# Fatigue Model of Bolts Based on Manufacturing Defects


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## Abstract

The existing standards for thread fastener defects, which specify the acceptable level of defects, are antiquated and overly cautious as they allow no defects in the thread root. To address this issue, a mathematical model has been created to determine the appropriate size of thread defects that should be permissible. The model utilizes Murakami's equation on fatigue strength and is integrated into a user-friendly graphical interface. This interface allows for the assessment of a batch of bolts with defects in the thread root to determine if they meet customer standards.



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## Background & Objectives

- Current standards (e.g. ISO 6157-3) are outdated and too conservative. This can be seen in Figure 1, which shows that no defects are permitted in the thread root
- Can potentially cause Caterpillar to discard useable bolts

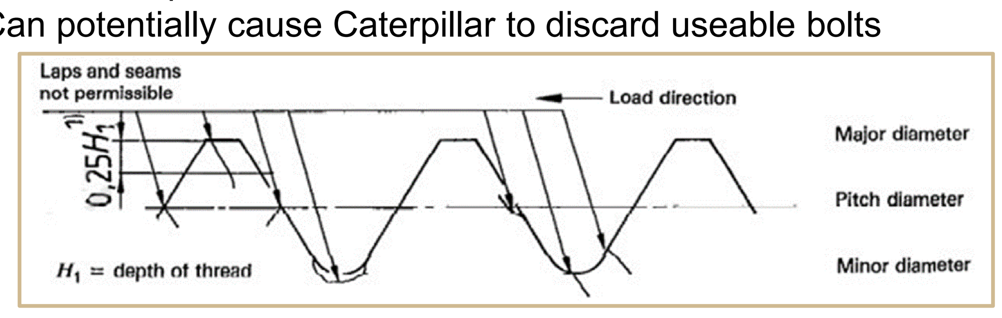



Figure 1. Diagram showing nonallowable thread defects in outdated standards [1].

**Purpose of Project**:

- Create a metallurgical analysis of defects in Caterpillar bolts
- Create an updated method (mathematical model) of determining if specific defects in fasteners are acceptable to be used in engine manufacturing
- Create graphical user interface with new mathematical model for customer use

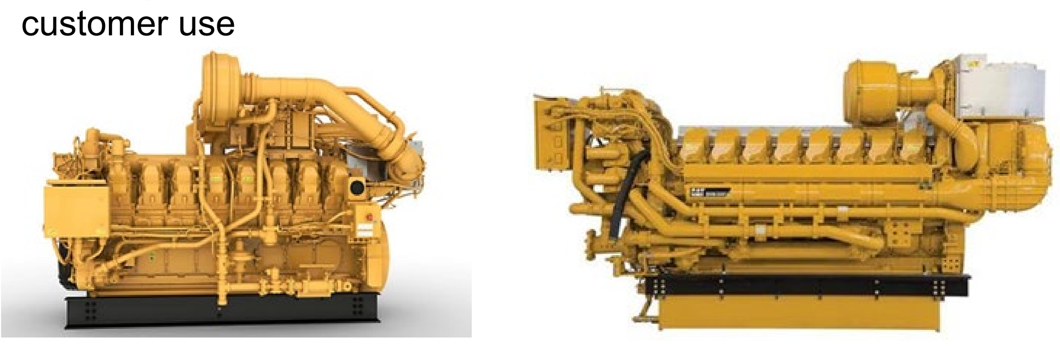


Figure 2. Caterpillar's 3500 engine is on the left and the C175 engine is on the right [2].

There are three different types of fasteners that were characterized:

- **Counterweight Bolts:** Attaches the counterweights that balance the rotating mass of the pistons and the connecting rods.
- **Connecting Rod Bolt:** Attaches the piston to the crankshaft.
- **Dampener Bolt:** Fastener for the dampener that absorbs engine vibration.

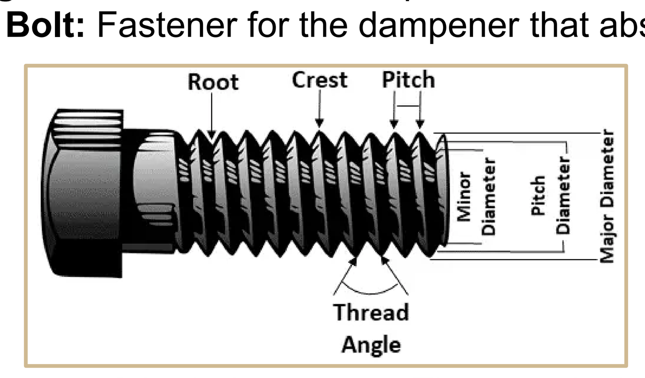



Figure 3. Diagram of the bolt anatomy. The crest is the top of the thread, and the root is the bottom of the thread. The minor and major diameters are the distances through the center of the bolt from root to root and crest to crest, respectively. [3].

## Experimental Procedure

**Fatigue Testing Method:**

- The bolts were cycled up to five million cycles, or until they failed.
- The mean load was 370 kN for counterweight bolts, and 320 kN for damper bolts. The amplitude of the cycling was about 23 kN for counterweight bolts, and 13 kN for damper bolts.

**Data Collection**

- Specimens were of pre-mounted cross sections of bolts, whole bolts, and bolts that had failed during testing. Examples of this are in Figures 4 and 5
- Data collection process is summarized in Figure 6, with the bolt sectioning diagram in Figure 7

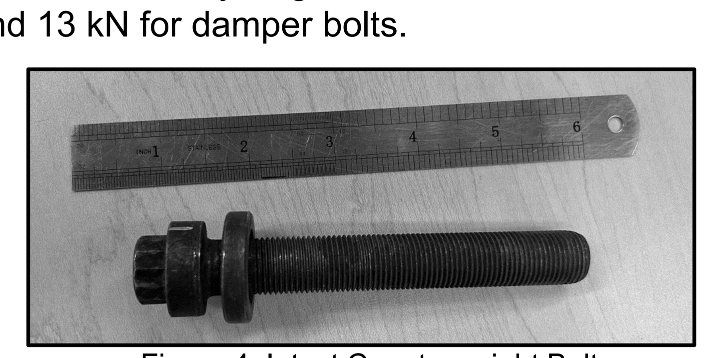


Figure 4. Intact Counterweight Bolt

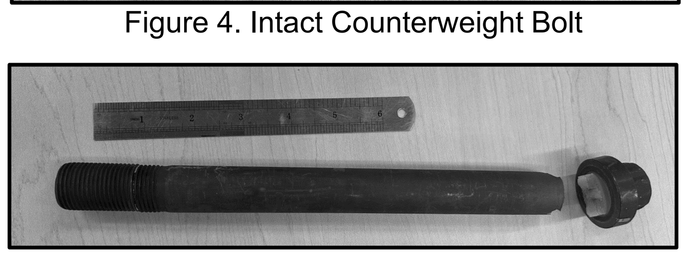


Figure 5. Failed Damper Bolt

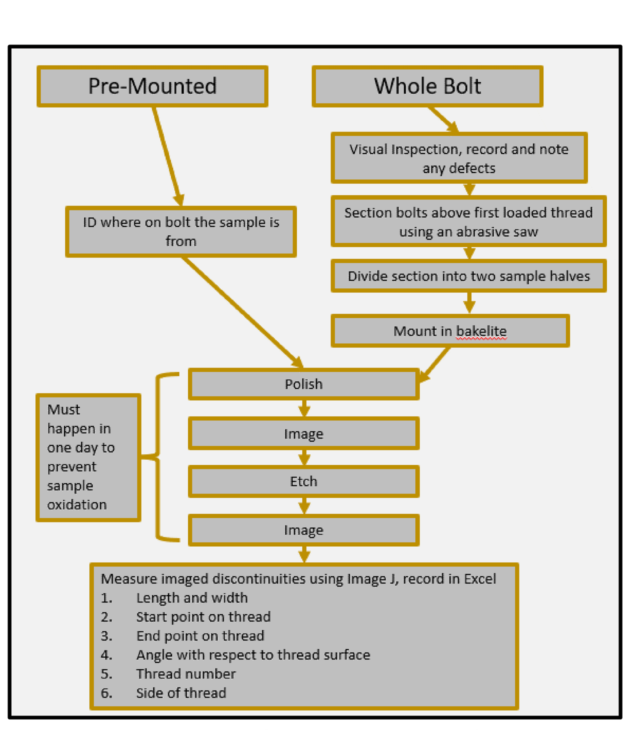



Figure 6. Data Collection Flow Chart

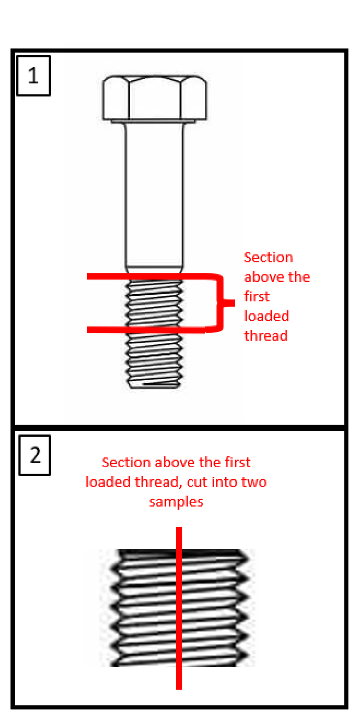



Figure 7. Bolt Sectioning Diagram

## Experimental Results

**Micrographs of Thread Defects**

- Micrographs of thread lap defects in bolts used for data collection
- Data was used to test the fatigue strength model

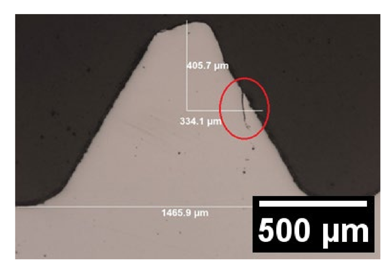



Figure 8. A defect along the flank of the thread of a 3500 counterweight bolt. The defect is 176.5 micrometers deep. Image provide by Caterpillar.

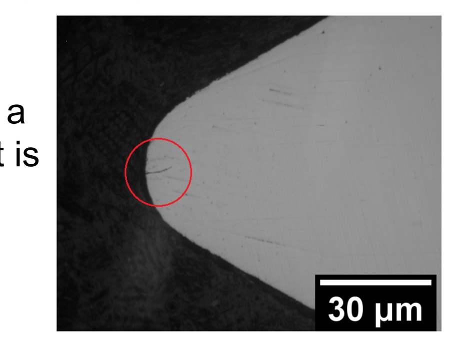



Figure 9. A defect at the crest of a C175 dampener bolt. The defect is 7.67 micrometers deep.

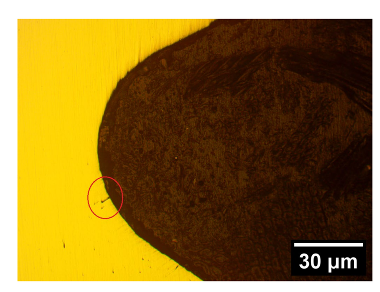
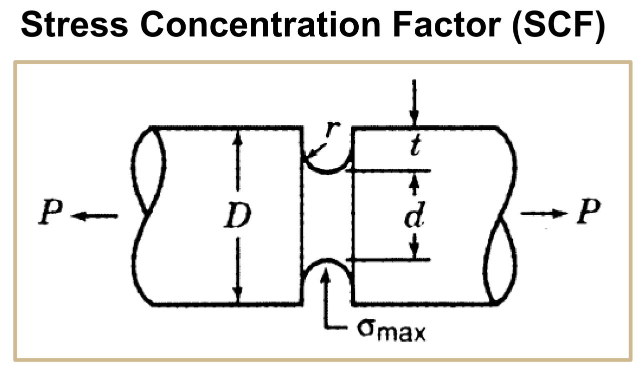



Figure 10. A defect at the root of a 3500 counterweight bolt. The defect is 3.69 micrometers deep.

- Shown above are the three areas the defects were found
- The order of increasing risk of premature fatigue failure based on defect location is the crest, the flank, and the root

## Model Development

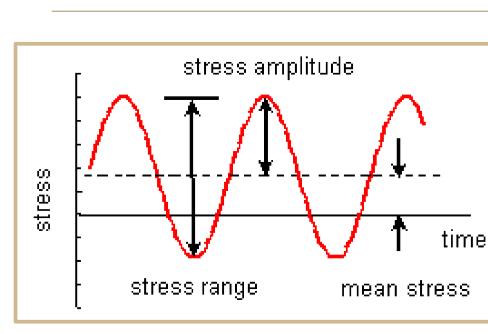
**Stress Concentration Factor (SCF)**




- Nominal stress is the applied force divided by the cross-sectional area
- The local stress is found by multiplying the nominal stress by the SCF.

Figure 11. The geometry used to derive SCF of the thread roots is shown, where P is the applied force, r is the root radius, t is the thread depth, D is the major diameter, and d is the minor diameter [4].

- SCF depends on the geometry of the thread
- SCF is derived from a graph of experimental data
- The defects are assumed to be at the root of the thread where the maximum local stress is located




- The bolt in an active engine vibrates and causes stress variations as shown in Figure 12.
- It is assumed the amplitude and mean stress are constant for the model

Figure 12. Example graph of stress versus time for a part undergoing fatigue. The mean stress is calculated through the addition of residual and applied stresses. The stress amplitude is the value of cyclic stress during testing. The stress range is the maximum stress minus the minimum stress [5].

- The model calculates the fatigue amplitude strength of the bolt.
- If the stress amplitude is greater than the calculated fatigue amplitude strength, the part will fatigue and fail prematurely.

**Murakami's Equation**

- Equation 1 is Murakami's equation for calculating fatigue strength where $\sigma_w$ is the fatigue strength amplitude (MPa), $H_v$ is the Vicker's hardness, R is the stress ratio, and area refers to the defect area (μm) [6].
- The approximate $\sqrt{area}$ for shallow, long cracks is $\sqrt{10c}$, where c is the depth of the crack (μm).
- Equation 2 gives the equation for the stress ratio
- Equation 3 gives the value of alpha in the Murakami equation.
- Equation 4 gives the calculation for $\sigma_w$ where FF is the fatigue factor which is a tolerance factor defined as $\sigma_w$ divided by $\sigma_{amplitude}$
- Equation 5 is a rearrangement of equation 1 solving for defect depth
- The approximation is accurate up to $10^7$ cycles of fatigue.

$$\sigma_w = \frac{1.43(120 + H_v)}{\sqrt{area}^{\frac{1}{6}}} * (\frac{1-R}{2})^{\alpha} \quad \text{Eqn. 1}$$

$$R = \frac{(\sigma_{applied} + \sigma_{installation} - \sigma_{amplitude}) * SCF + \sigma_{residual}}{(\sigma_{applied} + \sigma_{installation} + \sigma_{amplitude}) * SCF + \sigma_{residual}} \quad \text{Eqn. 2}$$

$$\alpha = 0.226 + (H_v * 10^{-4}) \quad \text{Eqn. 3}$$

$$\sigma_w = FF * SCF * \sigma_{amplitude} \quad \text{Eqn. 4}$$

$$c = (\frac{1.43(H_v + 120)}{\sigma_w} * (\frac{1-R}{2})^{\alpha})^6 * \frac{1}{\sqrt{10}} \quad \text{Eqn. 5}$$

## Model Results

**Model Objectives:**

- The model is designed to be a user-friendly way for Caterpillar to quickly evaluate the viability of defects in bolts via a graphical user interface.
- It offers a range of user inputs, as well as an option for FEA values to be used
- Although the model is conservative in its estimates, it is much more comprehensive and specific than the outdated standards

**User Inputs (grey boxes)**

- Vicker's hardness
- Range of fatigue factors
- Stress concentration factor
- Amplitude cycle regime

**Custom User Inputs**

- Mean stress
- Amplitude
- Installation stress
- Residual stress

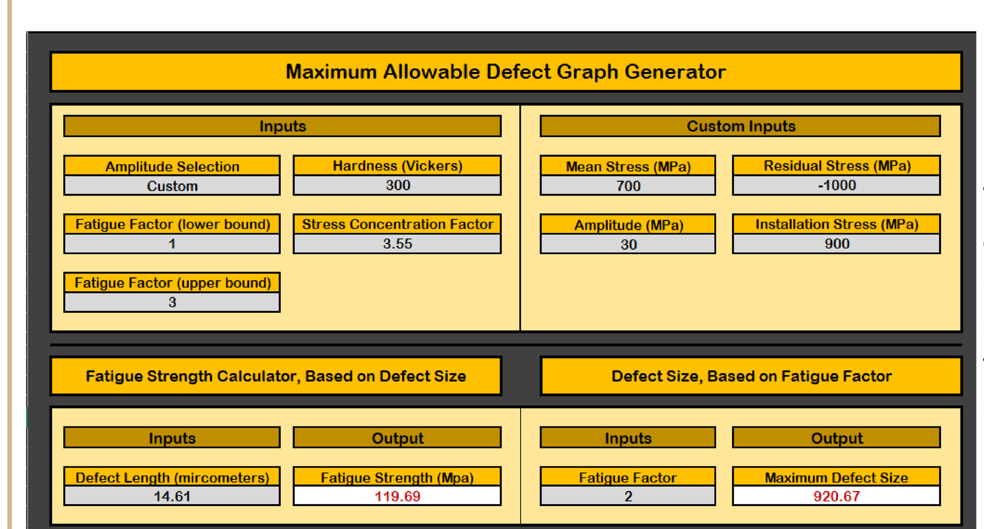



Figure 13. The graphical user interface for the model inputs.

**Graph Data Selection**

- Can enable or disable custom, low amplitude, medium amplitude, and high amplitude data.

**Outputs**

- Graph (Figure 14) that shows the maximum acceptable defect size based on fatigue factor
- White boxes with red text

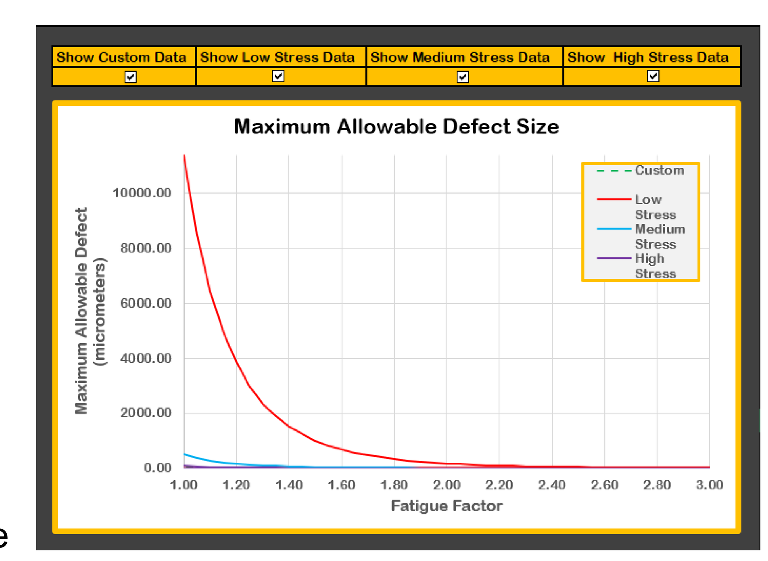



Figure 14. Maximum allowable defect size versus the fatigue factor. The inputs from Figure 13 are used to calculate the data for this graph.

- Increases to amplitude, SCF, or mean stress will lower the maximum allowed defect size.

## Conclusions & Recommendations

**Conclusions**

- A created mathematical model satisfies the lack of contemporary allowable defect standards.
- Created a graphical user interface for the mathematical model.
- Murakami's equation for fatigue strength is the basis of the model.
- The model produces a tradeoff curve (Figure 14) of the maximum allowable defect based on the desired fatigue factor.

**Recommendations**

- Future work can look towards implementation of defects located at the fillet of the bolt by adding the stress concentration factor of the fillet
- FEA analysis can be done to determine the change in stress concentration factor on the defect as it moves along the flank of the threads of the bolts in order to incorporate the position of the defect on the thread into the model.

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