Effect of Inspection Strategies on the Weight and Lifecycle Cost of Airplanes

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Inspections of aircrafts fuselage panels are performed periodically, at scheduled intervals, to repair damage that can threaten the safety of the structure. Recently, structural health monitoring techniques have been developed that use sensors and actuators to detect damage, paving way for condition-based maintenance. This paper quantifies the effect of inspection strategies on the safety and lifetime cost of an airplane. The lifecycle of an airplane was modeled as blocks of damage propagation interspersed with inspection. The Paris model with uncertain parameters is used to model fatigue damage growth, and the detection process by inspections is modeled by the Palmberg equation. Two inspection strategies are compared based on their effect of optimal weight and lifecycle cost of the panel, while maintaining a desired level of reliability. Direct integration procedure computes the reliability for a given set of maintenance parameters. It is found that the better inspection model leads to about 15% savings in weight of airplane and about 35% savings in lifecycle cost of an airplane over scheduled maintenance.

I. Introduction

TRADITIONALLY, aircraft structures have been designed using the concept of damage tolerance (Hoffman, 2009 [1], Simpson, et al (1999) [2]) in which the structures are designed to withstand small damage, and large damage is repaired through scheduled inspections and maintenance. This concept is more cost-effective than safe-life design because airplanes designed based on safe-life would be much heavier and thus, more costly. In damage tolerance design, it is important to inspect the airplane regularly such that all damages that can possibly threaten the safety of the structure should be repaired.

Scheduling inspections requires a trade-off between the safety and lifecycle costs. Frequent inspection may provide safety to the system in the expense of high cost. The current FAA guideline is to inspect a B-737 aircraft every 6000 flights [27]. This inspection schedule is chosen such that the probability of about 1 mm sized crack to grow beyond the critical crack size is less than 10^{-7}. Finding the optimum preventive maintenance schedule is richly addressed in literature. Taghipur, et al (2010) [3] optimizes the schedule for complex repairable system to minimize cost, Curcuru, et al (2010) [4], for a system with imperfect monitoring to minimize the global maintenance cost, Kim, et al (2011) [5], for ship hull structures to minimize expected damage detection delay, to name a recent few.

Scheduled maintenance leads to savings in weight of a structure, in addition to the life cycle cost, compared to the safe- life design. Curran, et al (2006) [14] devised a numerical method for cost weight optimization of stinger skin panels. Kale et al. (2008) [15] showed that weight and lifecycle cost of an aircraft fuselage panel are reduced by 30% compared to safe-life design, at the same level of safety.

Alternatively, condition-based maintenance has gained in popularity. This type of maintenance monitors / tracks a parameter continuously and request maintenance when the value of the parameter crosses a certain threshold. Tsang (1995) advocates the use of condition-based maintenance over scheduled maintenance. This method only fixes those cracks that actually grow close to the critical crack size. Therefore, the number of cracks that are fixed is much less than that of the scheduled maintenance. A condition-based maintenance system is usually optimized to match a certain level of reliability (Jardine, et al (1998) [6]) or for cost (Niu, et al (2010) [7]).

Recently, structural health monitoring (SHM) systems have become available using on-board sensors and actuators. These systems can perform damage assessment as frequently as needed, and prove to be a good tool for condition based maintenance. Lopez, et al (2010) [8] delineates some practical application of SHM systems and also reviews

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the various uncertainties in damage monitoring, diagnostics and prognostics. Boller and Meyendorf (2008) [9] observed damage monitoring by SHM as a good tool to enhance inspection. However, the detectable damage size from most SHM devices is much larger than that of the manual inspections. Even if some SHM technologies allow detecting damage as low as 125 µm. (Papazian et al (2009) [10]), they are only for laboratory conditions.

SHM based conditional maintenance is a useful tool to reduce lifecycle costs. Boller (2000) [11] observed that using SHM for condition based maintenance would lead to lower downtime and inspection costs. Fitzwater, et al (2003) [12] combines SHM with traditional scheduled maintenance to minimize lifecycle cost of F-15 fighter frame station 626 bulkhead. Pattabhiraman, et al (2009) [13] quantified savings on lifecycle cost on using SHM for condition based maintenance, over scheduled maintenance. This paper focuses on cost and weight savings of SHM based conditional maintenance system over preventive maintenance.

The effect of SHM based conditional maintenance over scheduled maintenance on cost and weight savings is demonstrated using crack propagation in fuselage panels. Excessive crack growth due to fatigue loading on aircraft fuselage panels is considered as the mode of failure. Condition based maintenance, using onboard SHM inspection equipment is used to prevent failure at a desired level of reliability. The objective of this paper is to quantify the effect of inspection accuracy, on weight and lifecycle cost of panel.

In this paper, fatigue crack propagation in fuselage panels under repeated pressurizations is modeled using the Paris model[16] with uncertain parameters. The Palmberg equation[17] is used to model the probability of damage detection during the inspection process. The difference in inspection accuracy is modeled by changing the crack length with 50% probability of detection parameter in the Palmberg equation.

The organization of the paper is as follows. In Section 2, the process of damage detection and replacement are explained. Section 3 presents the data used for illustration. Section 4 delineates the direct integration procedure to compute the CDF of the damage size distributions at specific damage locations. Section 5 computes the permissible range of maintenance parameters to maintain a specific level of reliability. Section 6 compares the scheduled and condition based maintenance in terms of cost, for a specific level of reliability and Section 7 compares between 2 different inspection models in terms of lifecycle cost.

II. INSPECTION PROCESS MODEL

The scheduled or condition based maintenance process monitors damage and replaces/repairs the fuselage panel before the damage reaches a critical size so as to threaten the safety of the airplane. Because the crack sizes are randomly distributed and because the detection process has uncertainty (refer to Appendix B), the inspection process partially truncates the upper tail of the damage size distribution. The procedure is illustrated in Figure 1 for typical values of damage size. The red curve represents the damage size distribution when the airplane enters the maintenance hangar; i.e. before inspection. In the maintenance hangar, all panels with detected damage of size greater than a_{rep} are replaced. Since the detection is also a random process, a fraction of panels with damage size greater than a_{rep} are detected and hence, only a part of the tail of the damage size distribution is replaced. The partially truncated damage size distribution obtained after inspection is shown in green in Figure 1. This section discusses the inspection process considered in this paper

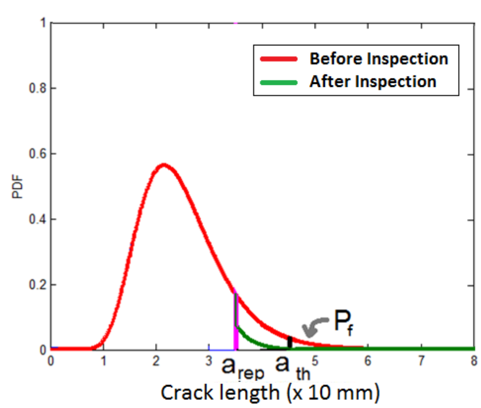


Figure 1: The effect of inspection and replacement process on crack length distributions

A. Scheduled maintenance

Aircraft maintenance is scheduled at specific pre-determined intervals. Let N_{man} denote the number of flights between inspections. Due to repeated pressurization, the damage propagates during those N_{man} flights. In damage tolerance design, the inspection schedule is designed in order to remove panels with large cracks that threaten the safety of the structure. At the time of scheduled maintenance, the airplane is sent to the maintenance hangar. At the hangar, the maintenance inspectors inspect all the panels in that airplane and replace / repair those in which damage might hamper the safety of the airplane until the next maintenance. The flowchart in Figure 2 depicts the scheduled maintenance process. The desired level of reliability in the aircraft is set by the value of threshold, $a_{rep-man}$.

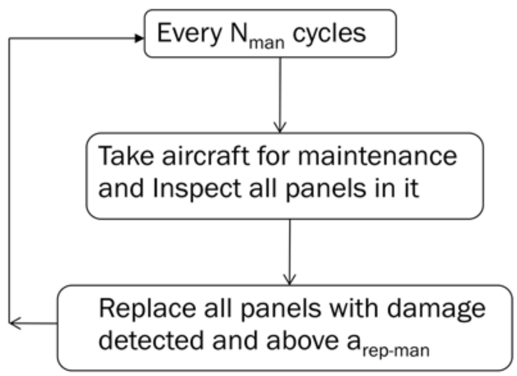


Figure 2: Flowchart of the scheduled maintenance process

Condition based maintenance procedure

Condition based maintenance process tracks damage continuously and requests maintenance when the damage grows quickly and threatens the safety. Structural health monitoring (SHM) is an enabling tool for condition based maintenance. SHM uses on-board sensors and actuators to detect existing damage. SHM based maintenance assessment can be performed as frequent as a couple of flights, but in this paper, the assessment is performed every N_{shm} flights due to computational constraints.

The damage propagates in between the scheduled maintenance assessments due to repeated fuselage pressurization. Maintenance during a maintenance assessment is requested when a damage grows over a threshold a_{th}. This threshold is chosen based on reliability constraints, i.e. to maintain a specific level of reliability until the next maintenance assessment. In the maintenance hangar, all the panels in the airplane are inspected by the on-board SHM equipment and panels with threatening damage are repaired / replaced. Mathematically, a threshold $a_{rep-shm}$ is set to quantify the threatening damage, and set so as to prevent frequent maintenance for that airplane. The flowchart in Figure 3 depicts the maintenance scheduling procedure for SHM-based inspection.

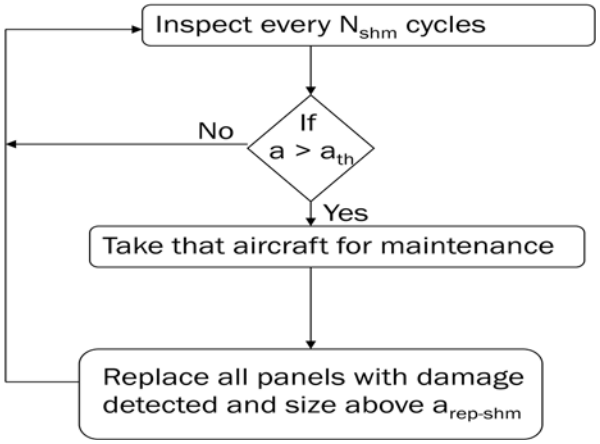


Figure 3: Flowchart depicting maintenance scheduling and assessment procedure for SHM based inspection

After inspection and maintenance, the upper tail portion of damage size distribution is partially truncated at $a_{rep\text{-shm}}$. For SHM-based inspection, the distribution beyond a_{th} corresponds to the fraction of panels with large damage sizes, missed due to randomness in the inspection process or to growth after the inspection. Hence, in Figure 1, the area beyond a_{th} for the green plot is the fraction of panels that have large damage size but are missed during the inspection and possible to fail in due time. The difference between area beyond a_{rep} for the green and red plots gives the fraction of panels replaced during that particular inspection.

It can be seen clearly that for SHM based inspections, the average maintenance trips by airplane and the average number of panels replaced per airplane, and hence, the inspection cost of the airplane depends on the frequency of inspections (N_{shm}), the threshold for sending the airplane for maintenance (a_{th}), and the threshold for replacement for highly damaged panel in the maintenance hangar ($a_{rep\text{-}shm}$). These variables have been collectively called the SHM parameters.

III. DATA USED FOR ILLUSTRATION

Aluminum alloy 7075 – T6 is considered as the material of the fuselage panels. All panels are of dimension 609.6mm (2') × 609.6mm (2') × 2.48mm (0.1") and are assumed to possess a single crack at the center of the panel and subjected to Mode I stress status. The lifecycle of an airplane is assumed to last 50,000 flight cycles.

The fatigue crack growth could be modeled in myriad ways. Beden, et al (2009) [18] gives an extensive review of the same. Mohanty, et al (2009) [19] uses an exponential model to model fatigue crack growth. Scarf (1997) [20] advocates use of simple models, as opposed to complex models, if the objective is simply to demonstrate methodology. In this paper, a simple Paris Law model is considered. The simple Paris Law model is described in Appendix A. Kim, et al (2011)[5], Packman et al. [21], Berens and Hovey [22], Madsen et al. [23], Mori and Ellingwood [24], and Chung et al. [25] have modeled the damage detection probability as a function of the damage size. In this paper, the inspection of panels for damage is modeled using Palmberg expression. Palmberg expression gives probability of detection of a given damage as a function of the damage size, and id discussed in Appendix B. Table 1 shows the parameters used.

Table 1: Parameters and their values

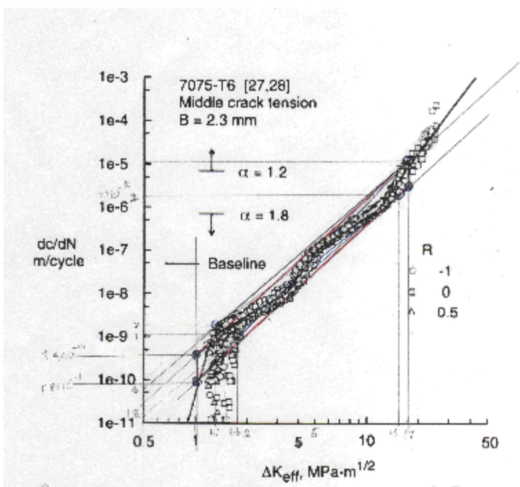
Parameter	Type	Value
Initial damage size (a_0)	Random	LN(0.2, 0.07) mm
Pressure (p)	Random	LN(0.06,0.003) MPa
Radius of fuselage (r)	Deterministic	3.25 m
Thickness of fuselage panel (t)	Deterministic	2.48 mm
Paris Law constant (C)	Random	U[$\log_{10}$(5E-11), $\log_{10}$(5E-10)]
Paris Law exponent (m)	Random	U[3, 4.3]
Palmberg parameter for scheduled maintenance ($a_{h\text{-}man}$)	Deterministic	0.63 mm
Palmberg parameter for scheduled maintenance (β_{man})	Deterministic	2.0
Palmberg parameter for SHM based inspection- Model 1 ($a_{h\text{-}shm1}$)	Deterministic	5 mm

Palmberg parameter for SHM based inspection – Model 1 (β_{shm1})	Deterministic	5.0
Palmberg parameter for SHM based inspection – Model 2 ($a_{h\text{-}shm2}$)	Deterministic	2.5 mm
Palmberg parameter for SHM based inspection – Model 2 (β_{shm2})	Deterministic	5.0

Newmann et al (1999) (Pg 113, Fig. 3)[26] shows the experimental data plot between the damage growth rate and the effective stress intensity factor for Al 7075 – T6 with a center crack in tension. The picture has been reproduced in Figure 4. The Paris law parameters C and m are estimated from the intercept and slope, respectively, of the region corresponding to stable damage propagation in the figure.

The data points in the region of stable damage propagation do not lie on a straight line in the log-log scale plot. Hence the region was visualized as bounded by a parallelogram with one edge parallel to the ordinate axes and the other edge parallel to the best fit straight line through the data points. The left edge of the parallelogram has a ΔK_{eff} value equal to one. As the region of the stable damage propagation can be bounded by a parallelogram, only the estimates of the bounds of the parameters, C and m, are obtained from the figure (Fig. 3, Newmann et al (1999)).

For the same reason, for a given value of intercept C, there is only a range of slope (m) values permissible. To parameterize the bounds, the left and right edges of the parallelogram were discretized by uniformly distributed points each assumed to be uniformly distributed. Each point on the left edge corresponds to a value of C chosen. For a given value of C chosen, there are only certain possible values of the slope, m. Figure 5 plots those permissible ranges of slope (m), for a given value of intercept (C). It can be clearly seen from Fig. 5 that the slope, and log(C) are negatively correlated; the correlation coefficient is found to be -0.8065.



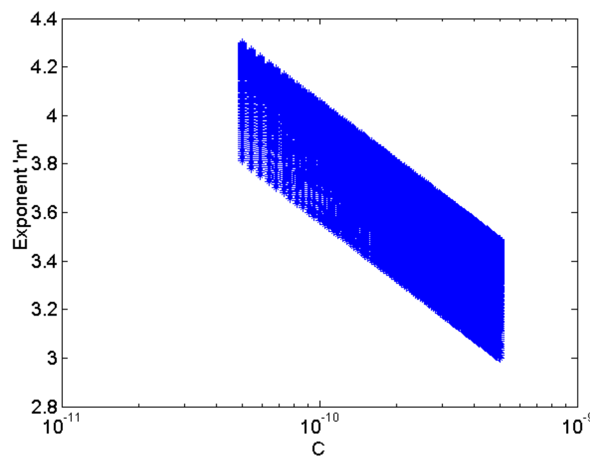


Figure 4: log-log plot of da/dN and ΔK for Al 7075- T6 Figure 5: Possible region of Paris model parameters

IV. COMPARING SCHEDULED AND CONDITION BASED MAINTENANCE ON RELIABILITY

Damage, missed during maintenance / maintenance assessment and that grows critical before the next scheduled maintenance / maintenance assessment affect the safety of the aircraft structure. In case of scheduled maintenance, the thickness of the fuselage panel (t), number of flight cycles between scheduled maintenance (N), and the threshold for replacement in the maintenance hangar ($a_{rep\text{-}man}$) affect the safety of the airplane. In case of condition based maintenance, the thickness of the fuselage panel (t), frequency of maintenance assessments (N_{shm}) and the threshold for requesting maintenance (a_{th}) affect the safety of the airplane. This section deals with quantifying the range of parameters for SHM and scheduled maintenance to maintain a specific reliability.

From fracture mechanics, the critical crack length for a panel depends on the pressure load, and hence, is distributed. In this paper, a panel is considered to have failed, if the crack in it grows undetected beyond the 10^{-7th} percentile of the critical crack size distribution.

In scheduled maintenance, maintenance is scheduled to achieve a certain level of safety or reliability in the structure. For aircrafts, a typical reliability is of order of 10^{-7}. For B 737 aircrafts, FAA regulations recommend scheduled maintenance every 6000 flights [27]. The threshold for replacing panels in the maintenance hangar must be set in order to achieve the desired reliability. Figure 7 plots the variation of probability of failure as a function of thickness of fuselage panel. A target reliability of 10^{-7} is sought in this paper and based on Fig 7, a panel thickness of 2.36 mm help achieve the desired level of reliability.

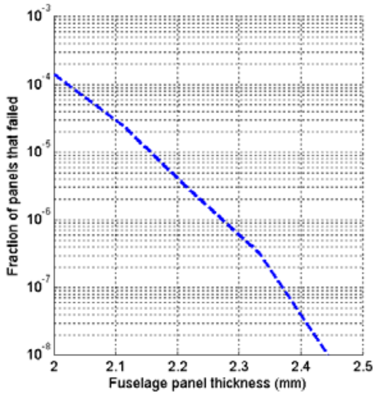


Figure 7: Variation of probability of failure as a function of thickness of fuselage panel, for scheduled maintenance every 6000 flights.

In condition-based maintenance, the threshold for sending aircraft to maintenance must be chosen to satisfy the reliability constraint until the next maintenance assessment. Based on practical considerations, the threshold for sending aircraft to maintenance (a_{th}) has been fixed at 40mm and the maintenance assessment frequency (N_{shm}) has been chosen to 100 flight cycles due to constraints on computational cost. The reliability for a given value of a_{th} and N_{shm} has been computed using direct integration procedure, detailed in Appendix D.

The lifecycle cost of an airplane is directly proportional to the average number of maintenance trips and average number of panels replaced per airplane. Table 3 compares the scheduled maintenance and condition based maintenance on the reliability and the parameters affecting the lifecycle cost

Table 3: Comparing scheduled and condition based maintenance on the reliability and the parameters affecting the lifecycle cost based on parameters tabulated in Table 1.

Type of maintenance	Thickness of fuselage panel (mm)	Probability of failure	Average no. of maintenance trips / airplane	Average no. of panels replaced / airplane
Scheduled	2.36	1E-7	8	473 (0.5)
Condition based	2.36	1.2E-13	3.6 (0.2)	43 (3.0)

It is noted that for the same panel thickness, condition based maintenance leads to better reliability and also leads to savings in the lifecycle of an aircraft. With condition based maintenance the number of maintenance is reduced by almost half and there is almost a 90% decrease in number of panels repaired / replaced. The reason for the savings is that scheduled maintenance replaces / repairs all panels with damage that might grow to be threatening until the next maintenance, while condition based maintenance replaces only those that actually grow to be threatening.

V. EFFECT OF INSPECTION ACCURACY ON WEIGHT

Table 3 concludes that condition based maintenance not only leads to savings in cost over scheduled maintenance, but also improves on the reliability. Condition based maintenance could also lead to reducing the weight of the structure while maintaining the desired level of reliability. This section focuses on quantifying the effect of accuracy of the inspection model on savings in weight of the fuselage panel.

Based on practical considerations, the threshold for sending aircraft to maintenance (a_{th}) has been fixed at 40mm. The effect of probability of failure as a function of panel thickness for various cases of maintenance assessment frequency (N_{shm}) is plotted in Figure 8. For a given set of maintenance assessment parameters, the probability of failure is computed using direct integration technique. The technique is described in Appendix D. It is noted the desired level of reliability is achieved with an assessment frequency of 100 cycles for most of the cases, while an assessment frequency of 40 cycles would achieve the desired level of reliability, for all cases of fuselage panel thickness.

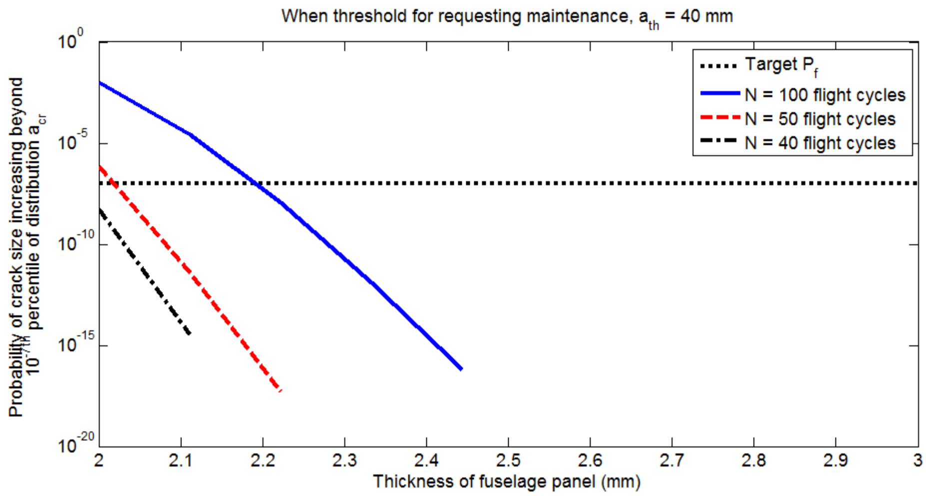


Figure 8: Variation of this probability of failure with thickness of fuselage panel for different cases of maintenance assessment frequency, N with the threshold for requesting maintenance (a_{th}) = 40 mm

This section compares different inspection models on the lifecycle cost of an airplane. Two different inspection models have been considered for the SHM based maintenance. The models differ in their accuracy of detection, and both inspection models are modeled using the Palmberg expression discussed in Appendix B. The accuracy of the detection is governed by parameter a_h of Palmberg expression, which is the crack length with 50% probability of detection. Figure 9 plots the probability of detection for the two models. The models differ only on the value of 50% probability of detection. The inspection model represented by dashed line has higher probability of detecting smaller crack lengths and is a better model.

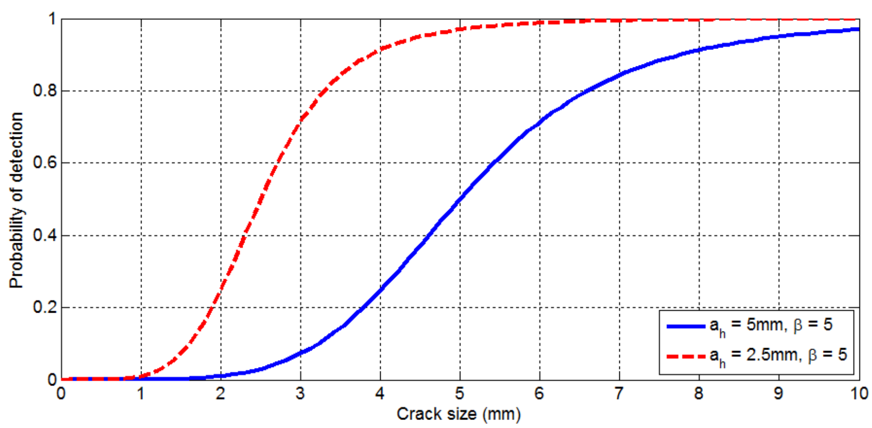


Figure 9: Probability of detection for the two inspection accuracies considered for SHM based maintenance

A maintenance assessment frequency of 100 flight cycles and threshold of 40 mm to request maintenance is considered to maintain a level of reliability of at least 10^{-7}. The effect of the threshold for replacement / repair of panels inside the hangar, ($a_{rep\text{-}shm}$) and the inspection model, on the average number of maintenance trips / airplane and average no. of panels replaced per airplane are plotted in Figure 10 below.

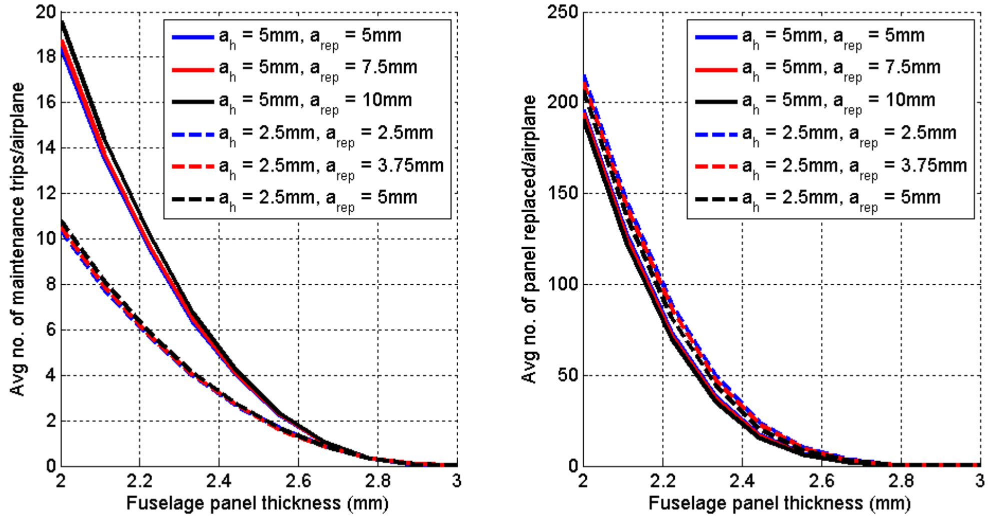


Figure 10: Effect of inspection accuracy on the maintenance requirements

It is noted that the average number of panel replaced / repaired is independent of the inspection model or the threshold for replacement / repair. But a better inspection model leads to fewer maintenance trips during the lifecycle of an airplane and thus leads to substantial savings. A better inspection model detects threatening damage much earlier and repairs / replaces the panel much earlier than the poorer inspection model. This leads to decrease in average number of maintenance trips per airplane, though the number of panels replaced / repaired remains constant until end of life.

In order to quantify the savings, a cost model is assumed, as discussed in Appendix C. As thickness decreases, the manufacturing and fuel cost of the panel decreases. But lower thickness leads to faster crack growth rate and warrants more frequent maintenance, leading to increase in inspection and maintenance cost. The total lifecycle cost of a panel would be the sum of fuel, manufacturing and inspection and maintenance cost. Figure 11 plots the variation of total cost / panel as a function of thickness of the panel, for different cases of inspection model and threshold for replacement / repair.

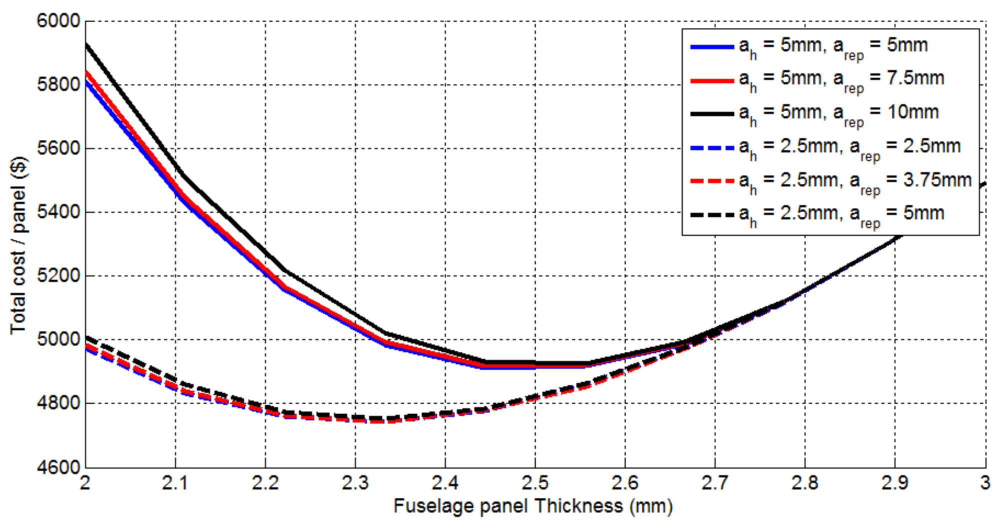


Figure 11: Effect of the two inspection models on the total cost / panel as a function of thickness for different threshold for replacement / repair of panels inside the hangar with maintenance assessment frequency of 100 flight cycles with fuel penalty of $200 / lb.

In Figure 11, dashed lines represent the better inspection model, and solid lines correspond to the lousier inspection model of the two. The optimal thickness of panel, as deemed by the SHM based maintenance, would be governed by the lowest lifecycle cost / panel. The optimal thickness of the fuselage panel has reduced when a better inspection model is used. The optimal cost for the better inspection model is also slightly lesser than the previous one. Table 3 tabulates the savings in cost and weight of condition based maintenance over scheduled maintenance when an inspection model with better accuracy is used, for different cases of fuel penalty.

Table 3: Savings in cost and weight of condition based maintenance over scheduled maintenance when an inspection model with better accuracy is used, for different cases of fuel penalty.

Fuel penalty	On weight of fuselage panel (%)	On total lifecycle cost/ panel (%)
$200/lb	2.54	46.63
$1,000/lb	15.24	34.45

It is concluded that using a better inspection model for the SHM based maintenance leads to savings in cost and weight while maintaining the same level of reliability. The fuel penalty causes a trade-off between the savings on weight of fuselage panel and savings on the total lifecycle cost of the fuselage panel.

VI. CONCLUSIONS AND FUTURE WORK

- The paper focuses on quantifying the effect of inspection model on weight and lifecycle cost of fuselage panel of aircrafts.
- SHM based inspection uses the on-board sensors and actuators to detect damage on fuselage panel of aircraft, could be performed as frequently as possible and is used as a decision making tool for conditional maintenance.
- Previous work has shown that conditional based maintenance with SHM would lead to substantial cost savings over scheduled maintenance, while maintaining same level of reliability.
- This paper quantifies the effect of inspection model on weight and lifecycle cost of fuselage panel of aircrafts.
- Using a better inspection model detects damage that might grow to be critical, much early in the life. This leads to fewer maintenance trips for the airplane, leading to substantial savings in cost.
- It has been found that the optimal thickness is lower for the better inspection model. This leads to substantial savings in weight and lifecycle cost of an airplane by using a better inspection model.
- Fuel penalty causes a trade-off between the savings on the weight of fuselage panel and the savings on the total lifecycle cost of the fuselage panel.

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VIII. APPENDIX

A. Fatigue damage growth due to fuselage pressurization

A through-the-thickness center crack in a fuselage panel of an airplane is the damage considered in this paper. The life of an airplane can be viewed as consisting of damage propagation cycles, interspersed with inspection and repair. The cycles of pressure difference between the interior and the exterior of the cabin during each flight is instrumental in propagating the damage. The damage propagation is modeled using the Paris model, which gives the rate of damage size growth with number of flight cycles (N) as a function of damage half size (a), pressure differential (p), thickness of fuselage panel (t), fuselage radius (r) and the Paris parameters, C and m.

$$\frac{da}{dN} = C(\Delta K)^m, \quad \text{.................. (1)}$$

where the range of stress intensity factor is approximated as

$$\Delta K = \frac{pr}{t}\sqrt{\pi a} \quad \text{.................. (2)}$$

There is uncertainty in Paris parameters, and effective initial flaw size (EIFS) between fuselage panels. Generally EIFS are derived through back-projection to time zero of the flaw size using a mechanistic linear–elastic fracture mechanics model, and may bear little resemblance to any physical dimension. In this paper, the uncertainty in EIFS is modeled using damage size distributions. The random nature of the atmospheric pressure causes uncertainty in pressure differential. The damage size after certain N flight cycles of propagation depends on aforementioned parameters and is also uncertain.

B. Inspection model

In scheduled maintenance and in SHM–based maintenance assessment, the detection probability can be modeled using the Palmberg equation given by,

$$P_d(a) = \frac{\left(\frac{2a}{a_h}\right)^{\beta}}{1 + \left(\frac{2a}{a_h}\right)^{\beta}} \quad \text{.................. (3)}$$

The expression gives the probability of detecting damage with size $2a$. In Eq (3), a_h is the damage size corresponding to 50% probability of deduction and β is the randomness parameter. The parameter a_h represents average capability of the inspection method, while β represents the variability in the process. Different values of the parameters a_h, β are considered to model the inspection inside the hangar for scheduled maintenance and also for SHM based maintenance assessment

C. Cost model

In order to estimate the cost efficiency of the SHM systems, it is necessary to discuss about the cost model first. The lifecycle cost of an airplane, ignoring the cost of ownership, depends mainly on four factors, manufacturing cost, fuel cost, crew cost and maintenance cost (refer to Fig 2, Curran et al (2009) [28]). The crew cost depends on the mileage on the airplane and hence is ignored for the comparison intended in this paper. The effect of fuel cost is considered through weight penalty.

The approach of a weight penalty, given as the lifetime fuel burn cost per weight has been introduced in the work done by Kelly and Wang (2003)[29], Wang et al.(2002) [30] and Curran et al.(2004) [31]. The quantification of weight penalty however is not trivial. Kaufmann, et al (2008) [32] used a weight penalty of €1500 / kg or about $930 / lb over the life of an aircraft considering composite aircraft structures. Kim, et al (2008) [33] refers to $200 savings over the life of an aircraft for every lb of weight saved. Based on the literature, two cases of weight penalties have been considered, the values of which are tabulated in Table 1. The manufacturing cost per lb of panel has been assumed to be $500.

The different maintenance operations performed on an airplane are classified in four categories, 'A', 'B', 'C','D', arranged in the increasing order of time spent for each type. Types 'C' or 'D' are the most time consuming and expensive of them all. This paper focuses on the 'C' type inspection.

The inspection and maintenance cost for an airplane depends on many factors such as number of labor hours, the revenue lost during the time the airplane is in the hangar and the cost for the facility and equipment. The B-737 of Lufthansa airlines [34] spends about four days on an average in the maintenance hangar for a 'C' type inspection and has about 1700 hours of labor, on an average, done on it during that period. Mcelroy (2006) [35] notes a labor rate of $60 /hr for inspection and maintenance work in the hangar and the industrial average revenue of $27,428 / day.

In SHM based inspection, the inspection would be done by sensors attached on board and hence, only the replacement / corrective action needs to be performed in the hangar. So, the number of days in the maintenance hangar for an airplane inspected by SHM has been assumed to be equal to one and the number of labor hours has been prorated from the information above. The inspection cost thus calculated is simply doubled to consider the effect of facility and equipment.

To replace a damaged panel, a cost of $500 / panel has been assumed. The cost of replacing simply the SHM equipment has been assumed to be 20% of the panel replacement cost. Table 2 show the cost model used in this paper. The downtime cost, inspection cost in the maintenance hangar, cost of replacing SHM equipment and the replacement cost constitute the inspection cost.

Table 2: Cost model

	Manual Inspection	**SHM based Inspection**	**Remarks**
Manufacturing Cost ($)	500 / lb	600 / lb	SHM installation costs 20% more
Fuel Cost ($)	Case 1: 200 / lb Case 2: 1000 /lb	Case 1: 240 / lb Case 2: 1200 /lb	SHM panel has a 20% extra weight.
SHM Installation Cost ($)	--	20 % of Mfg cost	
Maintenance Assessment Cost ($)	--	negligible	
Labor Cost in Hangar ($)	60/hr	60 / hr	
Downtime cost during Inspection ($)	27,428/ airplane/day	27,428 / airplane/day	
Time for Inspection in Hangar	4 days and 1700 hours of labor	1 day and 425 hours of labor	
Panel Replacement Cost ($)	500 / panel	500 / panel	
Replacing SHM equipment ($)	--	100 / panel	20% of Panel replacement cost

D. Direct integration Procedure

Direct integration procedure is a method to compute the cumulative distribution function (CDF) of an output variable at a given location, when the input variables are random. In this paper direct integration process is used to compute the CDF values of the damage size distribution at specific crack length values. The damage size distribution is a function of equivalent initial flaw size (EIFS), pressure load, Paris Law parameters (m, C) which are all random.

$$f_N(a) = h(f_0(a), f(p), J(C, m))$$

Where $f_N(a)$, $f_0(a)$, $f(p)$ represent the probability density functions of damage size distribution after N cycles of propagation, EIFS, pressure load respectively. $J(C, m)$ is the joint probability distribution of the Paris Law parameters, m, C.

Based on direct integration procedure, the CDF of the damage size distribution after N cycles of propagation, at damage size, a_N for instance, is the integration of the joint probability distribution of the input parameters in the region of input parameter cube that results in a damage size of a_N or less. Mathematically,

$\Pr(a < a_N) = \int_{C_{a_N}} f_0(a).J(C,m).f(p).dC_{a_N}$ … (4)

where, C_{a_N} represents the region of (a_0, C, m, p) which will give $a < a_N$ for $f_N(a)$.

For instance, the CDF value of the distribution of damage size at a_N = 40 mm after 50,000 cycles of propagation, is computed. The pressure varies at each flight, and after 50,000 cycles of propagation, effect of pressure distribution could be averaged out with its mean value. Hence, Eqn (4) reduces to be a function of EIFS, m, C.

Equation (4) is re-written as

$$F_N(40) = \int_{a_0} f_0(a) \iint_A J(C,m).dC.dm.$$

Where A represents the region of {C,m} that would give a_N < 40 mm for a given initial damage size ,a_0. Different values of a_0 are chosen and the area integral is computed for each value of a_0.

Figure 12 below plots the region of {C, m} for initial damage size, a_0 (= 1mm, say) after N = 50,000 cycles of propagation. The parallelogram represents all possible combinations of {C, m}. The region in blue results in a damage size (a_N) > 40 mm after N = 50,000 cycles of propagation, for the given initial damage size. The points 1, 2 that define the blue region are computed first using the analytical expression of Paris Law and the area of the polygon is computed from basic geometry.

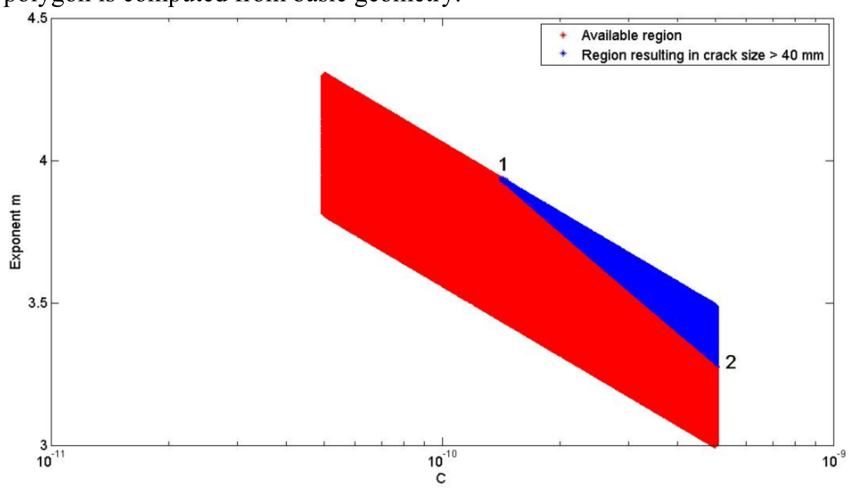

Figure 12: Regions of {C, m} for N = 50,000 and a_0 = 1mm

The integrand is evaluated at different values of the initial damage size and trapezoidal rule is used to compute the value of the CDF of the damage size distribution at the desired damage size.