

FEA-Based Fatigue Life Prediction of a Notched CGI Component

2011-01-2306

Published
09/13/2011

Xin Lei, Antoun Calash and John Cagney
Navistar Inc.

Copyright © 2011 SAE International

doi:10.4271/2011-01-2306

ABSTRACT

A cyclically pressurized hydraulic component made of compacted graphite iron (CGI) is examined in fatigue design. This CGI component has a notch, formed at the intersection of two drilling channels. This notch causes the stress to be locally elevated and may potentially serve as a fatigue initiation site. Traditional fatigue design approaches calculate the maximum stress/strain range acting at the notch and apply the Neuber correction when calculating fatigue life. It is, however, found that the fatigue life is dramatically underestimated by this method. This prompts the use of the critical distance method because the stresses are concentrated in a relatively small volume. When using the critical distance method, the fatigue life is correctly predicted. Finally, a fracture mechanics model of the crack check the reasonableness of the critical distance method results. The fracture mechanics model predicts that even if a crack were present, it would not propagate, which is consistent with the critical distance fatigue calculation.

combination of the type of material, the type of loading, and the size and the shape of notch geometry.

It has been well observed in many cases that notches do not reduce the fatigue strength of materials as much as predicted by the elastic stress concentration factor, K_t , which is the ratio of the greatest stress in the notch root to the nominal stress for the entire section^[2]. To address this discrepancy, the fatigue notch reduction factor K_f is commonly proposed. K_t and K_f are defined as below,

$$K_t = \frac{\sigma_{peak}}{\sigma_{nominal}} \quad (1)$$

$$K_f = \frac{S_e}{S_n} \quad (2)$$

INTRODUCTION

It was concluded in an extensive survey done by National Institute of Standard and Technology (NIST) that most mechanical failures are associated with fatigue^[1]. Among many factors that contribute to the occurrence of fatigue, notches are definitely on the top of the list. Notch is a common term for the geometric discontinuities in engineering components such as rivet holes in sheets, threads in bolts and keyways on shafts. While in service under loads, a notch can cause a significant increase in stress, so called stress concentration, from which fatigue cracks may originate. The effect of these geometric features on the fatigue life of engineering components is complex but can be related to a

Where σ_{peak} is the peak stress at the root of the notch, $\sigma_{nominal}$ the nominal stress over the net section, S_e the fatigue limit of the smooth specimen and S_n the fatigue limit of the notched specimen. Several popular explanations have been suggested for the $K_f < K_t$ effect^[3]:

1. Process Zone: The material is not sensitive to the peak stress, but rather to the average stress over some small but finite volume of material that must be involved for the fatigue damage development.
2. Crack Growth: A crack may initiate at a sharp notch but fail to grow further into a region of rapidly decreasing stress, which is the characteristic of a notch.

3. Plastic Effect: The plastic strain causes the actual stress amplitude at the notch to be less than calculated by K_t .

4. Weakest Link: There is a possibility that much less damage initiation sites exist in the small region of the sharp notch than in a smooth specimen.

It is generally believed that any one of the above fatigue damage mechanisms alone is insufficient to describe the $K_t > K_f$ phenomenon for most engineering metals. The weakest link argument requires a statistic point of view on metal fatigue, while the other three effects will be addressed in this fatigue design demonstration where a typical hydraulic component made of compacted graphite iron (CGI) is examined.

Compacted graphite iron has been increasingly selected to produce automotive parts of complex geometry due to its excellent castability and adequate mechanical properties, specifically, higher fatigue resistance when compared against conventional gray cast iron. In CGI, the graphite has a wormlike shape with rounded ends. The wormlike graphite shapes interconnect with each other to form a network through the ferritic or pearlitic metallic matrix depending on heat treatment. The CGI micro structure appears morphologically in between that of gray cast iron (graphite thin flake) and ductile nodular iron (spherical graphite). Gray iron has good damping and thermal conductivity. But its flaky structure makes it brittle, as reflected by its low tensile strength and fatigue strength. At the other end of the spectrum, ductile iron has a high strength in both tension and compression but relatively poor thermal conductivity and damping properties. Compared with these two extremes, CGI has thermal conductivity and damping properties roughly the same as gray iron and a tensile strength comparable to those of ductile iron. One possible reason for the improved tensile and fatigue strength is that the round-end graphite may serve as crack arresters instead of crack initiators, as is the case for the graphite flakes in gray iron.

Hydraulic components are heavily used in variety of power transfer applications, where pressurized hydraulic fluid is utilized to produce linear motion and force. When in operation, they are exposed to cyclic internal pressures in addition to some assembly loads. Their designs to prevent premature fatigue failure are very important since they are expected to operate for very long lives at high frequency loading. The interior structure of hydraulic components can be characterized as a network of internal channels through which the fluid is taken in at one hydraulic head (pressure), and output at a higher hydraulic head. Many these channels are made through drilling after casting. An internal notch is usually formed at the intersection where any two channels run into each other. This type of notch causes the stress to be locally elevated and potentially may serve as a fatigue initiation site.

According to the traditionally accepted fatigue design approach, the peak stress/strain range acting at the stress raise of the component is elastically calculated and corrected to take into account the local plastic deformation using the Neuber correction or other notch stress-strain conversion rules^[3]. This corrected value is then compared with the fatigue strength of the material to assure the structural durability. In this study, the magnitude of the peak stress calculated at a notch is considerably high compared to the ultimate tensile strength and the endurance limit of CGI, and, consequently, the failure of the CGI component is predicted at very low load cycles, which contradicts the existing field data and the pressurization test results. The field history of the engineering part also suggests the fatigue life of the notch is infinite since no fracture/failure has been reported on this location.

This study extensively investigates the fatigue life of an internal notch that is typical in hydraulic components. Both elastic and plastic stress analyses followed by a variety of strain-life fatigue calculation are performed to reveal a fatigue damage development where the stress concentration is considerably high. It is concluded that one of the critical distance methods, the point method, provides a reasonable result on the fatigue life for the notched CGI component. This predicted fatigue life is cross checked by linear elastic fracture mechanics (LEFM) based on the damage tolerance design methodology. The stress analyses and the corresponding fatigue analyses are performed using ANSYSTM and fe-safeTM, respectively.

STRUCTURAL ANALYSIS

MODEL DESCRIPTION AND BOUNDARY CONDITIONS

It is well accepted that an accurate stress/strain distribution is indispensable for a realistic prediction of fatigue life. The stress analysis using the finite element method is aimed at determining the peaks of stress at complex geometric features. Shown in [Figure 1](#) is the three-dimensional finite element model of the assembly, in which the CGI hydraulic component is mounted on an aluminum cover by four bolts. The aluminum cover is fully constrained on its cutting planes, which are considered to be far away from the CGI component. In addition to assembly loads such as bolt pretension and pressure fitting, the internal channels of the component can be exposed to a peak pressure up to 47MPa. Approximate dimensions of the part are 150mm×160mm×80mm, while the radius of the notch of interest is only 1.2mm ([Figure 2](#)). Therefore, the mesh is particularly fine at the material surrounding the internal notch to achieve a good accuracy in stress calculation. Elastic and plastic material models are used for the CGI component, respectively.

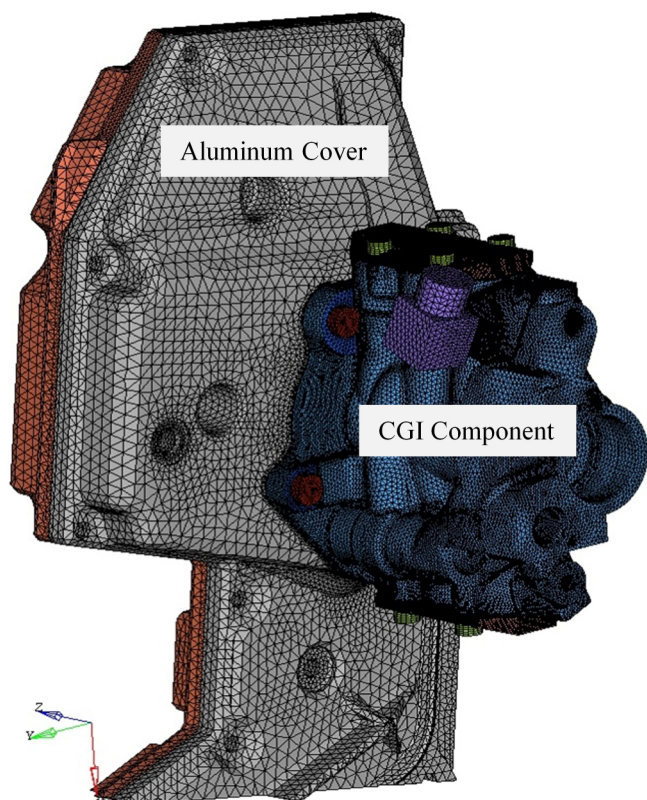


Figure 1. 3D Finite Element Model of the Assembly

SUBMODEL USED FOR ACCURATE STRESS PREDICTION AND FRACTURE MECHANICS

The sub-modeling technique is employed to accurately calculate the stresses in the investigated notch (Figure 3). The displacement boundary conditions extrapolated from the elastic solution of the full model are imposed on the cutting planes of the sub-model, while the pressure is applied to the surfaces of the drilling holes. The size of the sub-model is 26mm×30mm×20mm and the minimum size of elements at the notch is about 0.04mm. The sub-model is used to confirm the stress result at the notch in terms of the mesh convergence.

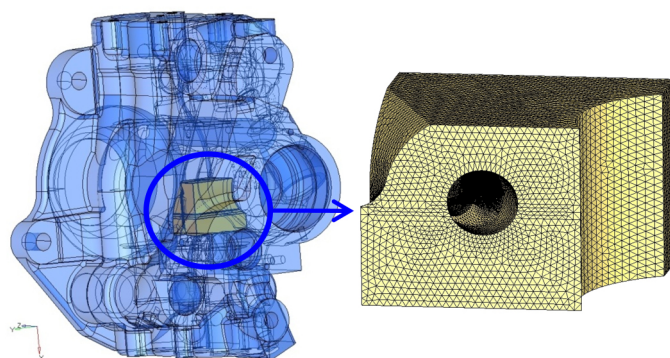


Figure 3. Mesh of the Sub-model cutting out of the Full Model

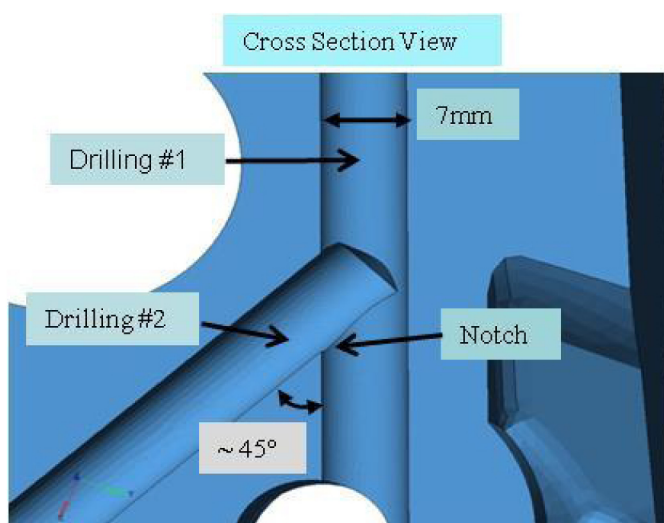


Figure 2. Internal Notch in the Close-up View of the Sectioned Model

For the fracture mechanics model, cracks of different sizes, 0.5mm, 1.0mm and 1.5mm in depth, are modeled at the notch root in the sub-model, respectively. It is implied that compared to that of the full model the crack size is so small that the effect of the crack on the stiffness and the displacement field of the full model is negligible. The crack faces are perpendicular to the 1st principal stress at the notch to simulate the crack faces moving apart under tension stresses, so called Mode I cracks. The crack of 1.5mm is shown in Figure 4. The elements around the crack front are quadratic, with the mid-side nodes placed at the quarter points. Such elements are called singular elements (Figure 5). The elastic material behavior is assumed for all the crack models. The stress intensity factors along the crack front are calculated to determine whether a certain size of crack, somehow present at the tip of the notch, will grow stably in the particular situation of geometry and repeated force. Here, the linear elastic fracture mechanics (LEFM) is leveraged to confirm the check high cycle fatigue (HCF) predictions.

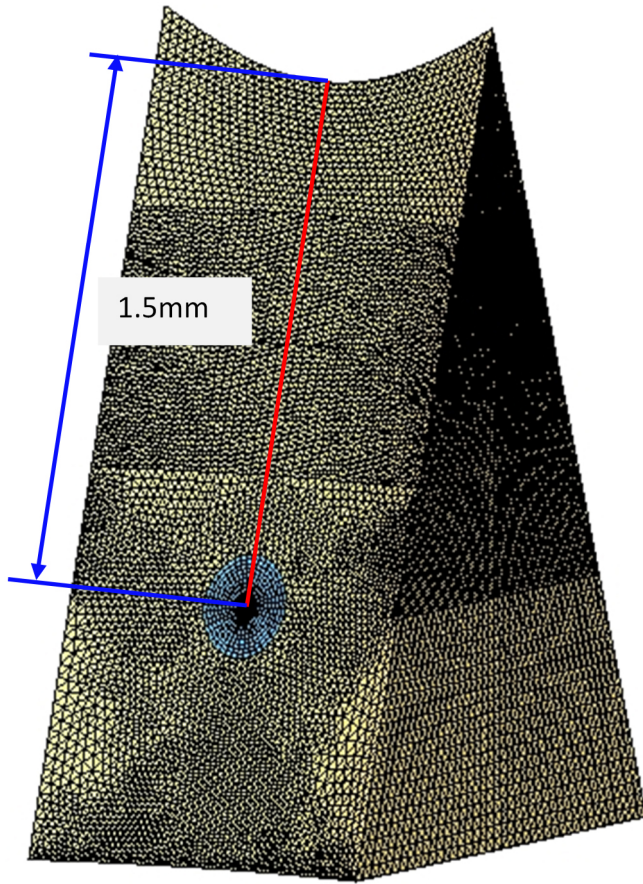


Figure 4. Crack of 1.5mm Placed at the Notch

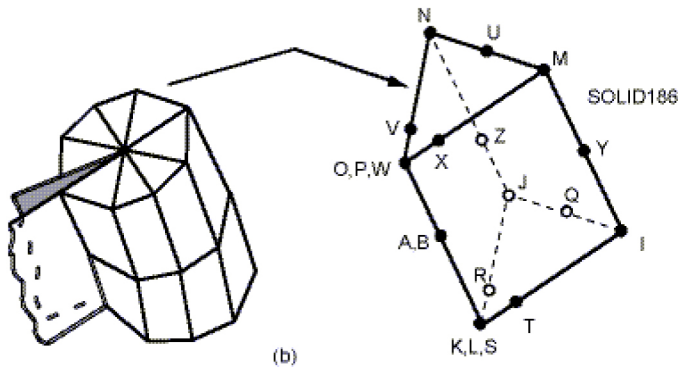


Figure 5. Singular Elements for a crack in ANSYS

LOADING

The loading sequence for the elastic model consists of the assembly load and the pressurization of 47MPa while that for the plastic model has two additional load steps: pressure unloading and pressure reloading. The pressure pulsation induces the alternating stresses in the component. Since the inner notch under investigation is far enough away from the areas where the assembly loads are applied, the stress ratio R is about 0 for the notch, which is seen in the results section.

FATIGUE ANALYSIS

FATIGUE DAMAGE CALCULATION ALGORITHMS

A wide range of strain-life algorithms^[4] are tested using the stress results from the full model. Among them, the principal strain fatigue criterion with the Morrow mean stress correction is recommended for cast iron materials, and is written as

$$\frac{\Delta \varepsilon_1}{2} = \frac{\sigma'_f - \sigma_m}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (3)$$

where $\Delta \varepsilon_1$ is the range of the 1st principal strain for the cycle, σ_m the mean stress, E Young's modulus, $2N_f$ the endurance in reversals, σ'_f the fatigue strength coefficient, ε'_f the fatigue ductility coefficient, b the fatigue strength exponent, and c the fatigue ductility exponent.

The Smith, Watson and Topper (SWT) parameter, $\frac{\Delta \varepsilon_1}{2} \sigma_{\max}$, can also be introduced to the principal strain criterion to obtain

$$\frac{\Delta \varepsilon_1}{2} \sigma_{\max} = \frac{(\sigma'_f)^2}{E} (2N_f)^{2b} + \sigma'_f \varepsilon'_f (2N_f)^{b+c} \quad (4)$$

where $\sigma_{\max}$ is the maximum stress for the cycle.

Another popular algorithm for ductile metals is the Brown-Miller criterion, which proposes the maximum fatigue damage occurs on the plane that possesses the maximum shear strain range, $\Delta \gamma_{\max}$. The damage is associated with both this shear strain and the strain normal to the plane, $\Delta \varepsilon_N$, as below

$$\frac{\Delta \gamma_{\max}}{2} + \frac{\Delta \varepsilon_N}{2} = 1.65 \frac{\sigma'_f}{E} (2N_f)^b + 1.75 \varepsilon'_f (2N_f)^c \quad (5)$$

It is generally understood that stress-strain curves for gray cast iron and CGI exhibit curvature at relatively low stresses in comparison with the 0.2% offset yield strength and they have different hardening trends in tension and in compression. A sophisticated treatment of cast iron fatigue data proposed by Downing^[5] modifies the standard

Ramberg-Osgood equation, $\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'} \right)^{1/n'}$, as follows