Diagnosis and Prognosis of a Welded Joint in a Mining Truck Suspension

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Outline

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- Sensing Techniques
- Modeling
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- Model Updating and Validation
- Correlation to Remaining Useful Life
- Implementation

Motivation and Problem Statement

Manufacturer is interested in analyzing the health of welded joints located in the suspension system for one of their mining trucks

Motivation:

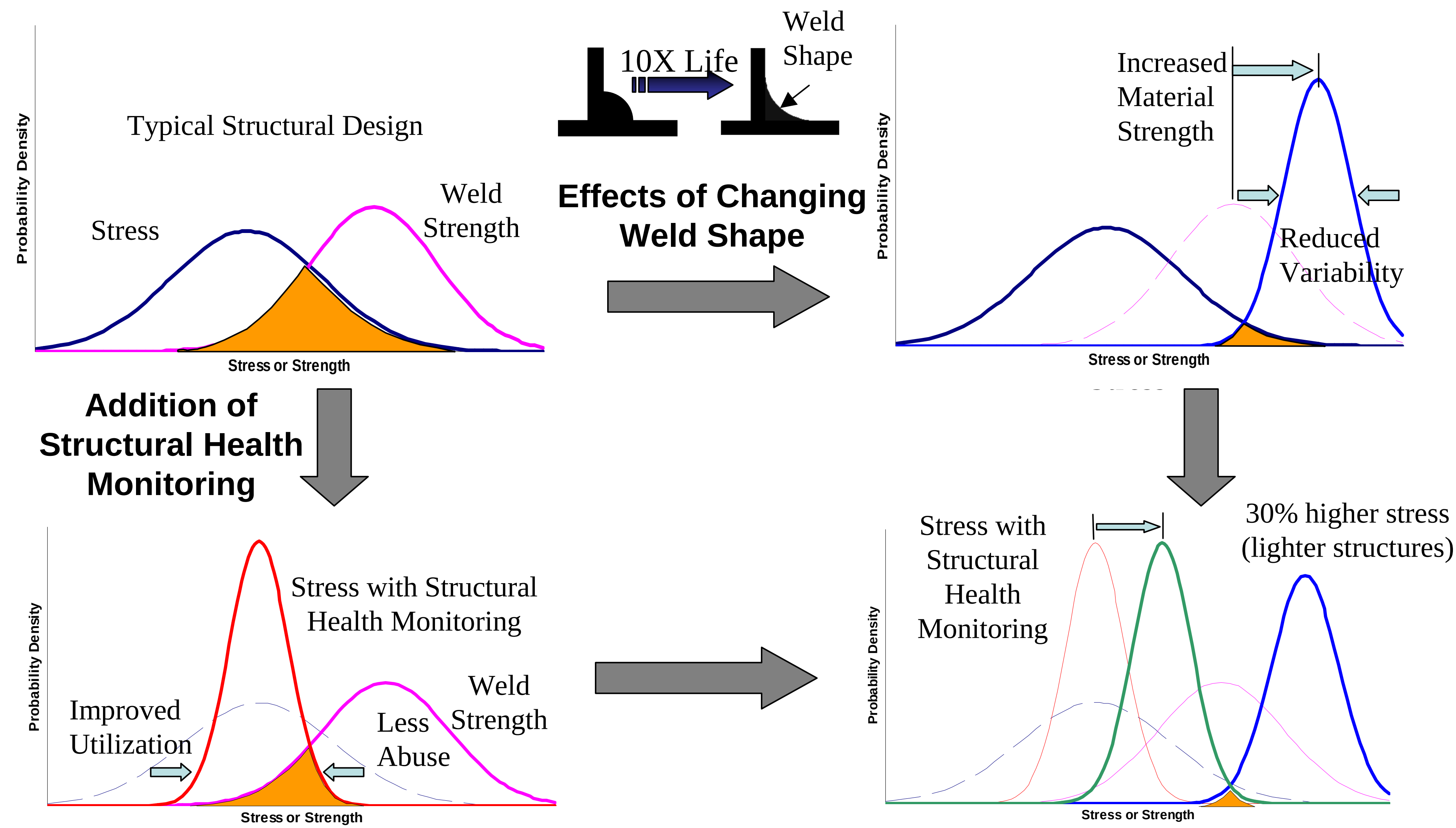
From manufacturer perspective:

- Increased revenue from leasers who abuse their vehicles
- Increased sales / leases due to added benefits to consumer
- Technological advantage over competitors

From customer perspective:

- Manufacturer 793C Mining Truck can hold 240 tons/load, 48 loads/day, generating revenues of about $90K+ / day
- 2% increase in downtime for a fleet of 20 trucks: $13M+ / year losses
- Increased operator safety, and reduced maintenance costs
- Possibility for reduced fees (incentives) for safe operation

Perspectives on using SHM



Sensing Techniques

Vibration Methods

Pros

1. Quantification of crack propagation
2. Real-time monitoring

Cons

1. Low sensitivity to stiffness changes before initiation region and for microcracks
2. Indirect measurement of crack size

Sensing Techniques

Impedance Methods

Pros

1. Qualitative determination of crack growth
2. Detection of local failure modes

Cons

1. Not able to quantify crack size
2. Not feasible for real-time monitoring (yet)
3. Degradation of PZT sensor

Sensing Techniques

Non-Destructive Test (NDT) Methods

Pros

1. 2D or 3D visual image of damage
2. Capable of measuring several types of damage

Cons

1. Expensive, bulky equipment
2. Special training, protective equipment
3. Not feasible for real-time monitoring

Sensing Techniques

Strain Propagation Gauges

Pros

1. Inexpensive
2. Accurate measurement of crack size

Cons

1. Requires some knowledge of crack location
2. Only provides information after a crack initiates

Sensing Techniques

Strain Gauges

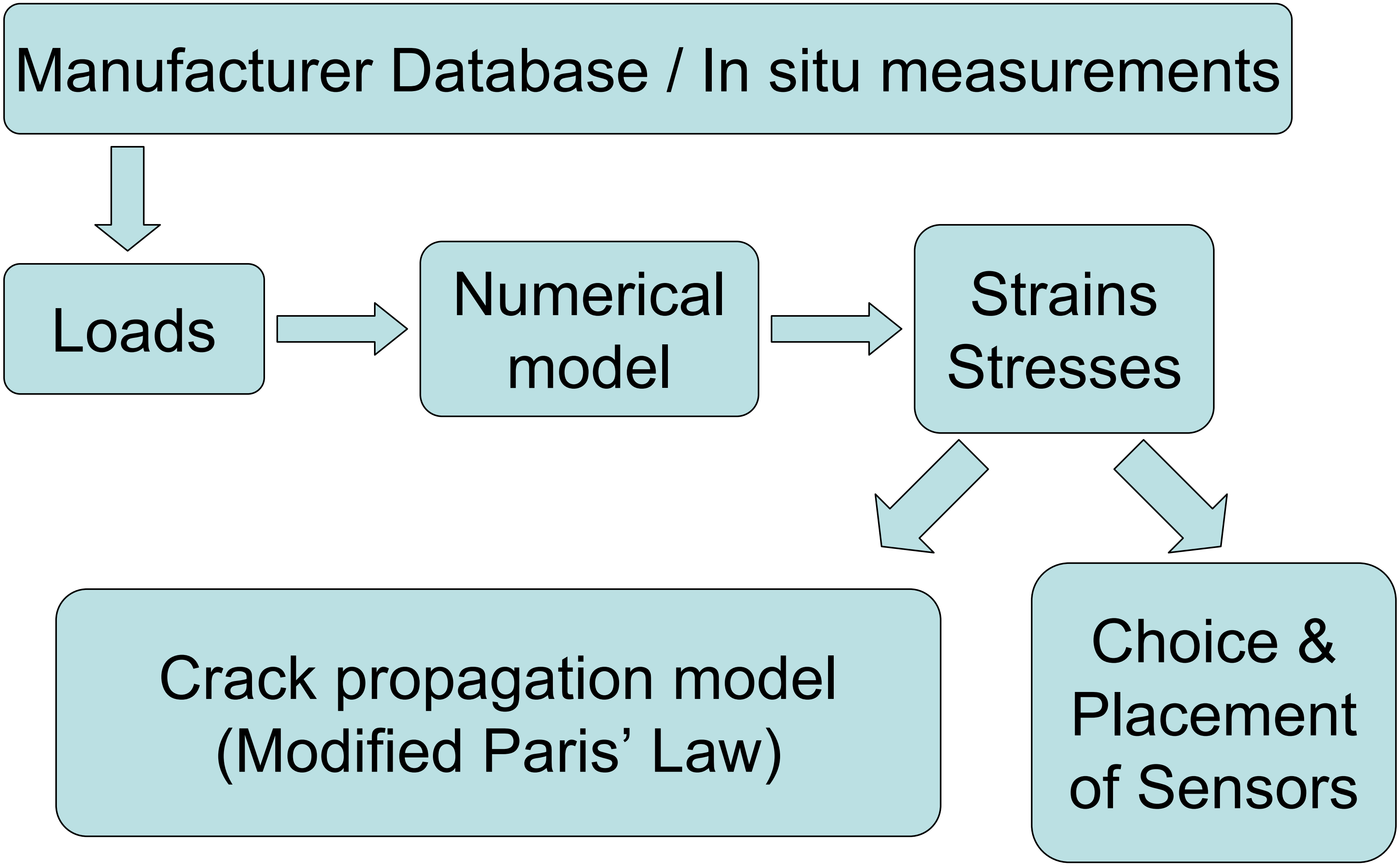
Pros

1. Inexpensive
2. Real-time monitoring
3. Provides information before and after crack initiation

Cons

1. Indirect measurement of crack size
2. Non-linear and environmental effects

Modeling


Manufacturer Database / In situ measurements
Loads
Numerical model
Strains Stresses
Crack propagation model (Modified Paris' Law)
Choice & Placement of Sensors

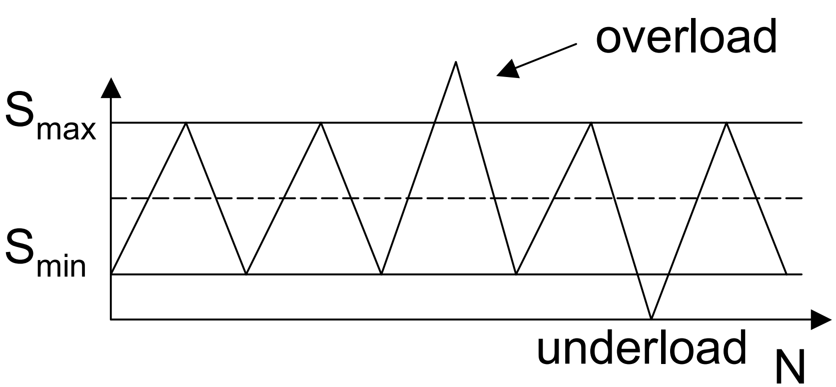
Model Updating and Validation

- Lab experiments using test specimens (impact, vibration, fatigue)
- Test track experiments: collect data from an actual vehicle riding on a test track
- Comparison with results from numerical model and crack propagation model

Overview of the Methodology

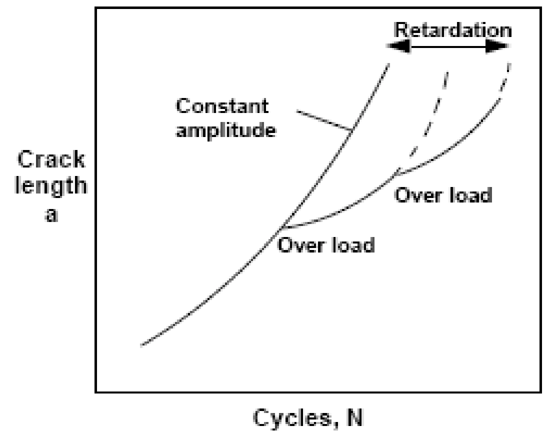
What events reduce the life of the structure?

Before a crack initiates



Overloads accelerate the crack initiation process, thus contributing to life reduction

After a crack initiates



- Under normal operation, crack will have a growth rate based on Paris' Law

- Overloads affect the crack propagation process

Introduction to Crack Propagation

Crack Initiation will begin when: $S > S_{\max}$

<u>Causes of Small Crack Initiation and Propagation:</u>

- Shear driven
- Interaction with microstructure
- Mostly analyzed using continuum mechanics methods.

<u>Causes of Large Crack Initiation and Propagation:</u>

- Tension driven
- Fairly insensitive to microstructure
- Mostly analyzed using fracture mechanics methods.

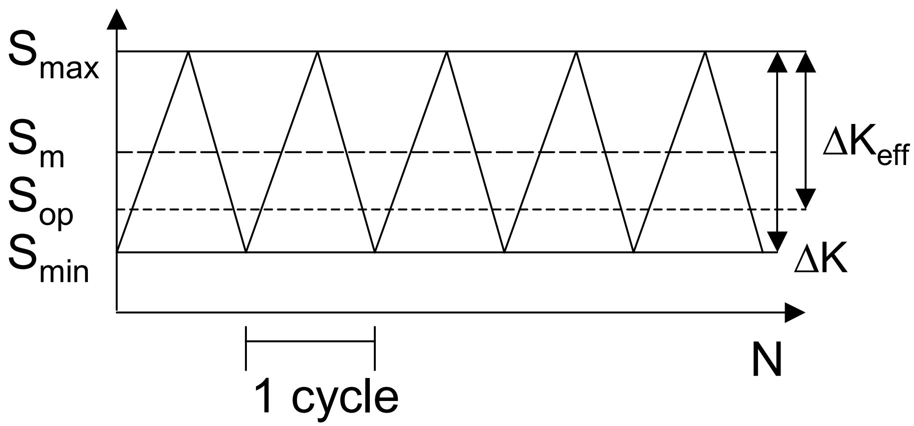
After initiation crack will grow in direction of maximum stress.

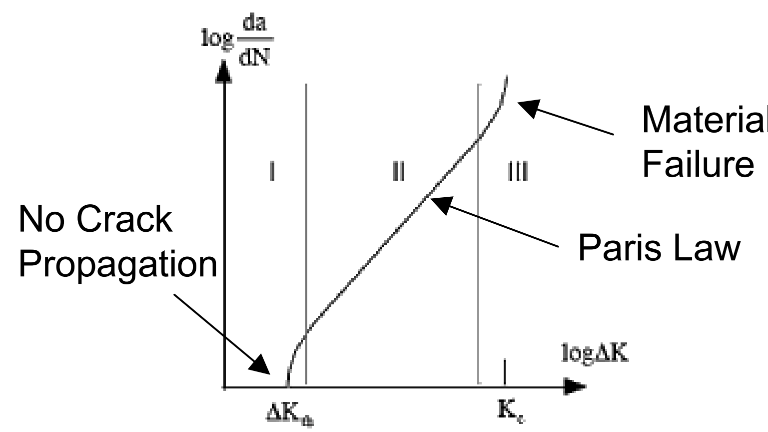
Two Main Classifications for Fatigue Induced Crack Propagation:

1. Constant Amplitude Fatigue Propagation
2. Variable Amplitude Fatigue Propagation

Crack Propagation Models

Constant Amplitude Fatigue Propagation Model:





$$\frac{da}{dN} = C\Delta K_{eff}^{m} = C\left(\left(\frac{1}{1-R} - \frac{S_{op}}{\Delta K}\right)\Delta K\right)^{m}$$

where: $R = S_{\min} / S_{\max}$

$$\therefore \Delta K_{th} = S_{op}(1-R)$$

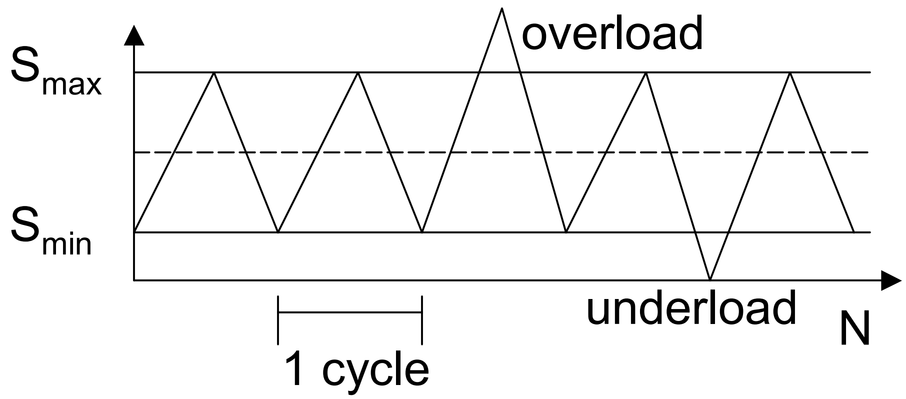
$$\therefore \Delta K_{eff} = S_{op}\left(\frac{1}{R} - 1\right)$$

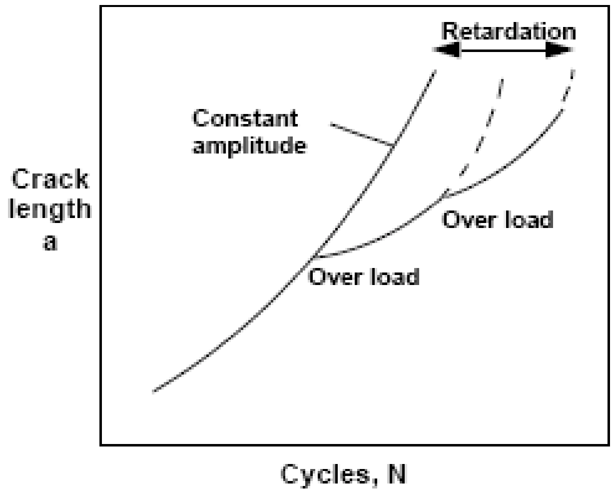
Factors Affecting da/dN:

- Material
- Cyclic Stress, overloads & underloads
- Temperature
- Material Processing
- Environment & Frequency

Crack Propagation Models (cont'd)

Variable Amplitude Fatigue Propagation Model:



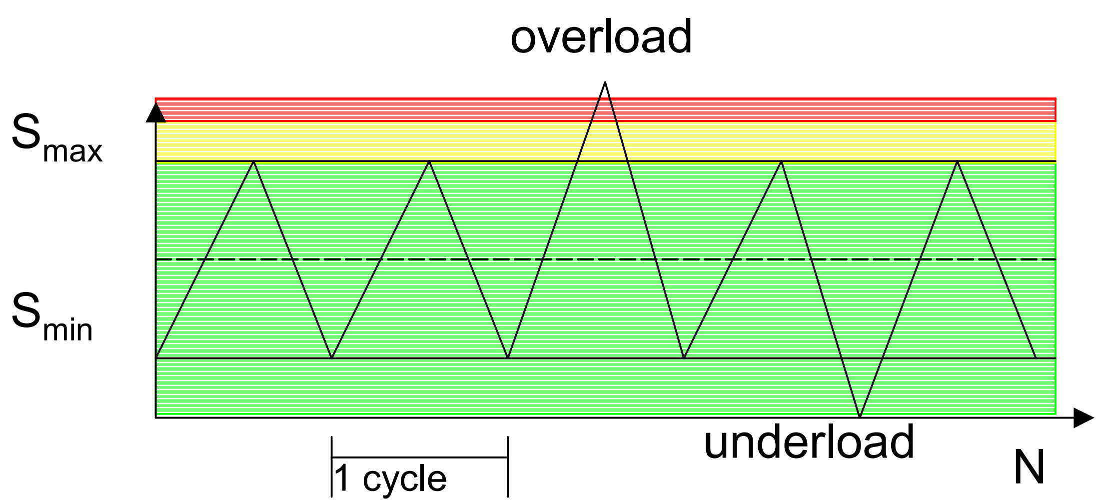


$$\left(\frac{da}{dN}\right)_{retard} = \phi\left(\frac{da}{dN}\right)_{const}$$

ϕ is a parameter related to the overload

Correlation to Remaining Useful Life

Step 1: Using stress level to predict remaining life



Crack initiation has begun → Step 2 $S > 1.05 S_{max}$

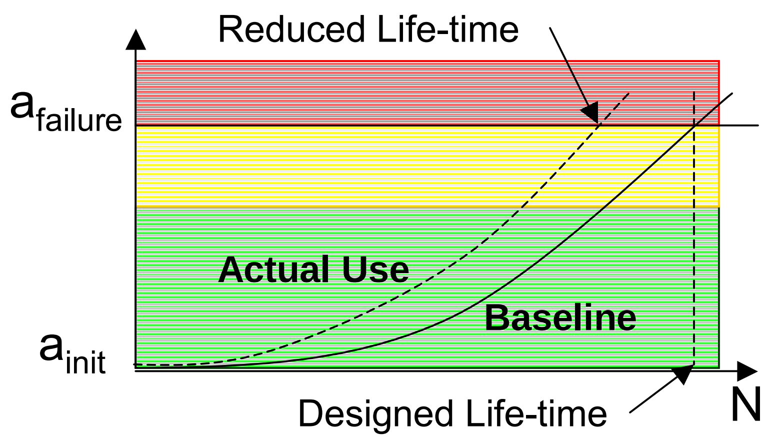
Cracks initiation likely, caution $S_{max} < S < 1.05 S_{max}$

System is undamaged $S < S_{max}$

Correlation to Remaining Useful Life (cont'd)

Step 2: Using crack size to predict remaining life

Modified Paris Law (Wheeler Retardation Model) will be used to estimate the crack length based on the number of cycles.



System has failed, have system replaced $a > a_{max}$

System is near failure, make repairs $0.75a_{max} < a < a_{max}$

System can remain in service $a < .75a_{max}$

Implementation

- Instrumentation: mounting, wiring, shielding
- Onboard data acquisition: fast sampling for online monitoring
- Onboard data processing: so measurements can be translated into warnings to the operator
- Simplified visualization panel: Green, Yellow and Red lights
- Storage: although we have fast sampling, we can choose to store events only, e.g. stress exceeds threshold by a certain amount for some period of time
- Computer Interface: for data harvesting

Verification Stage

- SHM system should be implemented on a few vehicles for a trial period
- Use other types of tests (NDT) as comparison basis to demonstrate to customers the ability of system to accurately detect damage, allowing them to dispute the diagnose, without legal implications
- This trial period and NDTs will also help us generate a database for future comparisons and updating

Technical Challenges

- Development of a numerical model capable of accurately predicting strains and stresses
- Validation of the crack propagation model
- Build a reliable database that substantiates a trustworthy prognosis or diagnosis.
- Convince consumer that the SHM system is not intended to increase the costs of leasing, but it is rather a fairer way of charging, which rewards good use and penalizes abuses

Conclusions

- Introduction of a real-time SHM system will benefit both the customer and the retailer.
- Using strain gauges and a two step analysis scheme allows for both usage monitoring and damage identification.
- The system can be easily implemented without precise knowledge of the damage location.
- The system can be continuously updated using empirical data and reliability analysis.

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Questions