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CME 8060

Assignment Part B - 'Lighting Column Failure Analysis Report'

Lifetime Prediction and Design for Reliability

CME 8060

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1. Discussion

1.1. Factors Affecting Structural Integrity of Lighting Columns

1.1.1. Definitions

Structural integrity is a measure of a components capability to bear loads safely while containing defects detected and sized and it consists of two theoretical values: the remaining strength and the critical flaw size (González Velázquez, 2020).

Fatigue is a progressive cracking process under repetitive or fluctuating loads that accumulate in the fracture of a material, it can occur significantly below the yield strength (Dieter, 1986).

1.1.2. Stress Concentration/Geometry

The materials geometry has the most significant influence on fatigue strength of lighting columns (Azzam & Menzemer, 2006). Sharp corners/notches can create stress concentrations by locally increasing the stress amplitude which reduces the fatigue strength limit exponentially (González Velázquez, 2020). Gausses in lighting columns can introduce stress concentrations (Gilani & Whittaker, 2000).

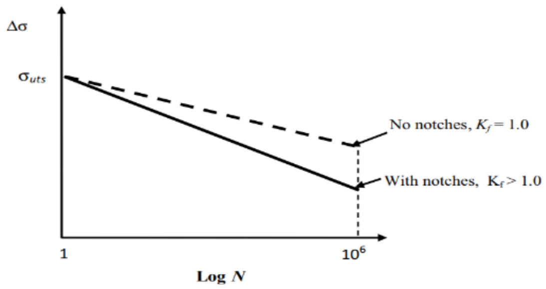

Fig 1. S-N Curve for Notched Specimen

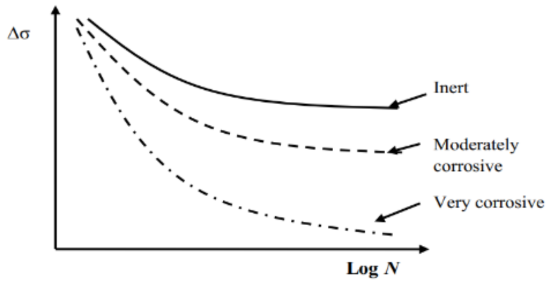

Fig 2. Environmental Effect of S-N Curve

1.1.3. Environment

When the environment is moderately or severely corrosive like air or seawater respectively, the fatigue strength lessens proportionally to the intensity of corrosiveness (Mehmanparast & Vidament, 2021). This is because new active surfaces absorb chemical species that increase the materials brittleness, facilitating crack growth (McEvily and Gonzalez, 1993).

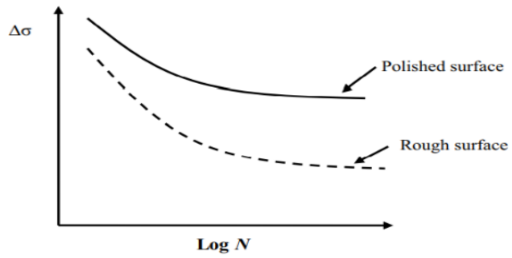

Fig 3. Surface Condition Effects on S-N Curve

1.1.4. Surface Finish

The rougher the materials surface is, the lesser the materials fatigue strength. For rough surfaces, the crack initiation stage is eliminated so crack growth begins early in the stress cycle (González Velázquez, 2020).

1.1.5. Mechanical Properties

The mechanical properties of the material such as its hardness and fracture toughness affect fatigue strength (González Velázquez, 2020), with tensile strength being proportional to its fatigue strength (Affonso, 2006).

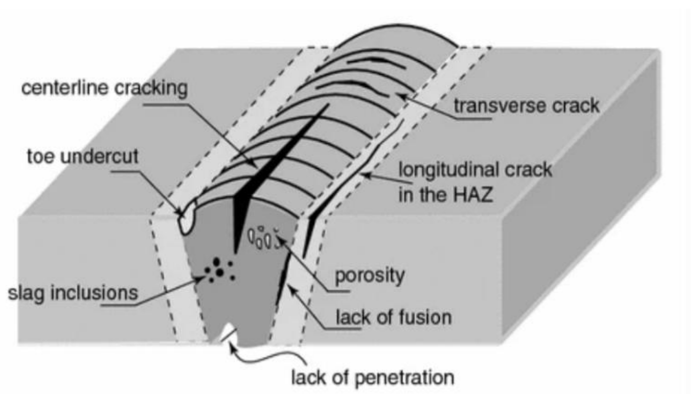

Fig 4. S-N Curve for Notched Specimen

1.1.6. Residual Stresses

Imperfections in welded structures can cause residual stresses to distribute around the welding zones causing stress concentrations and amplified stress intensities, reducing fatigue strength (Mazzolani et al., 1998) (De Matteis et al., 2009).

1.1.7. Other Influencing Factors

Many other factors can influence a materials fatigue life including (Affonso, 2006), (Dudek & Goroshko, 2019):

- Microstructure
- Reliability of Component
- Temperature
- Size of Component
- Thermal Treatment
- Nature of Stress (R Ratio)

1.2. Fatigue Failures and Failure Mechanisms

1.2.1. Failure Mechanisms

1.2.1.1. Dislocation Glide

Dislocation glide is best represented using Woods model of intrusions-extrusions (Fatigue Failure: Mechanism, 2018). Dislocations can propagate to the free surface through an alternating gliding process along the dominating slip plane, causing a metal extrusion. Due to continuity, on a nearby plane the opposite happens where dislocations are emitted into the material, resulting in the formation of an inclusion which act as an internal stress raiser. A crack is formed when the inclusion is sufficiently sharp and deep (González Velázquez, 2020).

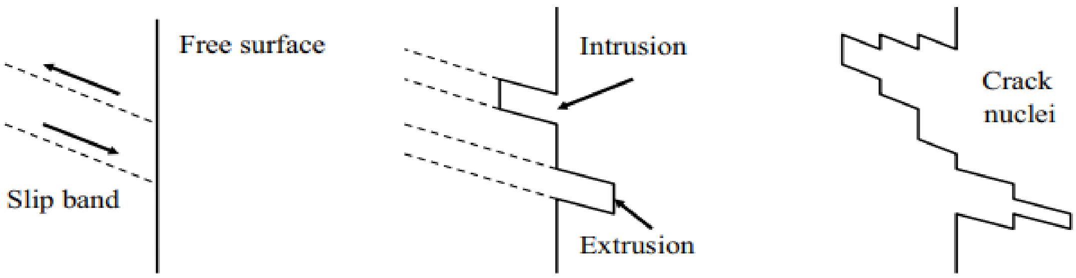

Fig 5. Nucleation of cracks by fatigue due to crack formulation on glide bands

1.2.1.2. Corrosion Fatigue

Corrosion fatigue occurs in gaseous corrosive environments when chemical species are absorbed through surface slip bands. Cavities are formed under the surface which causes decohesion of the slip band leading to the nucleation of cracks (González Velázquez, 2020).

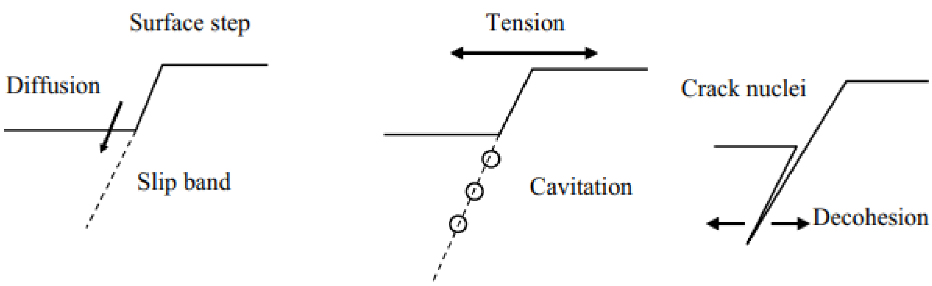

Fig 6. Cavitation of glide bands causing crack nucleation by fatigue

1.2.1.3. Planar Slip Condition

The planar slip condition describes plastic deformation along dense slip bands due to the shearing of precipitates. This event reduces the slip planes resistance to dislocation glide (Tayon et al., 2019).

1.2.1.4. Thermomechanical Fatigue

In high temperature oxidant environments, layers of brittle oxides fracture under tension forming microcracks that absorb oxidant agents. This forms an oxide penetration that cracks again and the process repeats (Bhanu Sankara Rao, Raj & Nagesha, 2017).

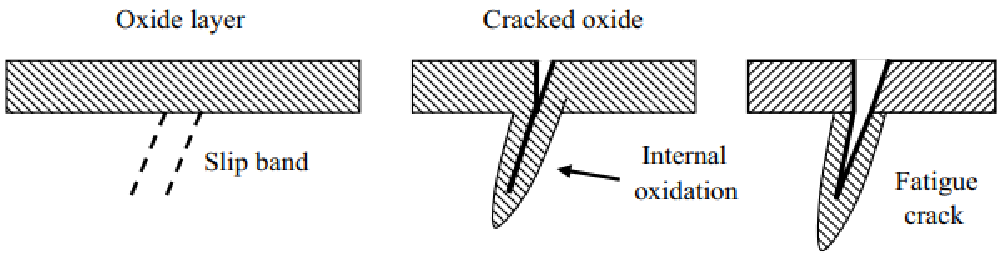

Fig 7. Thermal fatigue causing crack nucleation by fatigue

1.2.2. Failure Rates

1.2.2.1. Strain Relative to Yield Strain

Fatigue failure rates depend on the value of the strain relative to the yield strain. Low-cycle fatigue has a high fatigue failure rate, and it occurs when strains exceed the yield strain. Conversely high-cycle fatigue's failure rate is slower, occurring when strains are less (often substantially) than the yield strain. The value of the strain relative to the yield strain is proportional to fatigue failure rate (Gilani & Whittaker, 2000).

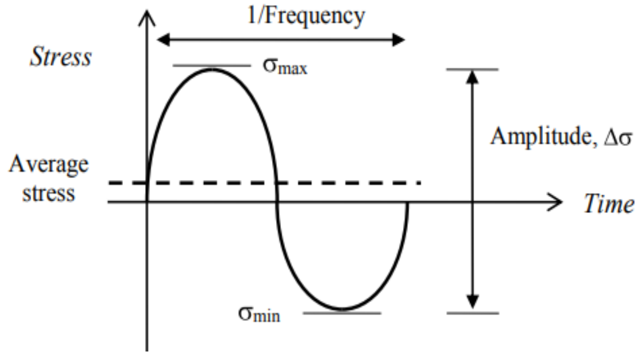

Fig 8. Fatigue Load Cycle Parameters

1.2.2.2. Type of Stress

Fatigue failure rates depend on the amplitude of the stress, its frequency off application and its load cycle nature (R ratio or mean stress location) i.e., if it's compressive, tensile or reversed (Affonso, 2006).

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1.3. Laboratory Tests to Understand Fatigue and Corrosion

1.3.1. Bending Tests

Much research effort has been attached to investigating the fatigue and corrosion behaviour of lighting columns to prevent collapsing structures (Alexander & Wood, 2009) (Azzam & Menzemer, 2006). Cantilever bending tests can simulate forces experienced by such structures to generate S-N curves for prediction of fatigue limits.

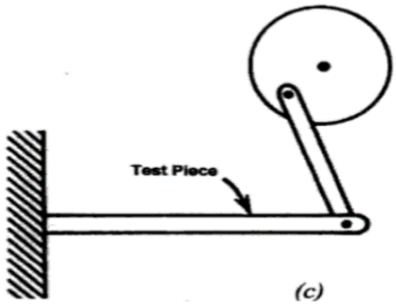

Fig 9. Cantilever Eccentric Bending

An extruded metal tube instrumented with strain gauges is constrained at one end to a support. At the cantilever tip is a servo-hydraulic actuator that loads the specimen by inflicting a controlled displacement which is varied until the target strain value is met (Gilani & Whittaker, 2000). This displacement is applied at a frequency until failure occurs or 20 million cycles are complete (AASHTO, 2015). This process is repeated for different stress amplitudes until a clear S-N curve can be plotted.

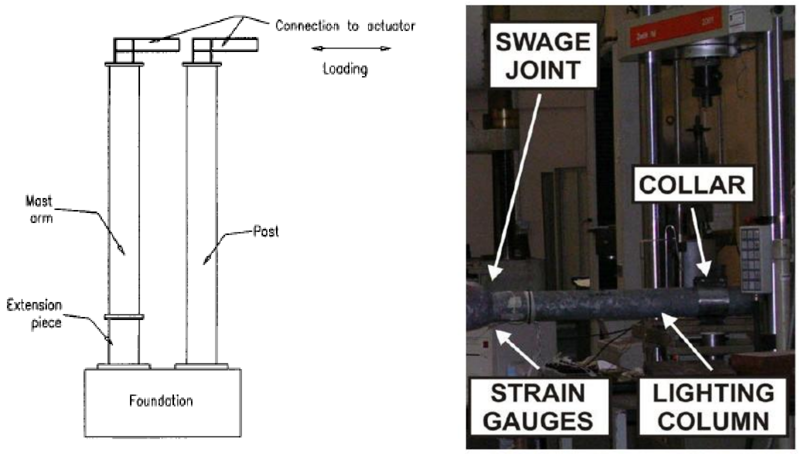

Fig 10. Typical Cantilever Servo-Hydraulic Displacement Actuated Bending Fatigue Tests

Limitations of this method include:

- No axial, torsional or shear stresses considered
- Expensive
- Time-consuming
- Hard to consider extreme weather conditions

1.3.2. Finite Element Analysis

Elastic finite-element analysis (FEA) modelling techniques are a cheaper and faster way to support experimental tests and predict stress concentration locations in lighting columns (Alexander & Wood, 2009), (Gilani & Whittaker, 2000). Sophisticated FEA software can predict the fatigue life and endurance limit of welded and bolted structures by simulating S-N curves, but this method is not yet accurate enough to pass standards. Some limitations of FEA include:

- Results are predicted
- Accuracy depends on the modelling
- Initially expensive
- Corrosive fatigue not considered
- Insufficient to pass standards

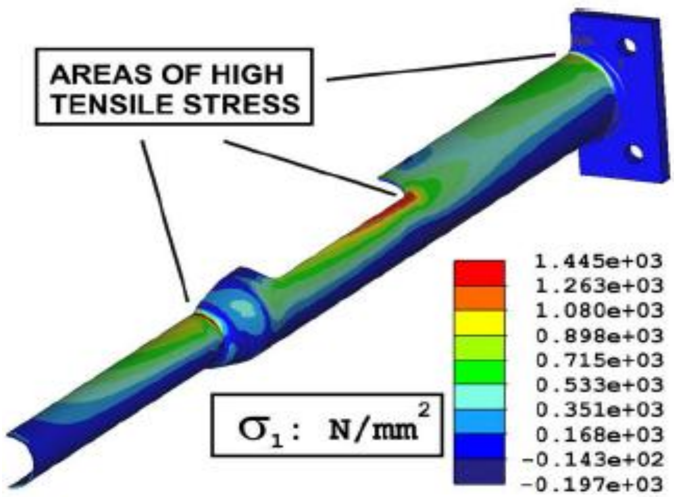

Fig 11. Finite Element Analysis Model of Uniaxial Loaded Lighting Column with Conduit

1.3.3. Corrosion Fatigue Testing

Oxygen concentration levels proportionally influence corrosive fatigue rates of lighting columns. Confining the specimen in a controlled oxygen pure/scarce environment allows investigation of oxygen levels o fatigue failure rate however, this method is very expensive and complex (Mehmanparast & Vidament, 2021).

1.4. Selection Criteria for Lighting Columns

1.4.1. Lighting Column Material Selection Criteria

The selection of material for lighting columns especially critical during extreme weather conditions. To ensure feasible operation, the lighting column material should unofficially meet the specification(Dudek & Goroshko, 2019):

- Durability
- Wear resistance
- Low cost
- Electrical insulation/safety
- Energy consumption
- Corrosion resistance
- Raw material availability
- Low maintenance
- Ease of manufacture
- Aesthetic qualities

More officially however, strict standards have been derived by the British Standards Institution that comprehensively specify the manufacturing process, material properties and installation methods that must be followed to erect a lighting column (BS EN 40-3-3, 2003).

British Standard EN12767 (BS EN 12767, 2007) designed for passive safety for road infrastructures states that:

- Lighting columns should withstand 50, 70 and 100Km/h collisions

BS EN ISO 1461 (BS EN 1461, 2009) designed for corrosion protection of metals:

- Steel columns should be hot-dop galvanized outside an inside and covered with a protective paint coat
- Aluminium columns should be anodised with a coating of minimum 20 µm

BS EN 40-7 (BS EN 40-7, 2002) is a specification for polymer composites reinforced with fiberglass designs.

1.4.2. Materials Advantages and Disadvantages

Below outlines the advantages and disadvantages of feasible lighting column materials (Dudek & Goroshko, 2019) (Verma, Atkinson & Kumar, 2001), (BS EN 40-7, 2002):

Aluminium and Steel Lighting Columns	
Advantages	Disadvantages
Resistant to Corrosion	Requires Coatings/Anodised
High Mechanical and Dynamic Strength	Relatively Heavy
Flexibility	Requires Maintenance
Ease of Manufacture	Requires Conduit Holes (Stress Concentration)
Recyclable	Susceptible to Expansion/Contraction Cycle
Availability of Materials	

Table 1. Advantages and Disadvantages of Aluminium and Steel Lighting Columns

Polymer Composite Material Lighting Columns	
Advantages	Disadvantages
Low Weight	Lower Mechanical and Dynamic Strength
No Maintenance Requirements	Relatively Expensive
Temperature and UV Resistance	Complex Manufacture
Dielectric Properties	Early on Research
Low Coefficient of Thermal Expansion	
High Vibration Dampening	

Table 2. Advantages and Disadvantages of Polymer Composite Lighting Columns

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