Manufacturing Remaining Stresses in Truck Frame Rail's Fatigue Life Prediction

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Abstract: Usually in Computer Aided Engineering (CAE) analyses, Computer Aided Design (CAD) data is meshed and analyzed with regard to displacements and stresses. So far, it is not common to account for residual stresses due to the manufacturing process in these analyses.

This work proposes a methodology based on simplified abaqus Standard/Explicit models to evaluate residual stresses due to stamping and bending manufacturing process in truck rails and suggests a methodology to use this residual stress data in truck frame CAE durability analysis making it possible to compare how different a predicted fatigue life can be when residual stresses are considered.

1. Introduction

There are some truck frame rails, especially in extra-heavy trucks, which do not have straight rails as shown in Figure 1. In such cases the rail manufacturing process leaves local residual stresses in the offset.

Frame durability CAE models in most cases have the road load data as the only load neglecting stress concentrators or local residual stresses.

In order to simplify the problem, this work will study only what happens on the rail flange leaving for further studies to solve the same problem for the entire rail. Although a flange behavior is quite different from a plate with the same dimensions performance; using only a plate with the same dimensions makes it easier to evaluate the sensitivity of residual stresses in fatigue life.

A 0.3x0.07x0.007 m plate will be taken as example of rail flange. This plate will be bent until the offset geometry and then cyclically loaded. As cyclic load, it will be used the maximum force the flange could take during a million of cycles if there were no residual stresses.
1.1 Residual stress calculation

Stamping simulation in Abaqus is a problem that can be divided in two very specific parts: \textit{loading} and \textit{unloading}.

The loading problem involves, besides material nonlinearities, great deal of contact nonlinearities; because of that, it is much better taken care of using Abaqus/explicit.

In real life stamping process the timing is usually much longer than the natural period of the involved parts what makes dynamic effects importance to vanish. That is why this is called a quasi-static problem.

In the other hand, the unloading step involves no contact whatsoever. Because of that this step is much better solved using Abaqus/Standard.

1.2 Fatigue life prediction

1.2.1 Stress life approach

Equation 1 (Bannantine, 1990) can represent Stress-Life relationship for steel where $S_u$ is the material ultimate stress; $S$ is the fully reversed stress amplitude and $N$ is the life under this cyclic stress in number of cycles:

\[ S = 1.62S_u.N^{-0.085} \]  

(1)

1.2.2 Strain life approach

When the stress level is over the material linear limit, a much better fatigue behavior representation is given by the strain life approach, Equation 2. In order to account for mean stress
effects, Smith, Topper and Watson – STW - (Smith, Topper and Watson, 1970), proposed Equation 3.

\[
\frac{\Delta \varepsilon}{2} = \left( \frac{\sigma}{E} \right) (2N_f)^b + \varepsilon_f (2N_f)^c \tag{2}
\]

\[
\sigma_{max} \frac{\Delta \varepsilon}{2} = \left( \frac{\sigma}{E} \right) (2N_f)^{2b} + \sigma_f \varepsilon_f (2N_f)^{b+c} \tag{3}
\]

with:

\[
\sigma_{max} = \frac{\Delta \sigma}{2} + \sigma_0 \tag{4}
\]

and:

- \(N_f\) = Number of reverses (1 cycle = 2 reverses)
- \(E\) = Young modulus
- \(\sigma_f\) = Fatigue strength coefficient
- \(\varepsilon_f\) = Fatigue ductility coefficient
- \(c\) = Fatigue ductility exponent
- \(b\) = Fatigue strength exponent
- \(\Delta \sigma / 2\) = Stress amplitude
- \(\Delta \varepsilon / 2\) = Strain amplitude

1.3 Material

As this work involves several different sorts of analyses and each analysis requires its own material properties set, this section shows the material properties hereby used.

1.3.1 True stress-plastic strain properties

The stamping analysis asks for the material true stress-plastic strain deformation curve that can be seen in Figure 2.
1.3.2 Fatigue properties

The material properties required for the fatigue analysis used in this work are presented in Table 1.

Table 1. Material fatigue properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ul}$ [Pa]</td>
<td>397E6</td>
</tr>
<tr>
<td>$\sigma_y$ [Pa]</td>
<td>236E6</td>
</tr>
<tr>
<td>E [Pa]</td>
<td>206.8E9</td>
</tr>
<tr>
<td>$\sigma'_f$ [Pa]</td>
<td>492E6</td>
</tr>
<tr>
<td>b</td>
<td>-0.094</td>
</tr>
<tr>
<td>$\varepsilon'_f$</td>
<td>0.178</td>
</tr>
<tr>
<td>c</td>
<td>-0.576</td>
</tr>
<tr>
<td>K' [Pa]</td>
<td>705.8E6</td>
</tr>
<tr>
<td>$n'$</td>
<td>0.164</td>
</tr>
</tbody>
</table>

2. Procedure

2.1 Residual stress evaluation

A model with the plate being meshed using plane stress elements and the punch and die being represented as rigid surfaces was built and the model configuration can be seen in figure 3.
The role of boundary condition and loading were played by two rigid surfaces (*punch* - Rigid Surface(1) and *die* - Rigid Surface(2)) shown in Figure 3 plus clamped nodes at the plate very right edge.

The load history was divided in two steps as shown in sections 2.1.1 and 2.1.2.

**2.1.1 Loading step**

Due to high contact nonlinear problems, dynamic explicit codes are much better recommended for numerical stamping simulation with some material properties and timing parameters adjusted for simulating as a quasi-static phenomena.

During the loading step, the punch was moved down 75mm and, as results, the plate principals stress distribution as well as the deformed configuration can be seen in Figure 4.
2.1.2 Unloading step

During the unloading step, contact nonlinearities are no longer a problem. As a matter of facts, all it has to be done is to release the plate and to calculate its new equilibrium state. So, Abaqus/Standard suits better in this case. However, depending upon how severe is the bent, when the plate reaches its final equilibrium some local areas can be beyond the material yield point making a nonlinear analysis required.

To perform an appropriate unloading step then, it is important to keep in mind that the same energy distribution found in the plate at the end of the loading step is supposed to be present as initial condition of the unload step.

The apposite initial condition can be reached using the *IMPORT option which makes possible to import elements along with their stress and strain state at the end of the loading step. A plot with the deformed shape together with residual principal stress distribution is shown in Figure 5.

It is meaningful to emphasize that, in this case, the residual stress distributions has a quite peculiar local area, called in Figure 5 as “hot spot”, which is 24% beyond the material yield stress. To make things even worse when it comes to fatigue, this area is under tension.

Figure 4. Loaded plate stress configuration.

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2.2 Fatigue life prediction

2.2.1 Fatigue Stress-Life prediction (S-n).

The maximum fully reversed stress the flange can take for a million of cycles can be estimated from Equation 1 as being $\sigma = 0.5 S_u$. In this case $\sigma = 198.5$ MPa.

Considering that the "hot spot" (Figure 5) is 0.25 m away from the flange's left side edge, such a stress level can be obtained applying a 4500N force at the left edge having clamped the right side.

2.2.2 Taking the residual stress as mean stress.

To consider residual stress using the Stress-Life procedure becomes possible taking the residual stress as mean stress and using Equation 5 as proposed by Goodman (Bannantine, 1990).

Figure 5. Residual stress configuration.
\[
\frac{\sigma_u}{S_e} + \frac{\sigma_m}{S_u} = 1
\]  

The stress observed for an amplitude load of 4500N is 197.3 MPa. Moreover, in Figure 5 it can be seen that there is a 290MPa tensile remaining stress at the hot spot area. Thus, if \( \sigma_u = 197.3 \) MPa and \( \sigma_m = 290 \) MPa, applying Goodman's equation it results \( S_e = 732 \) MPa.

This stress level is much beyond even the material ultimate stress and the S-n approach is not recommended in situations with excessive plastic deformation.

This analysis considers however, that a 4500N cyclic load drives the "hot spot" to undergo cyclic stress with \( \sigma_u = 197.3 \) MPa and \( \sigma_m = 290 \) MPa; but that can be quite away from reality.

In the very first reverse, as the residual stress in the "hot spot" area is already beyond the material yield point, a local yield happens and doing so, the residual stress level is brought back to a lower level. Thus, the mean stress acting is lower as a matter of facts.

This new residual stress level is the one that works as mean stress while the load value goes up and down. As there is a material nonlinear behavior, the first cycle needs to be analyzed as a nonlinear problem. It can be seen respectively in Figure 6 and Figure 7 that \( \sigma_{\text{max}} = 451 \) MPa and \( \sigma_{\text{min}} = 85 \) MPa The mean stress and the alternate stress become respectively: \( \sigma_m = 268 \) MPa and \( \sigma_a = 183 \) MPa. \( S_e \) is then 563 MPa and is still beyond the material ultimate stress.

![Figure 6. Plate after the first reversal.](image)
2.2.3 Fatigue Strain-Life prediction ($\varepsilon$-n).

To study the same case as a strain life problem, it is necessary Equation 2 and the strain range at “hot-spot”. The usual way to obtain the strain range is using CAE linear models. In this case, applying 4500N it can be observed $\varepsilon_{\text{max}} = 9.54 \times 10^{-4}$ and $\varepsilon_{\text{min}} = -9.54 \times 10^{-4}$ locally at the “hot-spot” area.

However, if the same cyclic load is applied using the residual stress/strain distribution as initial condition, a different strain range is obtained: it is observed $\varepsilon_{\text{max}} = 2.13 \times 10^{-3}$ and $\varepsilon_{\text{min}} = 0.39 \times 10^{-3}$.

Using the residual stress/strain distribution as initial condition for the cyclic load seems to be the first step to consider the residual stress in the fatigue analysis. However, as long as Equation 2 uses only the strain amplitude and the mean stress is important in fatigue life, better results can be obtained with equation 3. In order to use Equation 3 the only data so far missed is $\sigma_{\text{max}}$ that is taken as result from the nonlinear model when full loaded with 4500N (as shown in Figure 6): $\sigma_{\text{max}} = 451$ MPa.

Even though the nonlinear model somehow considers residual strains already, the residual stress level cannot be taken into consideration using the formulation expressed in Equation 2. In order to consider the residual stress value in the fatigue life prediction it becomes necessary to use Equation 3.

Using the material properties in Table 1, the strain amplitude in Table 2, and Equation 2 and 3, it is possible to have the fatigue life results as shown in Table 2.
Table 2. Fatigue life results.

<table>
<thead>
<tr>
<th>FEM Results</th>
<th>Minimum Strain</th>
<th>Maximum Strain</th>
<th>life (N)</th>
<th>STW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>0.954E-3</td>
<td>-0.954E-3</td>
<td>156681</td>
<td>-</td>
</tr>
<tr>
<td>Nonlinear</td>
<td>0.39E-3</td>
<td>2.13E-3</td>
<td>283975</td>
<td>9865</td>
</tr>
</tbody>
</table>

3. Conclusions

It can be seen that the load, which according to approximated S-n approach, would take the plate to endure for a million of cycles, when analyzed using strain-life approach for the same load endures less than 160000 cycles.

Due to the fact of in the nonlinear model the strain range is lower, the life is increased to more than 260000 cycles.

Although the range in the nonlinear model is lower, it happens in a much higher stress level. When it is taken into consideration, the predicted fatigue life drastically falls to less than ten thousand cycles.

It is interesting to mention that the residual stress in this case is above the material yield point and the first step of load takes place in such a way that there is tension in the hot spot while the residual stress is also tension making the stress level at the hot spot to rise even higher. At this moment it is observed some plastic deformation but after that, while the load amplitude is 4500 N, the behavior is pretty much elastic.

4. Future works

Although the residual stress is quite high in this study, typical cases are not so severe. So, the next steps in this research are to study the effects of lower residual stress level as well as to perform the complete rail stamping analysis to obtain better residual stress evaluation.

5. References