Fatigue Analysis of a Welded Structure in a Random Vibration Environment

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Outline

- Problem description:
  - Life assessment of welded bracket subjected to random vibrations.

- Background:
  - Stresses in welds.
  - Methods for calculating critical weld stresses.
  - Random vibration fatigue analysis.

- Analysis description:
  - Selection of weld stress approach.
  - Using ANSYS Mechanical and nCode DesignLife to perform random vibration fatigue of welded structure.
Problem Description: Welded Bracket

- Welded bracket with base excitation:
  - Input Power Spectral Density (PSD) provided.
  - Supported and excited at two holes.
  - Fillet welds along intersection of components.
The Importance of Weld Stress Prediction

- Key features of welds:
  - Sharp section changes.
  - Local discontinuities.
  - High tensile residual stresses.
  - Crack initiation sites.
  - Material properties vary over weld cross section.
  - Geometry of weld cannot be modeled in detail.

- Consequences:
  - Relatively low fatigue strength.
  - Dominated by fatigue crack growth.
  - Fatigue life not increased by use of higher strength material.
Weld Geometry and Terminology

- **Weld features.**
  - **Face:**
    - The exposed surface of the weld.
  - **Toe:**
    - The point or line where the face meets the parent material.
  - **Root:**
    - The point in the weld joint where the weld metal ends.
  - **Weld throat:**
    - The minimum distance from the root to the face of the weld.
    - It is the minimum load bearing section and considered the effective area.
Fatigue Failure in Welds

- The primary failure mechanism in welds is fatigue.
  - Fatigue is failure from cyclic loading.
  - The underlying mechanism in fatigue is the propagation of cracks.
  - Cracks are present from the welding process.

- Fatigue is typically assessed based on time-based loading.

- However, if random loading occurs:
  - Evaluation of fatigue is performed in the frequency domain.
  - Statistical approach is used.
  - Random loading characterized by Power Spectral Density function.
There are four methods generally used for calculated stress in welds:
1. Nominal stress method.
2. Structural hot spot stress method.
3. Effective notch stress method.
4. Stress intensity at a crack tip.

The method used in assessing welded structure life depends on:
- The nature of the problem.
- If the method is valid for approval of a particular component.
- If the welded design is catalogued in a welding standard.
- The ability to create detailed finite element analyses of local weld regions.

International Institute of Welding (IIW) has defined S-N curves for welds in aluminum and steel.

The S-N curve selected must match the method used to extract the stresses.
Nominal Stress Method

- Nominal stress method.
  - Classical analysis or hand calculation approach.
  - Stress calculated as section loads divided by net sections and bending moments divided by section moduli.
  - The focus of most welding standards.
  - Life prediction found using $S_N$-$N$ fatigue curves for the weld class.
    - More than 70 weld classes.

$$S_N = \frac{F}{A}$$
Structural Hot Spot Stress Method

- Structural hot spot stress method.
  - Accounts for stress concentration effects, ignores the local notch effect of the weld toe.
  - Hot spot stress found by linearly extrapolating stress from adjacent region to weld toe from FE analysis.
    - Various methods for extrapolating, such as along surface or through thickness.
  - $S_{HS}$-N fatigue curves based on hot spot stress range exists for some weld designs.
Effective Notch Stress Method

- Effective notch stress method:
  - The effective notch stress is the stress at the weld toe radius obtained assuming linear elastic response.
  - Real weld contour variations are approximated by an effective notch root radius of 1 mm.
  - For thin structures (under 5 mm), an effective notch radius of 0.05 mm is recommended.
  - A single $S_{NS}$-N curve is used for all welds depending upon the effective notch radius used.
Stress Intensity at a Crack Tip

- Stress intensity at a crack tip:
  - Models a known crack size and location.
  - Requires a fine mesh near the crack tip.
  - Calculates stress intensity at the crack tip using fracture mechanics approaches.
  - Analysis is repeated by extending crack perpendicular to the 1\textsuperscript{st} principal stress a small distance and recalculating stress intensity.

\[ \sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos \left( \frac{\theta}{2} \right) \left( 1 + \sin \left( \frac{\theta}{2} \right) \sin \frac{3\theta}{2} \right) \]
Comparison of Stress Techniques

- An illustration of the comparison of the different stress calculation techniques:

1. Nominal stress, $S_N$

2. Hot spot stress, $S_{HS}$

3. Effective notch stress, $S_{NS}$

4. Singular stress at crack tip (used to calculate $K_I$)

Distance from weld toe
Random Vibration Fatigue Analysis

- Random vibration fatigue analysis is performed by defining the amplitude of the applied loading as a function of frequency.
  - This is called the input Power Spectral Density, or input PSD (g²/Hz).

- Random vibration fatigue is determined using:
  - Statistical parameters that describe the PSD loading.
  - Miner’s Rule to accumulate total damage.
  - The appropriate S-N data based on weld stress method chosen.
  - A PSD cycle counting method.

- nCode DesignLife PSD cycle counting methods:
  - Narrow Band – original technique, rarely used.
  - Steinberg – simple approach based on Gaussian distribution.
  - Dirlik – general purpose technique.
Random Vibration Fatigue Analysis

- The output or response PSD is obtained by multiplying the input PSD by the square of a transfer function.
  - The transfer function is obtained from the results of a harmonic analysis.

- Statistical parameters from the random loading are determined:
  - No. of upward zero crossings (E[0])
  - No. of local peaks (E[P])
  - Irregularity factor ($\gamma = E[0]/E[P]$)

![Graph showing stress with zero crossings and peak locations]
Application to Bracket Problem

- What tools are available in nCode DesignLife?
  - nCode DesignLife has a random vibration module to perform vibration fatigue.
  - nCode also has two weld modules:
    - Spot weld, used to model welding of thin metal sheets.
    - Seam weld, for more general welding approach.
      - The seam weld is analogous to the hot spot weld stress approach.

- The effective notch weld stress approach was selected for this application.
  - Build model with 1 mm radius fillets at weld toe and root.
  - Perform harmonic analysis in Mechanical.
  - Feed the harmonic solution to nCode, perform vibration fatigue within nCode.
FAT 225 is the recommended S-N curve if using the effect notch stress approach with welds in steel.

- The fatigue strength at $2 \times 10^6$ cycles is 225 MPa.
- The curve represents a survival probability of 97.7% and a standard deviation of $\log N = 0.206$.
- Can adjust this S-N curve to the required survival probability level.

![Stress Life without UTS correction graph](image-url)

- **Slope = $-\frac{1}{3}$**
- **225 MPa**
- **Slope = $-\frac{1}{22}$**
- **$2 \times 10^6$ cycles**
Effective Notch: 1 mm Fillet Radii

- Weld regions modeled with 1 mm fillet radii at toe and root.
- Fine mesh in weld regions required for effective notch method.
- Weld geometry created using standard procedures in DesignModeler.
Analysis Settings/Assumptions

- Harmonic analysis used the following loading and solution settings:
  - Fixed supports in two holes.
  - Unit vertical acceleration = 1g = 386.4 in/sec$^2$
  - Frequency sweep from 0 to 7500 Hz.
  - Constant damping ratio = 0.05.

- Random vibration fatigue vibration analysis input:
  - Harmonic analysis fed to nCode as transfer function.
  - Input PSD and S-N curve defined.
  - Used Named Selections to limit fatigue calculations to weld regions.
  - Compare PSD cycle count methods.
nCode DesignLife Setup

- nCode requires input of the harmonic solution, the definition of the random loading via a PSD definition, and the S-N data:

  - Harmonic solution
  - Input PSD
  - Random vibration fatigue settings, and S-N data
Vibration Fatigue Results

- RMS stress and life prediction results using the LaLanne cycle count method:

  Max RMS stress = 2771 psi = 19.1 MPa
  Min life = 4.085e6 sec = 1135 hrs
To view inside the weld root region, plot results using the nodal point feature:
Vibration Fatigue Results

- Comparison of PSD cycle count methods:

![Comparison of PSD Cycle Counting Methods]

- Minimum Life (hours)
- PSD Cycle Counting Method
- LaLanne, Dirlik, Narrow Band, Steinberg
Summary

- Used the effective notch weld stress approach with the nCode DesignLife vibration fatigue module to estimate the life of a welded bracket.

- Approach requires detailed modeling of weld regions and mesh refinement.

- For steel welds, this method only requires the FAT 225 S-N curve.

- Efficient solution technique, particularly taking advantage of Named Selections to limit fatigue analysis to weld regions.