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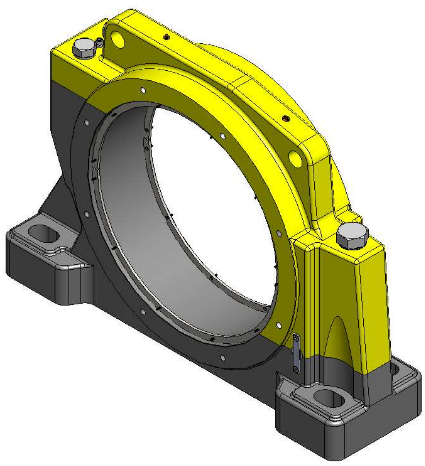
Probabilistic Design of Mechanical Components Subjected to Fatigue

1. Introduction

Many factors go into estimating the life of a product. What it is made from, how it is made and used are some of the aspects that affect component life. Safety factors to make things durable, strong, or safe, can seem like a common sense thing to do to account for these things and ensure longevity but can that be said to be reliable? And at what cost is that factor being assigned?

Powerful computational tools allow engineers to accurately determine a components' stress profile and deflections. FEA allows an engineer to take a CAD modelled part, assign it material properties, loads, restraints, and safety factors, and finally obtain detailed results revealing its strength and predicted life. Concerns arise when at each of these stages, uncertainties and sources of errors are introduced. Regardless of the safety factor used, confidence in the final results diminish, possibly resulting in a component being under-designed leading to early failure or being costly over-designed.



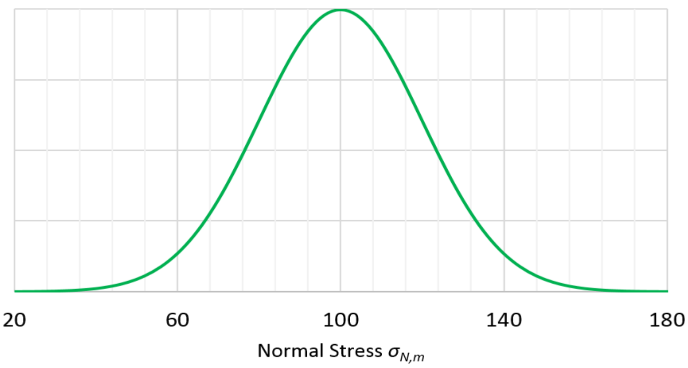
Probabilistic design allows for each set of variables along the way in a design process to be treated with some controlled uncertainty. By way of example, consider the bearing housing shown in the previous figure. The housing is to be manufactured from cast steel and it is desired that for 10 years in service, that each component have a 90% probability of survival.

2. Collect Mean Inputs

To begin an analysis it is necessary to determine or identify with as much accuracy and certainty as possible— the inputs. End-users or product owners can stipulate loading requirements. Reliable material properties can be extracted either from reputable databases or through specimen testing. Other factors such as stress concentration values relating to surface finishes are well published. Component stresses and strains can then be predicted through the use of FEA models.

3. Set Uncertainties

Even with great accuracy in obtaining the inputs, uncertainty with each variable exists. While many types or categories of inputs may be present, the attention here is focused on three: loads, material, and manufacture. Uncertainty of each is controlled by assigning variation using a technique such as a normal distribution as shown in the following figure. The strength of the distributions is set using

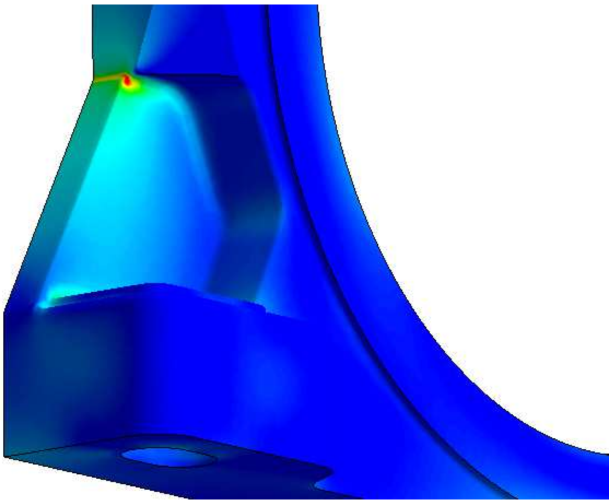


coefficients of variations (COV) which represent the standard deviation when mean values are normalised to unity.

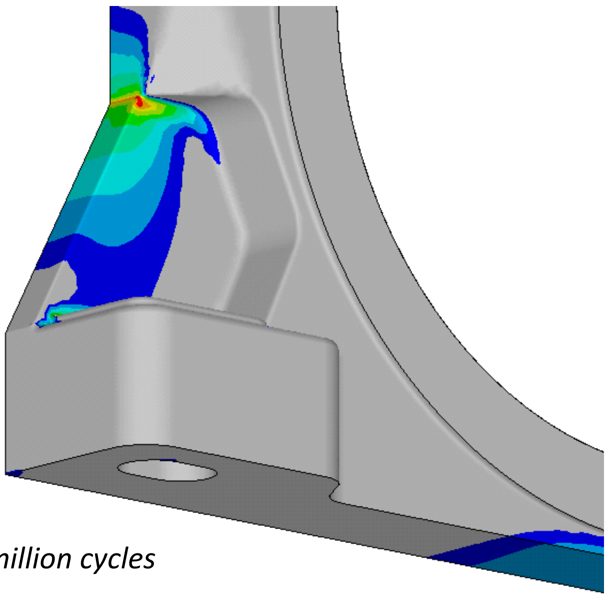
Loads can vary little if performed in a lab or a lot if in the field with little operation control [1]. How it is manufactured and the quality systems that oversee it affect the variation of material properties and surface finish. These levels need to be understood by the design engineer and applied with care. Here, values of COV = 0.2, 0.1, and 0.05 are applied to load, material, and surface finish respectively.

4. Obtain Mean Results

Average or mean life is determined with no consideration for variation of the inputs. Nominated values of load and material properties are attributed to the FEA model where converged values of stress and strain are obtained through mesh convergence techniques. These results combined with the fatigue parameters of the material, and any added stress concentrations, then produce the mean life of the component. For the bearing housing, this process is illustratively provided below using an appropriate strain-life criterion for the material. In this case the Brown-Miller criterion [2-3] for cast steels was used together with an N10 surface roughness grade.



$$\frac{\Delta\gamma}{2} + S\Delta\varepsilon_N = A\frac{\sigma'_f - \sigma_{N,m}}{E}\left(2N_f\right)^b + B\varepsilon'_f\left(2N_f\right)^c$$

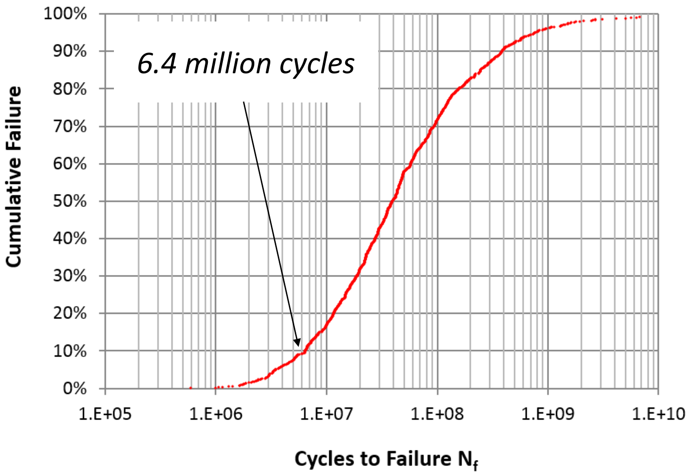


39 million cycles

5. Establish Confidence

Mean results give rise to a 50% cumulative failure of a component or they can represent a 50% probability of component survival. Another way to interpret this value is to treat it as a level of confidence. Performing a simulation with strictly mean values of the inputs yields a confidence level of 50%. Changing the values of the inputs slightly may either produce a component life of lesser or greater value. Reporting a component life with a set level of confidence can then be made by repeating a simulation a significant number of times.

In the bearing housing example, 1000 simulations were performed. Each time the simulation was performed, values of load, material properties, and surface finish stress concentration were picked from the distribution of values about the mean as described earlier. Each simulation resulted in a different life result. Once completed the results were sorted in increasing order and plotted as shown in the following figure. Establishing 90% confidence was made by noting the component life of the 100th simulation. At this point, 10% of the components have failed and 90% of components were expected to survive. Recalling that the housing had a mean design life of 39 million cycles, with 90% confidence that value was decreased to 6.4 million cycles.



6. References

[1] Wirsching, P. H. "Probabilistic fatigue analysis." *Probabilistic structural mechanics handbook*. Springer, Boston, MA, 1995. 146-165.

[2] Draper, John. *Modern metal fatigue analysis*. EMAS publications, 2008.

[3] Hardin, Richard A., and Christoph Beckermann. "Prediction of the fatigue life of cast steel containing shrinkage porosity." *Metallurgical and Materials Transactions A* 40.3 (2009): 581.