BOLT THREAD STRESS OPTIMIZATION

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Summary Designs of threaded fasteners are controlled by different standards, and the number of different thread definitions is large. The most commonly used thread is probably the metric ISO thread, and this design is therefore used in this paper. Thread root design controls the stress concentration factor of threads and therefore indirectly the bolt fatigue life. The root shape is circular, and from shape optimization for minimum stress concentration it is well known that the circular shape is seldom optimal.

An axisymmetric Finite Element (FE) formulation is used to analyze the bolted connection, and a study is performed to establish the need for contact modeling with regard to finding the correct stress concentration factor. Optimization is performed with a simple parameterization with two design variables. Stress reduction of up to 9% is found in the optimization process, and some similarities are found in the optimized designs leading to the proposal of a new standard. The reductions in the stress are achieved by rather simple changes made to the cutting tool.

SHAPE PARAMETERIZATION

The number of different thread designs makes a generic optimization impossible, instead the present papers focus on metric ISO thread coarse series as found in DIN13. For numerical shape optimization a detailed shape analysis is needed. In this work an analytical shape description is preferred. The feature of an analytical shape description is that it makes verification and comparison possible for other designers. Another important feature is that the position of new boundary nodes in a FE mesh refinement is easily found and stress converges checks is then possible.

From a machine element point of view the optimization results should focus on simplicity and generality rather than being very specific and involved. Optimization results should however still be near the optimal design. Thread top and side is kept unchanged, this implies that the new design will function with design defined by the standard. Thread is cut or rolled into the bolt, and the new design shall be made in the same manner, this restricts the design domain. The parameterization strategy chosen is to use the super ellipse because of the simple parameterization and due to previous results obtained with this shape in relation to stress concentrations [1]. The super elliptic shape is shown in gray in Figure 1. Symmetry is

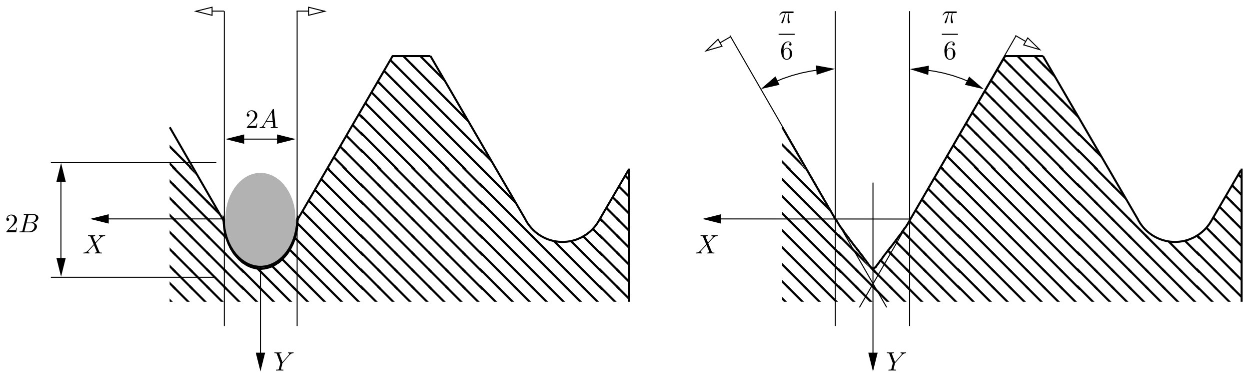

Figure 1. Design parameterization. Shown are half axis A and B, the super elliptical power used here is $\eta = 2$.

assumed relative to the defined Y-axis. In parametric form the super elliptic shape is given as

$$X = A\cos(\theta)^{(2/\eta)}, \qquad \theta \in [0 : \frac{\pi}{2}] \tag{1}$$

$$Y = B\sin(\theta)^{(2/\eta)}, \qquad \theta \in [0 : \frac{\pi}{2}] \tag{2}$$

where A and B are the two half axes and η is the super elliptic power. Due to symmetry the parameterization is only presented for positive X and Y values. For the metric ISO thread the following constraints apply to the half axis

$$A = \frac{P}{4} \qquad B \in [0 : \frac{P}{8\tan(\pi/6)}] \tag{3}$$

where P is the thread pitch. The super elliptic shape do not fit into the design space although the constraints on the half axis are fulfilled. To push back the super ellipse into the design domain a distortion is applied. This is done by rotating the two lines as indicated by the hollow arrows in Figure 1. Rotating the two lines by an angle of $\pi/6$ the parameterization attains the wanted property. The full parameterization is given by

$$X = A\cos(\theta)^{(2/\eta)}(1 - \frac{B}{A}\sin(\theta)^{(2/\eta)}\tan(\frac{\pi}{6})), \qquad \theta \in [0 : \frac{\pi}{2}] \tag{4}$$

$$Y = B\sin(\theta)^{(2/\eta)}, \qquad \theta \in [0 : \frac{\pi}{2}] \tag{5}$$

THREAD OPTIMIZATION

The optimization is first applied to the metric ISO M12 bolt. The optimization is performed as a parameter study since the root parameterization only has two design variables. Stress concentration factor for the original ISO thread is $K_{tg} = 5.49$ For the M12 bolt we find the design shown in Figure 2, in the figure the original ISO design is also shown for comparison.

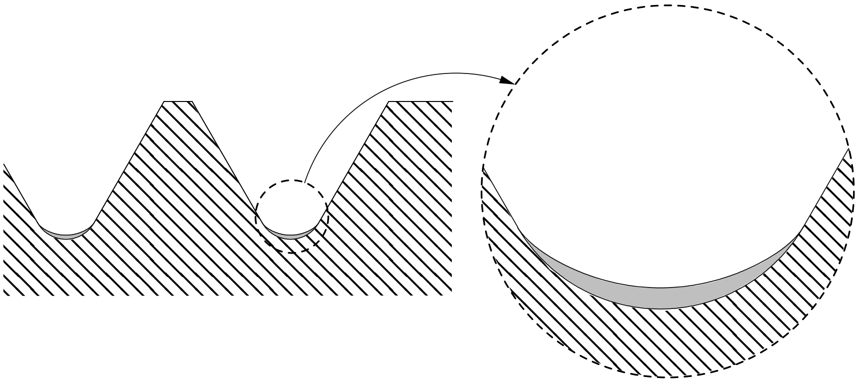

Figure 2. Original design and optimized root design, the optimized design is illustrated by the added gray area.

The design parameters are: $B = 0.0062H$ and $\eta = 2.06$, here $H = P/(2\tan(\pi/6))$ is the full thread height if no rounding was used.
The von Mises stress along the optimized root 2 is seen in Figure 3 together with the stress for the ISO thread for comparison, both obtained using contact modeling. It is clear that the original design is a good and robust design with limited possibilities for improvement. The stress concentration factor for the optimized design is $K_{tg} = 5.00$, therefore the reduction in stress is 9%. The optimized curve in Figure 3 is not totally flat indicating that a possible further reduction

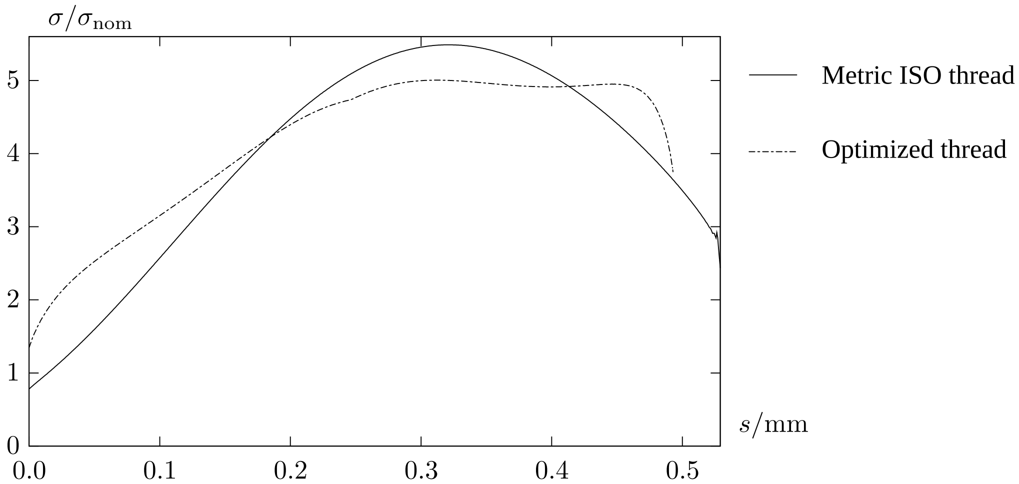

Figure 3. Normalized von Mises stress along the root 2, for the M12 design. The stress is shown for the metric ISO thread and the optimized design. The maximum stress is reduced by 8.9%. Note that the optimized designs arc length is smaller than the original one.

in the stress level is possible. To find this improvement you need a more involved root parameterization, e.g. with the use of B-splines. From the shape of the stress distribution it is believed that the possible improvement in the maximum stress relative to the increase in design complexity is not significant. In machine elements the results should be practically realizable and robust.

References

[1] Pedersen N.L.: Optimization of straight-sided spline design. *Archive of Applied Mechanics* **81**(10):1393-1407, 2011.