beam. To estimate the static deflection at the damage location, one has to consider the beam as an assembly of three subbeams with the damaged subbeam having a different sectional property than the undamaged ones. Considering continuity in displacement and slope at the interface points a and b, the static deflection can be solved in closed form (Pakrashi *et al.* 2007) .

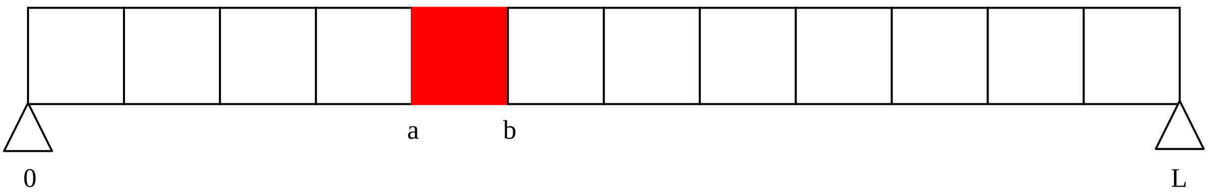

Figure 2. Smeared Damage Model.

3. Results

3.1 Simulation Process

A crude Monte Carlo simulation is performed for the damage evolution process for a period of fifty years. The germination period is considered to be random and depends on a toss is performed for each iteration of the simulation for each month. A beam is considered to be germinated if the value of toss in a month exceeds a certain preselected value. Thus, there can exist cases(however low) where the germination does not occur within the time frame considered. Once the beam is germinated, the propagation phase is initiated by introducing the activity rate for the month from a given noisy profile. Checks for both owner's and engineer's criteria are performed for every month. The failure probabilities are computed for different criteria over different years. The number of failures for a given month can also be computed. The beam is divided into 20 number of parts.

3.2 Numerical Experiments

The probability of failure for the owner's definition of failure for different activities with fudge (associated random noise) is given in Figure 3. The values are comparable in terms of average activity over a year. The nearly parallel loci of points of the points indicate the basic deterministic nature of the failure process and the deviations account for the interaction between the germination time and activity rate. Figure 4 shows the numbers of failures for different activity rates for each of the months in a year for owner's definition of failure. The high activity months account for more number of failures. The presence of noise smoothes out any sudden change in the modal month that might numerically arise due to the specification of a definite cut-off value for the affected length of failure.

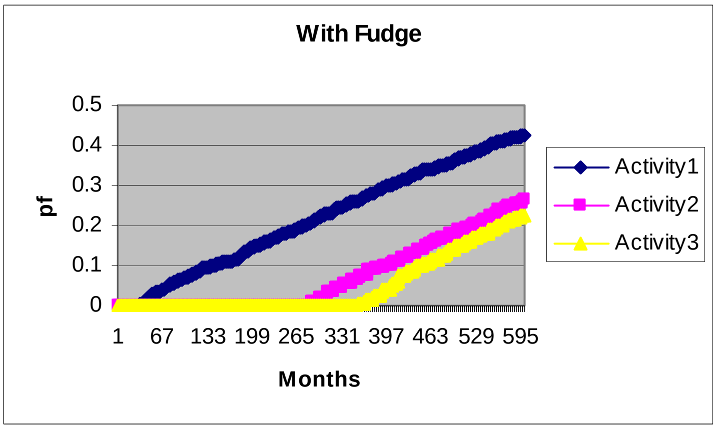

Figure 3. Probability of Failure for Owner's Criteria.

Figures 5 and 6 represent the cumulative probabilities of failure from the engineer's viewpoint and the numbers of failures for a given month respectively. The shape of the activity profile resembles a triangular pattern. The pf and the number of failures are according to combined (1), moment (2), shear (3) and deflection (4) criteria respectively in Figure 5. Figure 6 illustrates the presence of modal months using the engineer's criteria for moment (1) shear (2) and deflection (3) respectively. The moment failure criterion governs the total failure probability. The months of higher activity in terms of failure are seen to match the activity pattern of fungal activity.

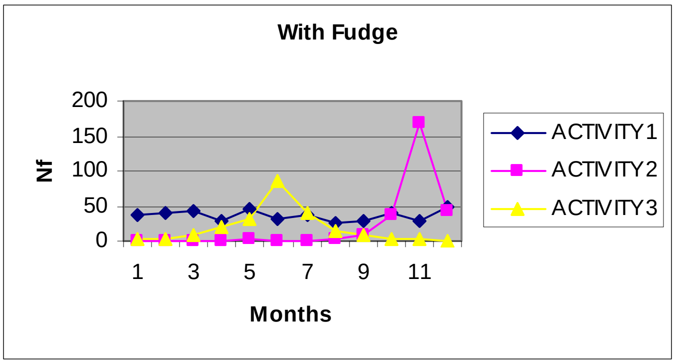

Figure 4. Number of Failures over Different Months for Owner's Criteria.

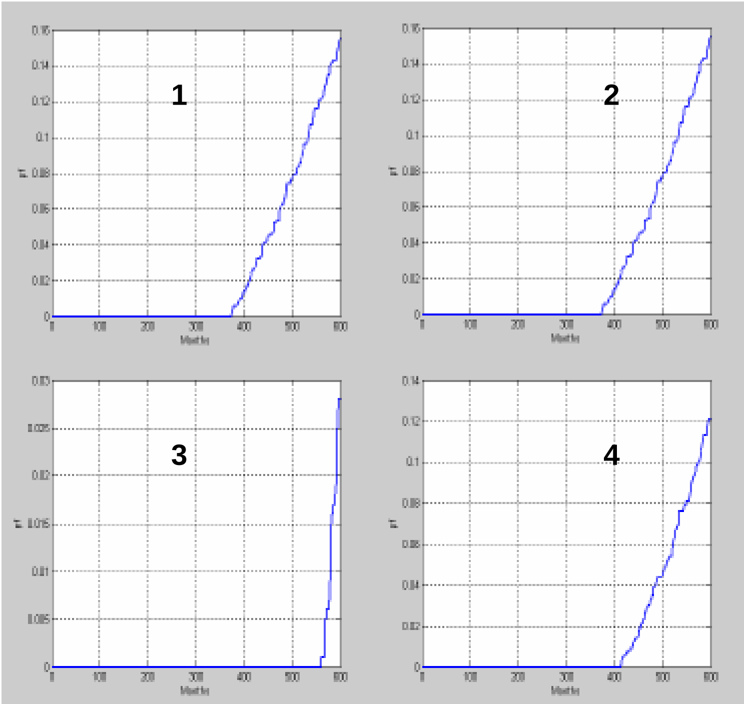

Figure 5. Probabilities of Failure for Engineer's Criteria for Combined (1), Moment (2), Shear (3) and Deflection (4).

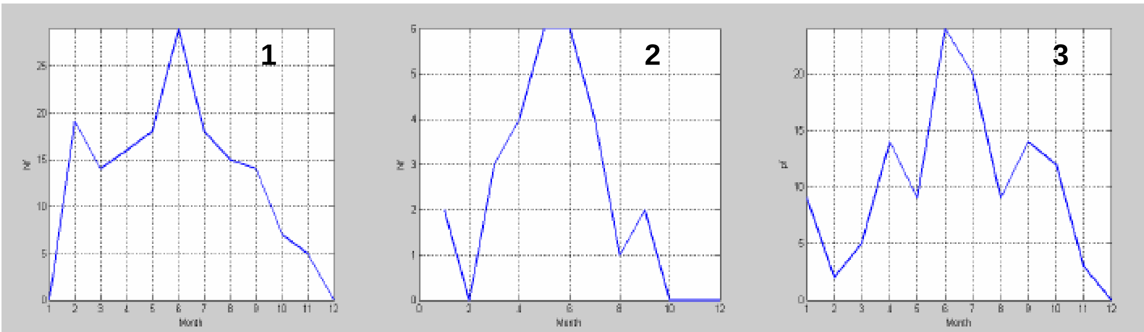

Figure 6. Number of Failures over Different Months for Moment (1), Shear (2) and Deflection (3) following the Engineer's Criteria.

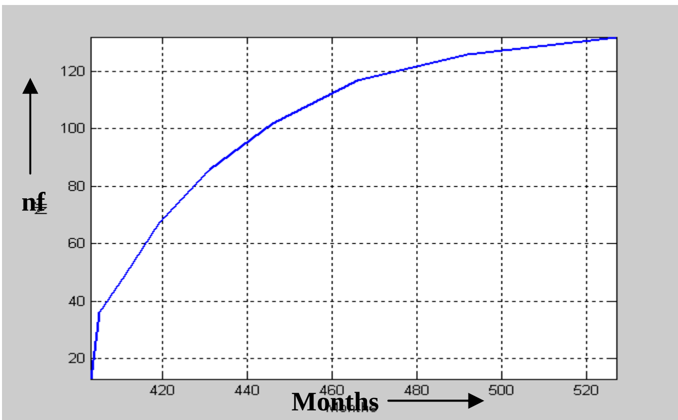

Figure 7. Number of Failures versus Time to Fail once Germinated.

Figure 7 describes the cumulative number of cases of failures recorded as per engineer's criteria with respect to the time to fail. It is assumed that the time to fail is considered from the time of germination. It is seen that there exists an intermediate month after which the number of failure in a single month keeps becoming smaller, as is indicated by the point of inflection in the graph.

The average failing time, once the beam has failed, against the position of damage is provided in Figure 8. The midpoint of a simply supported beam is identified correctly as a critical location in this regard. The variation in time to failure is indicative of changing risk for different sections under a given set of damage, failure mode and failure definition.

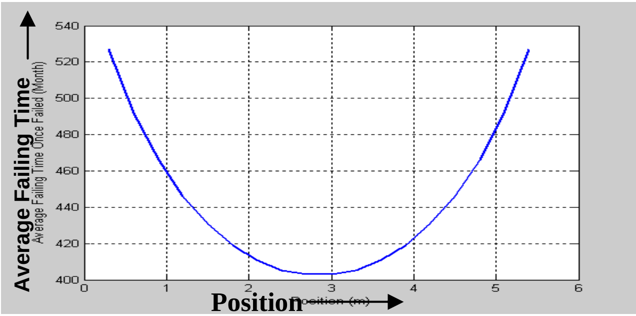

Figure 8. Time to Fail versus Position of Damage.

The results of simulation based studies for probabilistic degradation of materials (as presented in this paper) can be used for decision making purposes at various levels. Once the most active months are discovered, the appropriate time for using an NDT technique can be chosen to maximise the efficiency of the technique. The identification of critical locations in a structure enables to decide where instrumentation should be carried out in a structure. Information update from structures enables to reassess its condition. By recomputing the performance indicators through information update, options of maintenance and repair can be chosen as per their cost-benefit while keeping the structure safe. Also, structures are sometimes guided by non-engineering criteria set by infrastructure owners. During reassessment such the same criteria need not necessarily govern and engineering based safety criteria can be used to reassess the performance index. When probabilistic simulation based information is available regarding the impacts of different criteria of safety and serviceability on the performance indices, it is easy to reassess and take decisions since the structure must satisfy a target performance index. Updated information can improve the performance index even before any repair is done.

4. Conclusions

The importance of probabilistic damage evolution within the framework of structural maintenance, rehabilitation and decision making process has been illustrated through an example of a wood beam affected by fungus. Effects of environmental parameters on damage evolution in the presence of noise have been studied. It is observed that some months are more important in terms of failure than the other months because of variable damage activity rate dependent on environmental parameters. Effects of conflicting criteria for failure defined by owners and engineers are investigated. The principal damage mode has been identified by the proposed probabilistic method. The critical section of a structure in terms of a failure definition is obtained. The probabilistic damage evolution framework helps to identify the time and location for assessment, health monitoring or any non destructive technique on a case specific basis. The probabilistic study provides information for final cost optimal decision making strategy on a damaged structure.

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