Bolt Preload

January 20, 2025

1 Intro

Preload is the amount of force in a nut or bolt resulting from its initial tightening at assembly. In aerospace applications, preload can be very high, nearing the bolt's tensile yield strength. Additionally in aerospace applications, it is typical to use a very large nut or bolt[1] to clamp the stack that the aircraft's thrust acts through. Because the bolt is keeping the stack clamped against thrust, it is both highly stressed, and highly critical to operation. Furthermore, given the large size of these bolts/nuts, the preload is typically very high—so high that it is far too conservative to assume the entirety of the thrust *and* preload acts through the bolt. It is therefore important to understand how preload affects force transmission into the bolt because, as it will be shown, the bolt stack's stiffness has a profound influence on the bolt's load.

2 A simple spring model for bolt preload

A typical bolt stack cross section is shown in Figure 1. There are several members in the stack which the bolt squeezes by means of a nut on the opposite end. Such a system is not the best place to start however for developing an understanding of how preload affects the bolt. Simpler instead is to begin with the cross-section shown in Figure 2. This can be modeled simply as two springs in parallel, one spring being the bolt, the other spring being everything the bolt is clamping, termed the bolt stack. To understand the forces generated in the bolt we begin with modeling the system at the point just before any preload is applied to the bolt. At this instant, the bolt has been screwed down just to the point that its head is in contact with the stack but no further. This means that the stack and the bolt are at their undeformed shapes and no force is transmitting between them yet. The two-spring model of this instant is shown in Figure 3.a.

As the bolt is turned past this point, the bolt is stretched and the stack compressed. It is not immediately obvious how to model this behaviour in the two-spring system. But consider the following thought experiment: Imagine we

[1]E.g. 5 in. diameter or even larger.

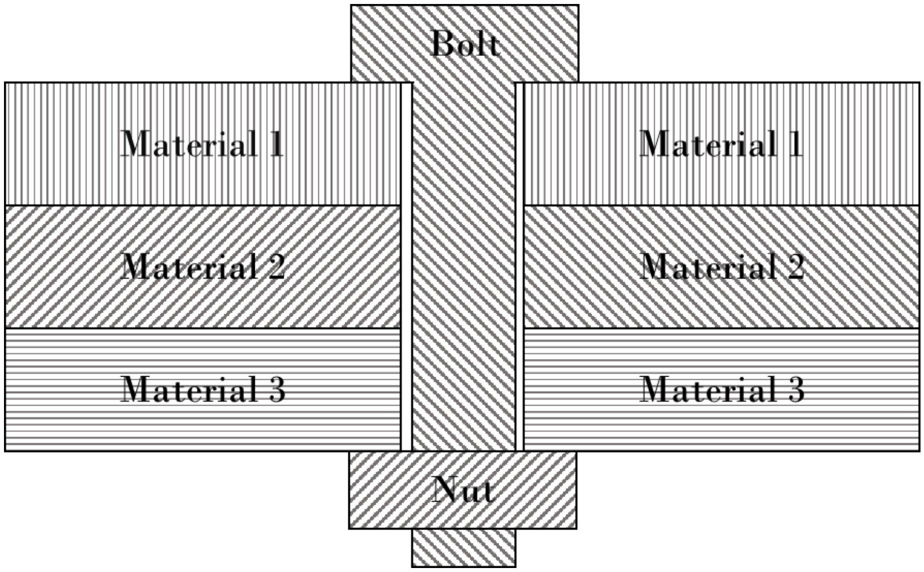

Figure 1: Example cross section of a bolt stack.

instead begin with bolt outside the stack and stretch it, then somehow teleport the bolt to inside the stack where it belongs. The bolt retracts somewhat as it compresses the stack and the system reaches its equilibrium state. This end state is equivalent to having screwed the bolt down as in reality. But it is easier (I think) to see how this fictitious method of tightening the bolt corresponds to the two-spring system. This method is equivalent to stretching spring B in Figure 3.a to the length of spring A, connecting them with a massless rod and allowing them to reach their equilibirum length as in Figure 3.b. Denoting the bolt's stiffness as k_b and the stack's as k_s we can see that

$$(F_b)_1 + (F_s)_1 = 0 \tag{1}$$

$$(F_b)_1 = k_b(l_1 - l_b) \tag{2}$$

$$(F_s)_1 = k_s(l_1 - l_s) \tag{3}$$

where $(F_b)_1$ and $(F_s)_1$ are the forces in the bolt and stack respectively, l_b and l_s are the undeformed lengths of the bolt and stack, and l_1 is the equilibrium length of the system at preload. Note that $l_b < l_1 < l_s$. These equations are not particularly helpful in and of themselves for it is difficult to determine a priori what the equilibrium length of the stack is in practice. What we do know in practice is the torque the bolt was tightened to. We can determine the force in the bolt this would correspond to, the preload F_{pre}, using the equation

$$F_{pre} = C\frac{T}{D} \tag{4}$$

where T is the torque, D is the bolt's nominal diameter, and C is typically

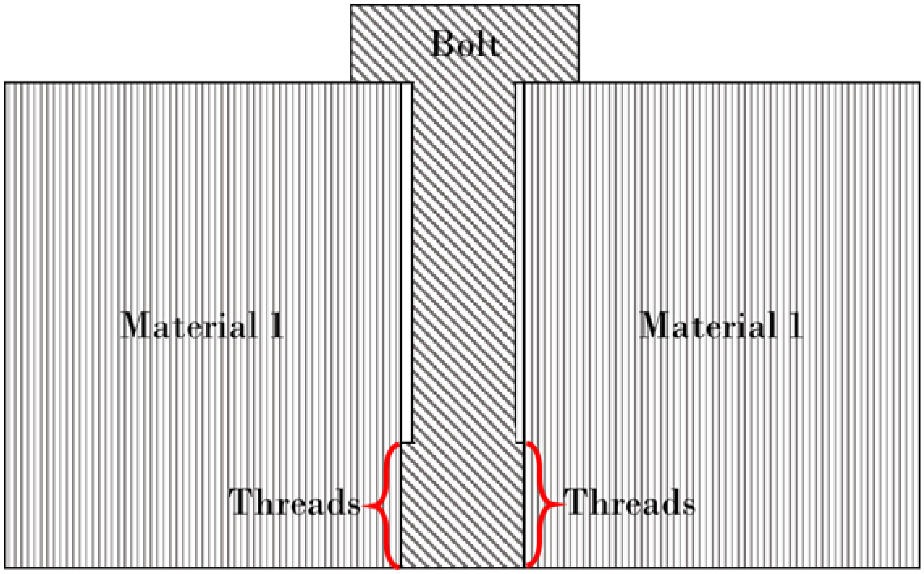

Figure 2: Example cross section of a bolt stack.

between 5 and 10. The exact number of C depends on the condition and material of the threads. Unlubricated steel-on-steel is closer to 5 whereas lubricated silver-on-steel is closer to 10. Therefore, from Equation (1) we can say that

$$(F_b)_1 = -(F_s)_1 = C\frac{T}{D}. \tag{5}$$

The next step is to apply the load as in Figure 3.c. Now the force equations become

$$(F_b)_2 + (F_s)_2 - P = 0 \tag{6}$$
$$(F_b)_2 = k_b(l_2 - l_b) \tag{7}$$
$$(F_s)_2 = k_s(l_2 - l_s) \tag{8}$$

where $(F_b)_2$ and $(F_s)_2$ are the forces in the bolt and stack respectively after the load is applied and l_2 is the new equilibrium length of the system after the load is applied. Because the springs are in parallel, we expect some of the load to be taken up by the stack and some by the bolt. We can determine exactly how much goes into each spring as follows. Begin by rewritting Equation 7 as

$$(F_b)_2 = k_b(l_2 - l_1 + l_1 - l_b) = k_b(l_2 - l_1) + k_b(l_1 - l_b) \tag{9}$$

The second term we can recognize as the force in the bolt at preload so

$$(F_b)_2 = k_b(l_2 - l_1) + F_{pre}. \tag{10}$$

The same procedure for the stack arrives at

$$(F_s)_2 = k_s(l_2 - l_1) - F_{pre}. \tag{11}$$

We can then substitute these two equations into Equation (6) to arrive at

$$(k_b + k_s)(l_2 - l_1) = P \tag{12}$$

and hence

$$(l_2 - l_1) = \frac{P}{K} \tag{13}$$

where $K = k_b + k_s$. This leads to the result that the force in the bolt during operation is

$$(F_b)_2 = \frac{k_b}{K}P + F_{pre} \tag{14}$$

while for the stack

$$(F_s)_2 = \frac{k_s}{K}P - F_{pre}. \tag{15}$$

These last two equations are more useful because in practice the stiffnesses, or at least the stiffness ratio, $R = k_s/k_b$ is known. If only the stiffness ratio is known the equations can be rewritten as

$$(F_b)_2 = \frac{1}{1+R}P + F_{pre} \tag{16}$$

$$(F_s)_2 = \frac{R}{1+R}P - F_{pre} \tag{17}$$

Before we interpret the physical implication of these equations, there is one more important equation to derive. Notice that as we increase the load from zero, the force in the stack begins negative and approaches zero. At some critical load, call it P_c, the load will be large enough to cause $(F_s)_2 = 0$ and this implies

$$P_c = \left(1 + \frac{1}{R}\right) F_{pre}. \tag{18}$$

This is the separation load. Beyond this load the stack will separate and no longer be able to carry any load as in Figure 3.d.

So what is the physical interpretation of these last three equations? Equations (16) and (17) show that the effect of preload on a fastened stack is to split the externally applied load between the fastener (in this case a bolt) and the stack. This is because the external load must act to simultaneously decompress the stack and stretch the bolt at the same time. Notice that for large stiffness ratios (stack much stiffer than bolt, $R >> 1$), the majority of the load is driven into the stack, while for small stiffness ratios (bolt stiffer than stack, $R << 1$) the opposite occurs. Equation (18) shows that as the stiffness ratio is increased, the separation load decreases and approaches the preload.

If the stack separates, the fastener has failed to perform its function properly. This may or may not be an issue for the function of the part/machine/etc.

depending on the degree of separation and what ramifications this has on its operation. But structurally stack separation poses another issue. As alluded to previously, once the stack separates, it no longer takes any of the external load and suddenly the entire load is driven into the fastener. This is very bad for fatigue resistance: if an oscillatory load's peak is high enough to separate the stack, the peak stress in the bolt will increase severely. Add to this all the sharp corners within the threading and very quickly a seemingly innocuous load can turn supercritical. In addition, bolts are often preloaded to within 10 percent of their yield, sometimes well beyond. This only serves to amplify the sensitivity to oscillatory stress. For this reason, it is desirable structurally to avoid stack separation.

Note that from Equation (16), oscillatory stress in a fastener can also be reduced by increasing the the stiffness ratio; however, from Equation (18) this will simultaneously decrease the separation load. It is hence a balancing act to find a stiffness ratio that minimizes oscillatory stress in the fastener. Too low and too much of the external load is taken by the bolt, but too high and the stack separates driving the entire extneral load into the bolt. Increasing the preload can help prevent stack separation, but in a fully clamped state it does nothing to lower oscillatory load in the fastener.

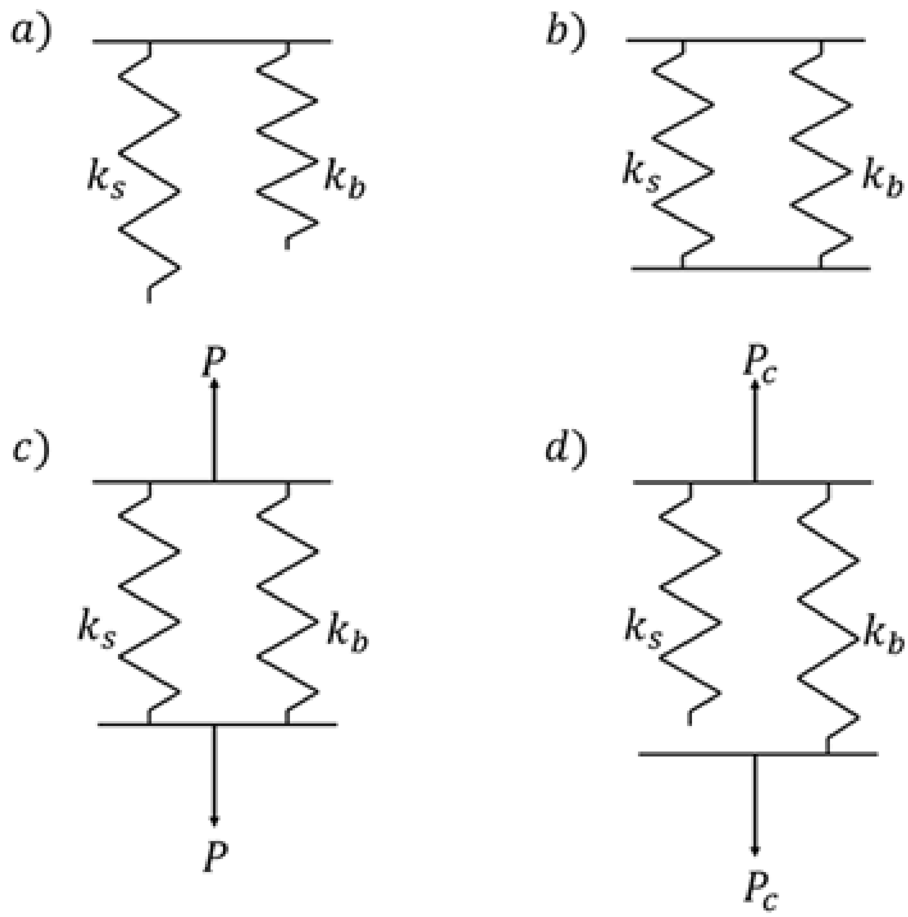

Figure 3: Spring model of a bolt stack being clamped and loaded. In each panel, the spring on the right represents the bolt, with stiffness k_b while the spring on the left represents the entire stack with equivalent stiffness k_s. a) The fastener is threaded until it is seated but no further; all members are still at their unloaded lengths. b) The bolt is tightened to its specified torque, stretching the bolt and compressing the stack. c) Load is applied. d) Applied load has reached the critical value to cause stack separation.