What can explain a Bolt Connector Axial force lower than the pre-load force when bolted components are loaded in tension?

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Discussion

Bolted connections are often more complex than one may think. There are various behaviors that can have opposing and counter-intuitive effects. The magnitude of these behaviors depend on the geometry, loading conditions, and many other factors.

It is quite possible for the axial force of bolt connectors to decrease when you apply a tensile load to the bolted connection.

Stiffness of the bolted connection

A bolted connection behaves like two springs in parallel: the bolt and the members (bolted components).

Bolt stiffness

Textbooks typically consider the screw head and the nut to be rigid. This simplifies the bolt stiffness to that of its shank. You can calculate the axial stiffness of the bolt shank using:

k=AE/l

Where:

A is the undeformed cross section of the bolt shank

E is the elastic modulus

l is the undeformed length of the bolt shank in tension, usually called “the grip”.

Note:

- Some textbooks propose a more complex formula that takes into account the threaded and unthreaded portions of the shank.

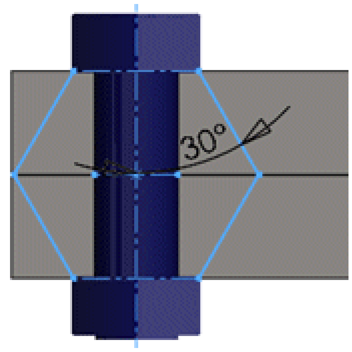
The stiffness of the bolt shank remains the same as you apply external forces because *A*, *E*, and *l* do not change value.

Member stiffness

The portion of tightened material belonging to the bolted components behaves like springs in series. There may be more than two members included in the grip of the fastener. Combined, the members behave like compressive springs in series. Therefore, the total spring rate of the members can be expressed as:

$1/k_m = 1/k_1 + 1/k_2 + \ldots + 1/k_i$

Each contributing stiffness affects the response of the overall model.



“The stiffness of the members is rather difficult to obtain except by experimentation”, write Shigley and Mischke in Mechanical Engineering Design, 5th edition. They mention using various simplifications and estimate that the region subjected to compressive stress in the clamped zone has a conical shape with half apex angle of about 30˚. They mention the “compression of a member assumed to be confined to the frustum of a hollow cone”

This assumption may be violated. Shigley and Mischke mention “cases in which the material is insufficient” as one possible circumstance.

Another possible circumstance is when the contact area changes with the application of external loads. In this case, the hollow cone assumption is incorrect by a variable amount, which depends on how the distribution of contact pressure changes as you apply external loads.

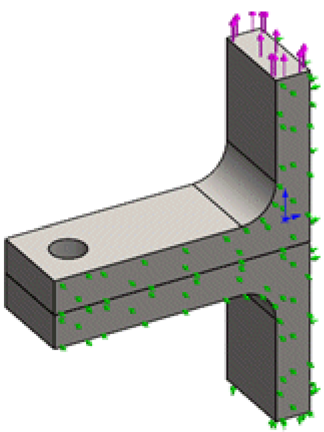
In many cases, the application of an external load to a bolted connection creates a gap between the contacting faces. This typically reduces the area of the contact. Consequently, this also reduces the member stiffness. The culmination of these effects is that the shank of the bolt receives less resistance and therefore shows a lower axial force.

As previously mentioned, many hand calculation of bolt forces in textbook assume that the contact area does not change. They do so to make a hand calculation possible. They rarely explicitly state that this significant simplifying assumption may not be realistic.

Finite element simulations do not make this simplification, and therefore offer results that are closer to reality, and further from those found in textbooks.

It is easy to illustrate this phenomenon with relatively simple test models.

Example 1



You can find the first test model in 'S-078250-Sample model 1'.

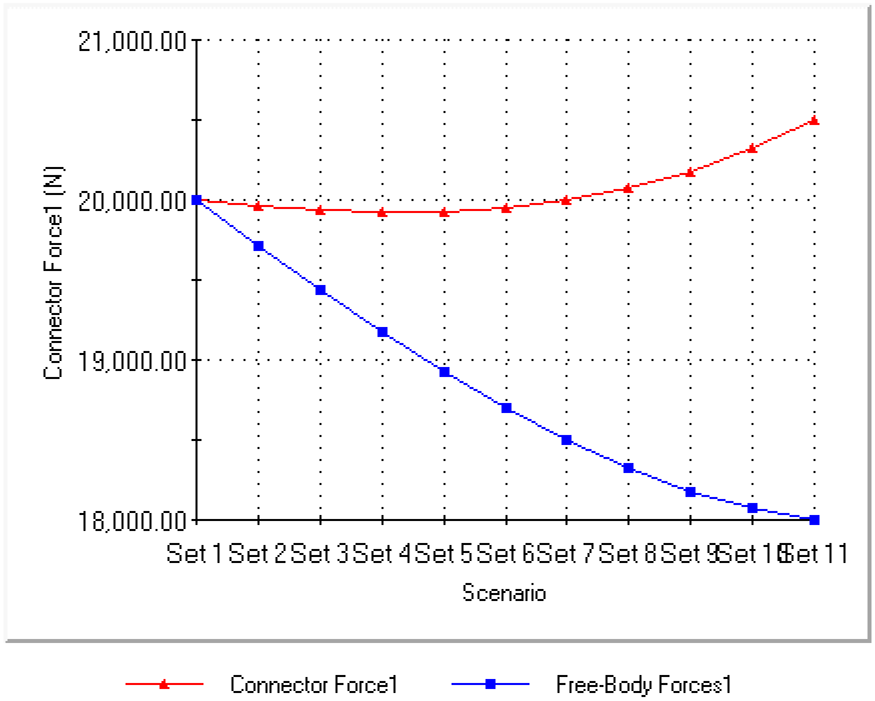
The model represents two components with a Bolt connector that has a 20,000N pre-load.

An external force pulls the two bodies apart.

After running the Design study, you can see that without any external force, the bolt axial force is 20,000N. As expected, this is equal to the pre-load value.

With a force between 250N and 1250N, the bolt axial force is lower than the pre-load.

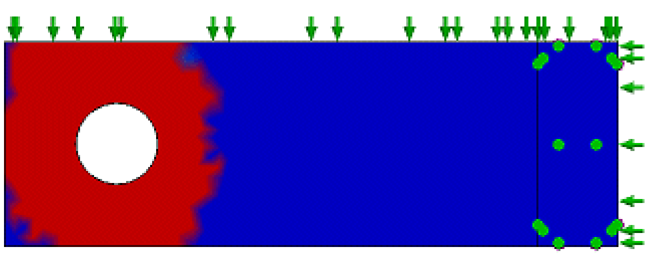
See "Evolution of bolt axial force and contact force with increasing external force values.png".



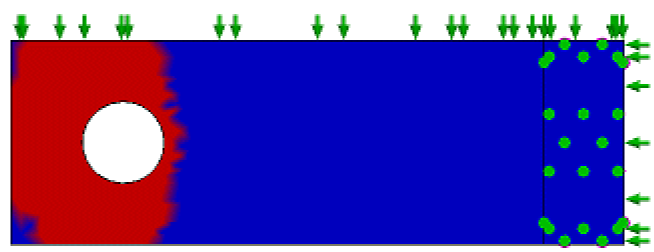
Evolution of bolt axial force and contact force with increasing external force values

As explained earlier, this happens because the external force bends the components and creates a gap between them. This reduces the contact area.

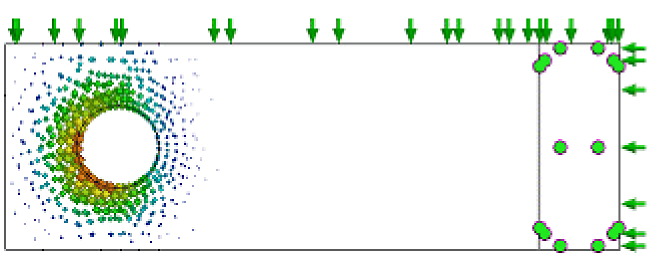
You can confirm this by plotting the contact pressure. Compare these images "Contact area with 0N force applied" and "Contact area with 1000N force applied".



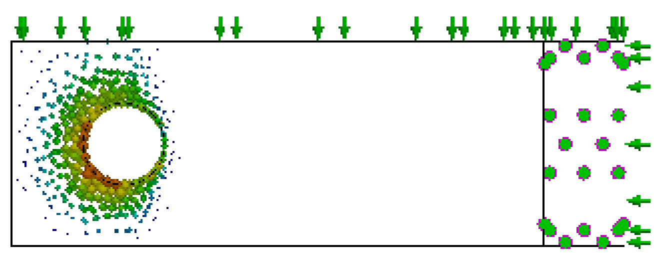
Contact area with 0N force applied



Contact area with 1000N force applied



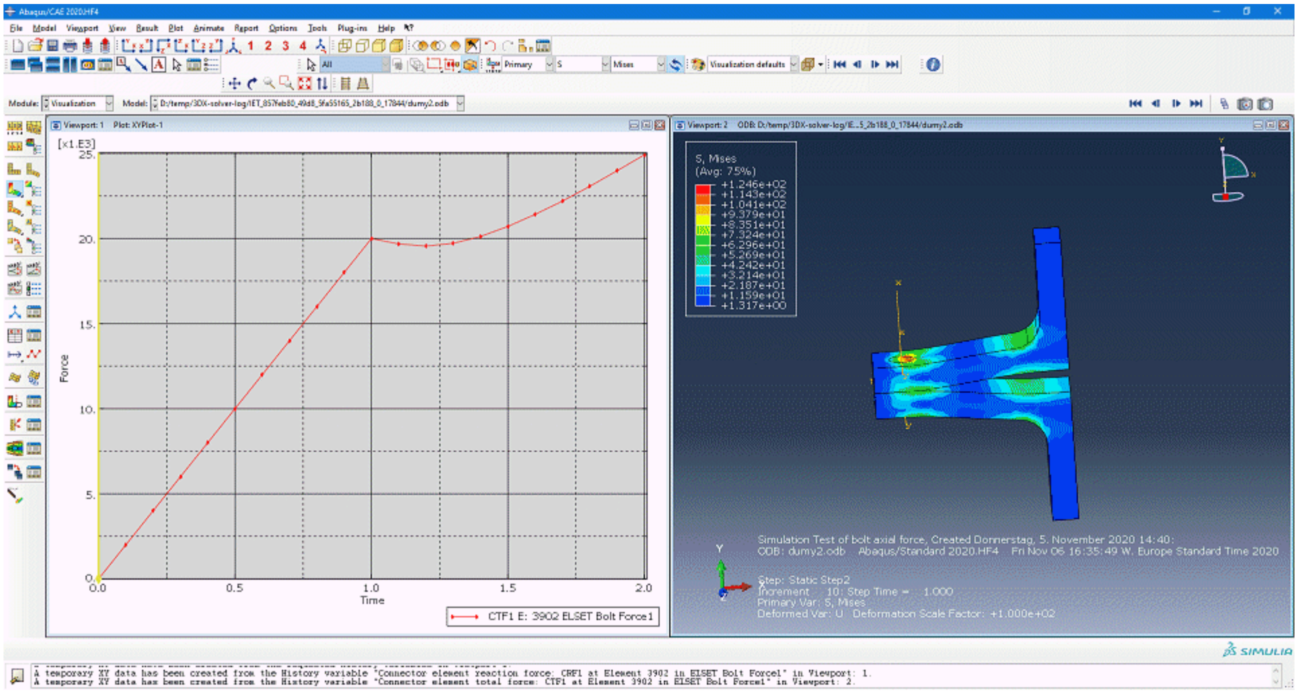
Contact pressure vectors with 0N force applied



Contact pressure vectors with 1000N force applied

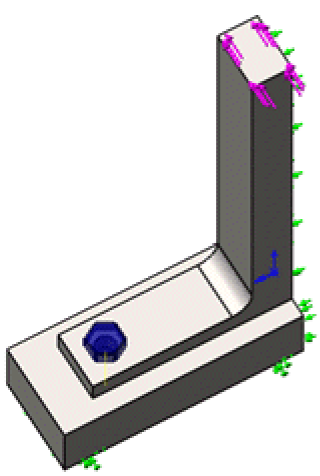
Note that with force values higher than 1250N, there isn't much further reduction of the contact area, and the additional force is sufficient to make the bolt axial force larger than the bolt pre-load.

Solving an equivalent simulation in a different FEA program (ABAQUS/CAE) also shows that the bolt axial force can be lower that the pre-load and confirms SOLIDWORKS Simulation result trends. The image below shows the variation of the bolt axial force as the 20,000N pre-load is gradually applied (from 0.0s to 1.0s), and then when a 5000N external force that pulls the two bodies apart is applied (from 1.0s to 2.0s). You can clearly see the bolt axial force being lower that the pre-load for values of the external force lower than approximately 1500N.



See “ABAQUS CAE - Bolt axial force for recreated Sample model 1.png”.

Example 2



You can find a second sample model in 'S-078250-Sample model 2.zip'.

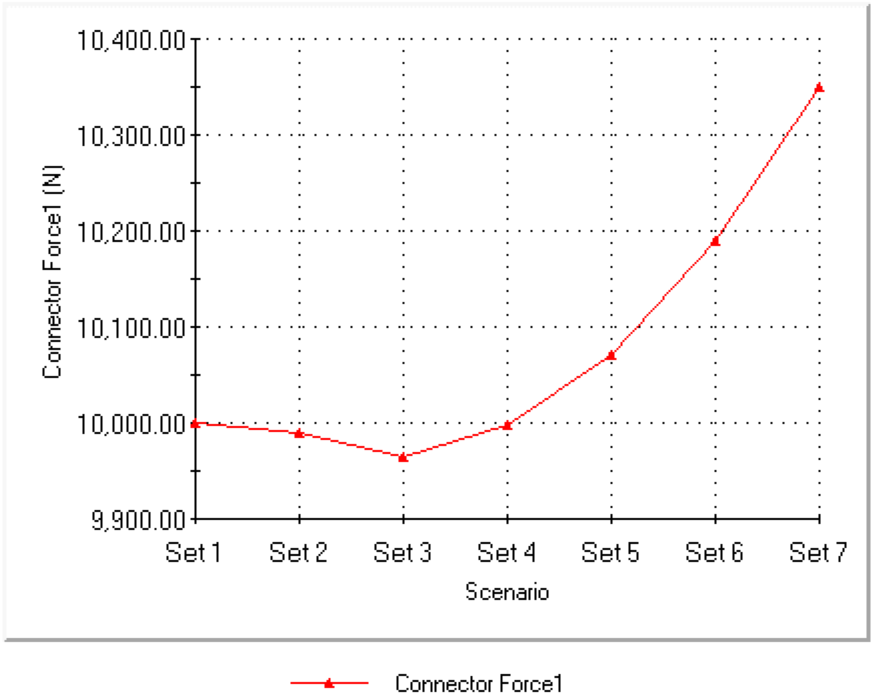
The model represents two components with a Bolt connector that has a 10,000N pre-load.

An external lateral (side) force creates shear and bending without directly adding any tensile load to the bolt.

After running the Design study, you can see that without any external force, the bolt axial force is 10,000N. As expected, this is equal to the pre-load value.

With a force between 50N and 150N, the bolt axial force is lower that the pre-load.

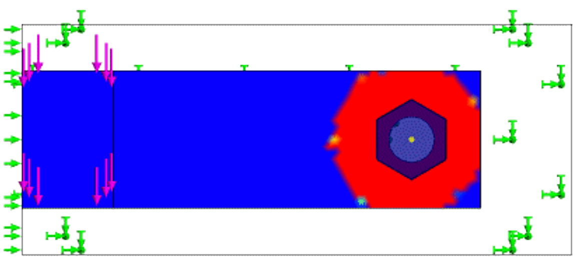
See "Evolution of bolt axial force with increasing external force values.png".



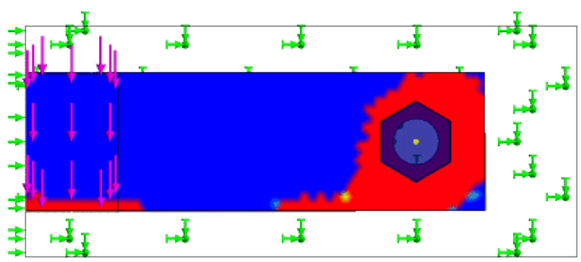
Evolution of bolt axial force and contact force with increasing external force values

As explained earlier, this happens because the force bends the components and creates a gap between them. This reduces the contact area, though it is not as clearly visible as with the first sample model.

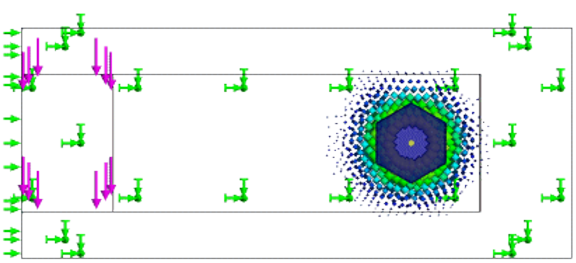
You can confirm this by plotting the contact pressure. Compare these images "Contact area with 0N force applied" and "Contact area with 100N force applied".



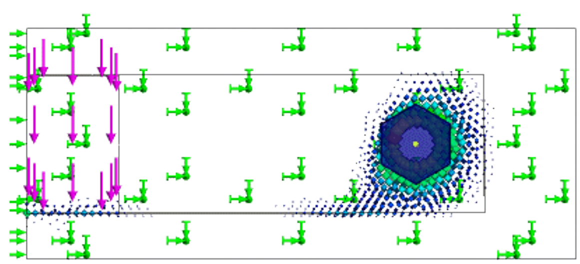
Contact area with 0N force applied



Contact area with 100N force applied



Contact pressure vectors with 0N force applied



Contact pressure vectors with 100N force applied

Note that with force values higher than 150N, there is no further change to the contact area.