TECHNICAL REPORT

Bolts Are Not Nails: Overcoming Misconceptions about Wedge Bolt Use in Permanent Rigging

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Abstract

Considerable misinformation circulates in mountaineering and cave exploration circles concerning the torque needed to correctly install the wedge anchors used in technical rigging. Misunderstanding the proper operation of wedge bolts has caused serious accidents. This explanation of bolt physics defends the installation of bolts using the torque specifications given by manufacturers and engineering guidelines against the common beliefs of many who install them for climber protection and permanent rigging.

KEY WORDS: *bolted joint, wedge bolt, permanent rigging, physics, engineering mechanics, shear force*

Introduction

Understanding how wedge bolts work can save your life. This article is an explanatory analysis, not instruction or original research. It describes how wedge bolts are designed to work and how they are often misunderstood and misused. Serious accidents have resulted from unwanted bolt pullout (Orndorff, 2022, Williamson, 2012).

A great deal of misinformation, inconsistent with mechanical principles, the laws of physics, and abundant industrial evidence is on the web and in the communities of climbers, cavers, and rescuers that use bolts. Accomplished climbers, for example, have emphatically stated that over-tightening the nut on a 3/8-inch wedge bolt is a significant risk. It is not. Engineers' perspectives are in fact the opposite, as observed by John Bickford (1995) in the classic text, *Introduction to the Design and Behavior of Bolted Joints*: "How much preload? We always want the maximum possible." Climbers often see it differently.

> *"The only reason for tightening anchors at all is to ensure the grabbing mechanism is engaged. This is easily achieved with very little torque. If you want additional insurance the mechanism will remain engaged over time I recommend using a locknut and/or lockwasher."*
>
> *"The pre-load of the bolt is only used to keep the bolt from coming loose during cyclic loading. In my opinion, the lowest possible torque that will prevent the bolt from loosening is the ideal."*
>
> *"When placing bolts I've come to use the rule of finger: I tighten to snugness and then some with a couple fingers."*
>
> *"I have no doubt I could twist the head off a bolt with a 6" wrench and have had friends actually do it several times."*

Discussion

The following analysis applies to wedge bolts and sleeve bolts only (fig. 1, below). Sleeve bolts were invented for use in weak materials like cinderblock, and extensive testing by Caltrans (Dusel, 1981) showed them to have poor pullout performance. A ⅜-inch wedge bolt has 50% more cross-sectional area because ⅜-inch is the hole diameter, not the sleeve bolt shank diameter. For those reasons we'll use wedge bolts as the subject of this piece, and ⅜-inch diameter because they're popular in the US.

Wedge bolts have a solid shaft threaded on one end and an integral expander cone on the other end. A collar around the base of the bolt gets forced up the expander cone and into the rock as one tightens the nut. The physics of self-drives, concrete screws, and glue-in anchors is completely different and will not be covered here. This article assumes good, solid rock, though it need not be homogeneous or isotropic.

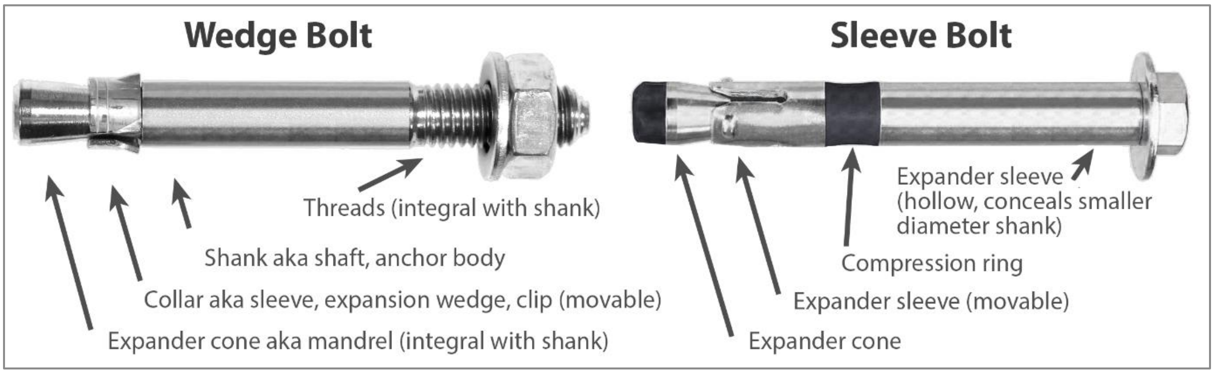

Fig. 1 Nomenclature for wedge and sleeve bolts.

This article uses only two physical principles, also called laws of nature, and prior knowledge of them isn't required. First is Newton's 3rd Law: for every action there is an equal and opposite reaction. If A pushes on B, B pushes back with an equal force. Second is the Law of Friction: friction force is proportional to the perpendicular force (“normal” force, in physicist parlance) exerted between surfaces. Proportionality in this context means that if the squeeze force doubles, the friction force also doubles.

Wedge bolts, like nails, rely on friction to do their job. But the underlying mechanisms of bolts and nails are very different. The first climber quote listed above, for example, reveals that he understands wedge bolts to function as nails, with the barbs on the collar providing the needed friction. If you use a wedge bolt in rock as you would use a nail in wood, it will not work as its designers intended. If you use a wedge bolt in an overhang or the ceiling of a cave as if it were a nail, tragedy is likely.

For each combination of materials involved in friction, there is a constant ratio, called *coefficient of friction*, between the squeeze force and the friction force. The coefficient is 0 for two perfectly slippery surfaces, and 1 for infinitely sticky surfaces. Real-world values fall somewhere in between. Though ice skaters are heavy, the coefficient of friction between skates and wet ice is close to 0, so the frictional force opposing the skater’s motion is tiny. In equation form, friction F equals coefficient μ times perpendicular force N. $F=\mu N$. This is the Law of Friction in equation form.

When you hit a nail with a hammer, the nail pushes the wood fibers apart, and the wood fibers push back on the nail. The force needed to drive a nail (F in the Law of Friction) equals the force with which the wood squeezes down (N, above) on the nail, times the coefficient of friction (μ) between nail and wood. The force required to pound a nail in is the same force required to pull it back out.

Bolts rely on friction, but in a more complex way. When you pound a wedge bolt into a good hole, you need to hit it hard, as when you pound a nail. Unlike the case with nails, this hammering force, caused by the barbs on the collar, has nothing to do with the force required to pull a *properly placed* wedge bolt out of its hole. Nothing.

Fig. 2. Resistance to pounding a wedge bolt into its hole comes from the barbs on its collar and is unrelated to the force needed to pull a properly placed wedge bolt out of its hole. In ceiling placement, friction caused by the barbs may even sustain someone's weight if the barbs. But, unlike the case with a preloaded bolt, every increment of applied load adds to the load felt by the bolt and its barbs, resulting in an unsafe joint.

As you apply torque, the collar contacts the sides of the back end of the hole. For you to feel resistance as you tighten the nut, the rock has to apply the same torque (Newton's 3rd law, in this case called Conservation of Angular Momentum) in the opposite direction. As long as the bolt hole is round (e.g., as opposed to a keyed hole), the only possible source of this opposing torque is friction between the hole and the collar. Thus, there is no mechanism by which you can tighten the nut and not have the collar seated in the hole.

When we join two parts together, like two girders, with a bolt, we call the assembly a bolted joint. Similarly, a wedge bolt connecting a hanger to a rock wall is a bolted joint. As the nut is tightened (or *torqued*, the term used below for emphasis), an immense friction force builds up at the expander cone and collar. This frictional force creates an axial stretching (tension) force in the bolt, which is exactly equal to the squeezing force the bolt applies to the rock, parallel to the bolt.

When you then use a horizontally-placed bolt by applying working loads underground, in most use cases there is not much pullout force on the bolt. The applied load is downward, perpendicular to the axis of the bolt. In construction and engineering, this situation is typically called a *shear joint*. Climbers, trainers, and web videos often say that, in this most common vertical-load case, the bolt is "loaded in shear." This is incorrect, however. Loading a properly assembled shear joint does not induce a shear force in the bolt used to make that joint.

A bolted joint where the load is in line with (in the direction of) the boot is commonly called a *tension joint*. A bolt placed in a ceiling where the load pulls downward is an example of a tension joint. Loading a properly assembled tension joint does not load its bolt in either shear or tension.

The absence of shear or tensile force in the bolt within shear and tension joints is counterintuitive for many people. This aspect of bolted joints is the magic of bolts (*bolts* in the engineering sense, which excludes screws having no nut, glue-ins, and anything that works like a nail). Loads applied to the joint, typically through a bolt hanger in mountaineering usage, are not transmitted to the joint's bolt. The work to install the bolt equals the work put into torquing the nut. It is the energy bound up in the bolt, which is being stretched, and in the rock, which is being squeezed. The amount of stretching force in the bolt is always exactly equal to the squeezing force applied to the rock. That force is called the *preload force*.

If a hole is too wide for the bolt because the drill was wobbly or the rock is crumby, the collar around the expander cone may never engage. In that case tightening the nut may just back the bolt out of the hole with little resistance - that is, without much torque. Or the collar might have enough friction with the hole interior to keep the bolt from backing out, but not enough friction to keep the shank from spinning, again resulting in not building up torque and preload.

If the amount of torque required by the design of the bolt isn't applied, the bolt does not get preloaded, and the joint cannot prevent applied loads from loading the bolt. This is the important part. Preload - and a lot of it - is essential to a properly placed bolt. Preload prevents the stress states in the bolt and in the rock from changing when a load is applied.

Preload - and a lot of it - is absolutely essential to a properly placed bolt.

The desired preload is always a large fraction of the amount of force that would permanently deform the bolt. This is desirable, done on purpose, and integral to the way threaded fasteners were designed to work. In critical applications such as aircraft, bolted joints are often specified to use a preload force *greater than* the point of permanent ("*plastic*") deformation.

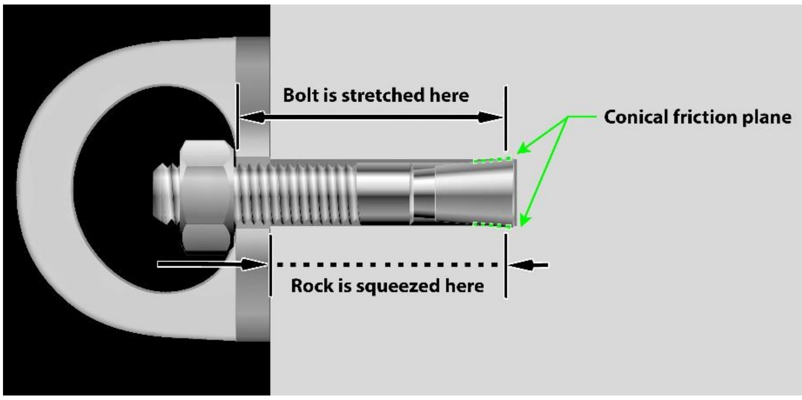

Fig. 3. Idealized hanger with a torqued nut showing equal and opposite stretching and squeezing forces and the regions where stretching and squeezing occurs.

For a ⅜ inch bolt with no grease applied to the threads, the torque needed for proper preload, according to both manufacturers' guidelines and engineering calculations, is about 28 foot-pounds [38 Nm] (Powers gives 28, Confast, 30). That's an extended 28-pound [125 N] tug on a one-foot wrench or a 56-pound [250 N] yank on a six-inch wrench (more like 80 pounds [350 N] because of where your hand ends up on a wrench). Putting that much force on a wrench handle is difficult and painful when you are pushing downward. Pushing sideways, as when a bolt is in the ceiling, with that much force while you are hanging in a harness is harder still.

Yield strength is the load that causes the onset of permanent deformation. *Ultimate strength* is the load to break the bolt. The ultimate strength of a 304 bolt is at least twice its yield strength (NASA, 1979). Specified torque values for 304 bolts are typically 65-75% of that which would yield the bolt (NASA, 2017). Thus the torque needed to break a 3/8 304 bolt is at least 60 foot-pounds [80 Nm], provided it didn't pull out. Therefore, despite anecdotes, the likelihood of breaking ⅜ bolts with hand wrenches is quite remote.

For the remainder of this article, we'll use as an example, ⅜ bolts torqued to 28 foot-pounds, causing a preload of 3000 pounds [13.3 kN]. Because of variability of friction coefficients in the bolt/nut/hanger interfaces due to environmental factors, the preload could range between 2500 to 5200 pounds [11,000 – 23,000 N]. We'll use 3000 pounds henceforth, a bit less than half the strength of the bolt, for our examples here.

Assuming 3000 pounds of preload, and therefore 3000 pounds of rock-squeeze, let's hang a 200-pound person from a bolt placed vertically in the ceiling. What is the resulting tension in the bolt? One might think it is 3200 pounds - the sum of the preload force and the person's weight. But that is not what happens, and the preload is why.

The mechanical properties of the relatively small bolt differ greatly from those of the big slab of rock. The steel is ductile and elastic, and the rock is stiff by comparison. The preload in the bolt, combined with the mechanical properties of the bolt and the rock, set up a situation where the load applied to the hanger does not increase the load in the bolt at all - not until the applied load gets close to the 3000-pound preload. Here it helps to remember that we hang on the hanger, not the bolt. The hanger does *not* transmit the 200-pound load to the bolt. Instead the weight of a 200-pound [900N] person merely decreases the squeeze force between the rock face and the hanger - from 3000 pounds down to 2800 pounds. This is why aircraft bolts are often torqued beyond their yield strength, by specification, to prevent the bolt from “feeling” any applied load. It cyclical-loading scenarios, the preload also prevents the bolt from feeling load oscillations that cause fatigue failures.

From here on, in our examples we’ll increase the applied load from 200 to 1000 pounds to better make the case.

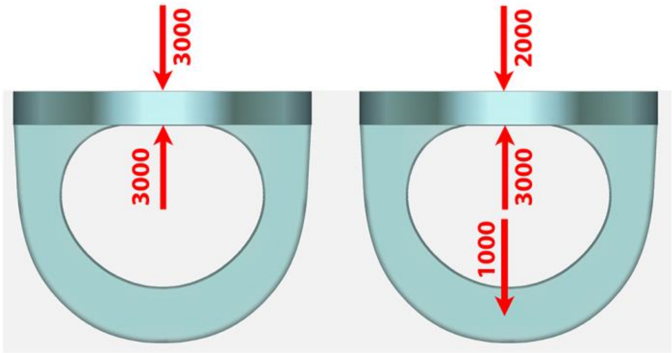

Fig. 4. Idealized hangers showing forces transmitted by bolt, rock, and 1000-pound applied load. Length of arrows does not indicate magnitude of force.

Consider only the external forces acting on an idealized hanger (not bolt) attached to a preloaded bolt. Compare the cases with no applied load (fig. 4, left) and with an applied load of 1000 pounds [4450 N] (right). In both cases the nut pushes *up* on the hanger with a force of 3000 pounds. With no applied load, the wall pushes *down* with an equal but opposite 3000 pounds. Net external forces on the hanger will always sum to zero (Newton’s 3rd Law). With a 1000-pound applied load, the wall pushes *down* with 2000 pounds and the nut continues to push *up* with 3000 pounds. Net external forces on the hanger still sum to zero.

To further clarify, consider, as an analogy, a loaded spring scale where we intentionally block the spring from retracting (fig. 5).

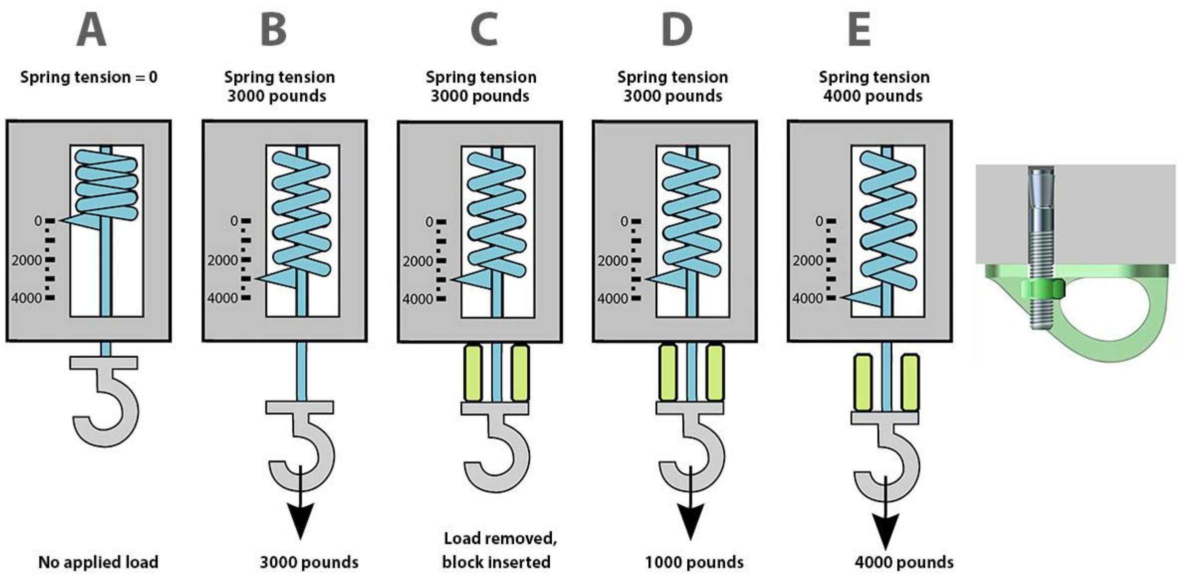

Fig. 5. A spring scale is a good analogy for wedge bolt placed in the ceiling. In state A, the spring is not loaded and therefore is not in a state of stress. In B we hang a 3000-pound load and the spring stretches so that the indicator reports the load. The spring is in a state of tensile stress. In C, we slip blocks between the flat top of the hook and the housing of the scale, thereby preventing the spring from retracting. There is no weight of the scale, but the block causes the spring to remain stretched and in tension. It is now preloaded with 3000 pounds of force. In D, we hang a 1000-pound weight from the scale's hook, noting that the blocks are still in place. The stress state of the spring, and the preload force within it, do not change at all. In E we hang a 4000-pound load, which exceeds the existing preload. The blocks separate from the bottom of the scale's housing and the tension force in the spring is now 4000 pounds.

Labeling the forces both on the hanger (hanger forces shown in red) and on the bolt (in blue, fig. 6, below) for the same two cases shown in figure 4 demonstrates how the bolt and hanger forces relate to each other. In this example we neglect the small effect of the offset between the carabiner hole and the bolt. That offset does not "lever the bolt" as reported by several instructional sources – again, because of the preload.

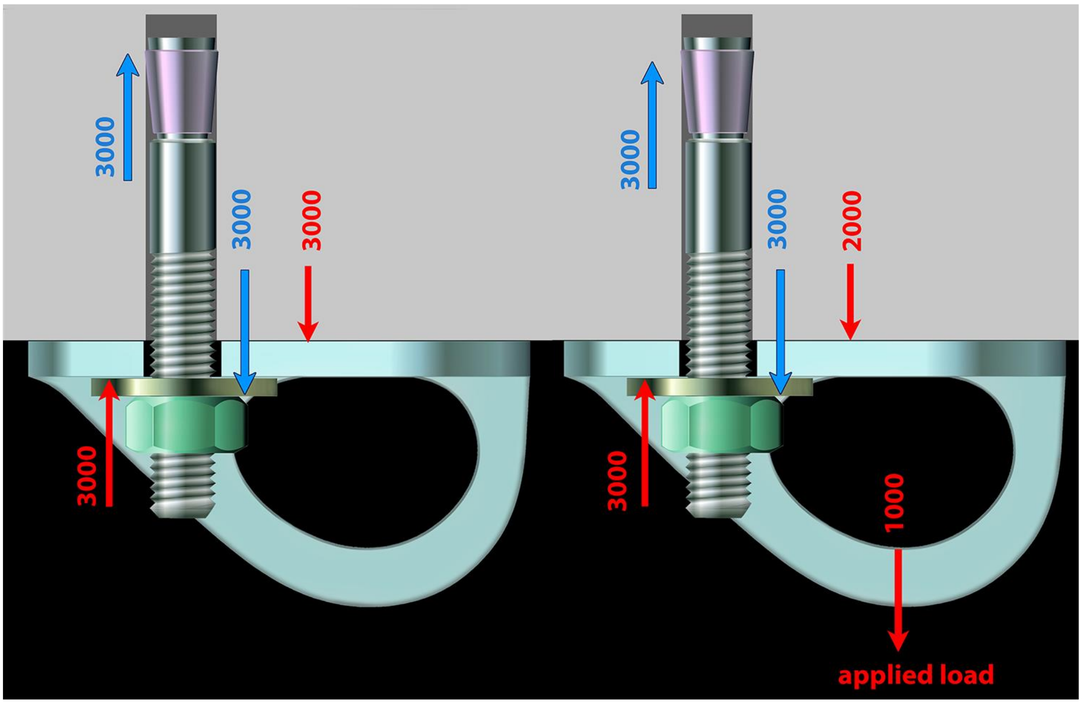

Fig. 6. At left the nut is torqued to 28 foot-pounds. The torque causes the nut to pull downward with a 3000-pound tension force on the bolt. The rock at the back of the hole pulls upward with 3000-pound tension force on bolt through its collar. The bolt is preloaded to 3000 pounds. The nut pushes upward on the washer, which pushes upward on the hanger with a 3000-pound force due to the nut being torqued. The rock wall (ceiling) pressed downward on the hanger with a 3000-pound force. The hanger is being squeezed with 3000 pounds. The forces on the hanger balance out and sum to zero. The forces on the bolt also add up to zero.

At right the nut is torqued and 1000-pound load is hung from the hanger. The torque causes the nut to pull downward with a 3000-pound tension force on the bolt. The rock at the back of the hole pulls upward with 3000-pound tension force on bolt through its collar. The applied load of 1000 pounds pushes down (or pulls down, depending on how you look at it) on the hanger. This reduces the force with which the rock pushes down on the hanger to 2000 pounds. The nut pushes upward on the washer, thereby pushing upward on the hanger with a 3000-pound force. The rock ceiling pressed downward on the hanger with a 2000-pound force. The forces on the hanger balance out and sum to zero. The forces on the bolt also add up to zero. The bolt is still preloaded to 3000 pounds.

Another counterintuitive consequence of preload is that a preloaded horizontal bolt is never loaded in shear. It is always loaded in pure tension, before and after any reasonable vertical load is applied. Any applied vertical load is transmitted by the hanger to the rock face by friction. So, until the applied load is equal to the coefficient of friction times the preload force, the hanger never pulls down on the bolt itself. The bolt feels no shear force.

The below diagram shows the forces in the hardware, with a load pulling down on a bolt with a loose nut, with a hand-tightened nut, and with a properly torqued nut. In all cases, both the horizontal and vertical forces sum to zero. Here we neglect the small effect of the offset between the carabiner hole and the wall.

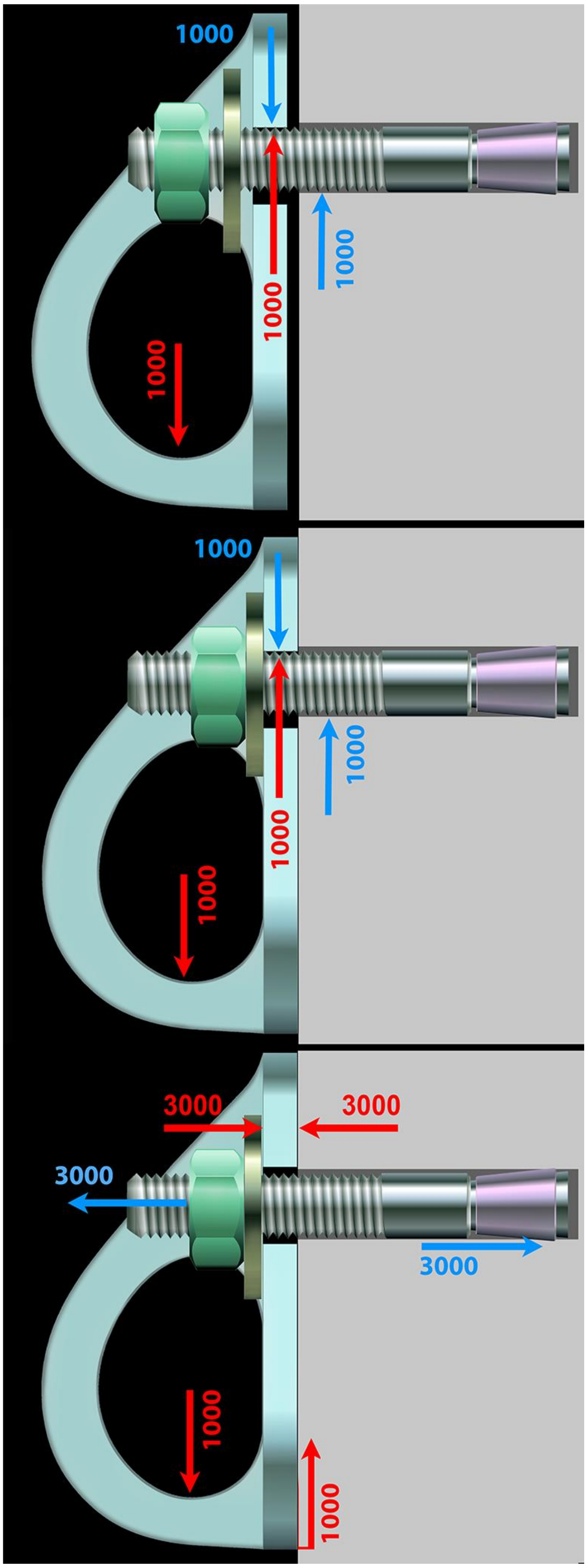

Fig. 7. The nut, washer, and hanger are loose on the bolt (nut is not torqued). The bolt is not preloaded. No tension force is in the bolt.

An applied 1000-pound load pushes down on the hanger. The bolt pushes upward on hanger with a 1000-pound force in the opposite direction. The hanger pushes downward on the bolt with 1000 pounds. The rock pushes up on the bolt with 1000 pounds. The bolt is loaded in shear.

"Push" and "pull" help us talk about the situation using natural wording but are not important to what is going on. Only the direction and size of the forces matter.

The nut is hand-tight against the washer hanger, and rock face. The bolt is not preloaded. No tension force is in it.

An applied 1000-pound load pushes down on the hanger. The bolt pushes up on hanger with a 1000-pound force in the opposite direction.

The hanger pushes downward on the bolt with 1000 pounds. The rock pushes upward on the bolt with 1000 pounds. The bolt is loaded in shear. Its threads are loaded in a way not intended by the manufacturer.

The nut is torqued to 28 foot-pounds. The nut applies a 3000-pound tension force (to left) on the bolt. The rock pulls to the right with a 3000-pound tension force on the collar of the bolt, which pulls to the right with the same force on the bolt shank. The bolt is preloaded with 3000 pounds of tension force. The hanger is being squeezed with 3000 pounds. *The bolt is not loaded in shear. No vertical forces act on it.*

A 1000-pound applied load pulls downward on the hanger. The rock wall pushes upward on the hanger with a 1000-pound frictional force.

Like the climbers' quotes above, sources of instruction on bolting often teach that very low torque values can or should be used in the standard horizontal-bolt situation shown above. They are thus calling for no bolt preload and using bolts as if they were nails. The load required to pull the bolt out will be the amount of force it took to hammer it in – not very much.

For a horizontal bolt with no preload, the bolt *is* in fact loaded in shear (the first two scenarios in fig. 7). The hanger bears down on the bolt and transfers the entire vertical load to it. ⅜ inch bolts can handle this except for ruining the threads. The absence of preload can go unnoticed for years - until the dynamics of a fall happen to place a horizontal (pullout) load on the bolt. This can happen during a fall, for example, if the belayer is at some horizontal distance from the first bolt or in rescue scenarios with hauling systems.

Bolts in a ceiling with inadequate preload are deadly. The nail analogy applies; the force to pull it out equals the force it took to push it in. An improperly torqued ceiling bolt may even sustain someone's weight if the barbs on the collar can provide friction equal to the applied load, which is now along the axis of the bolt. But, unlike the case with a preloaded bolt, every increment of applied load now *does add* to the load felt by the bolt, thereby calling on the bolt-rock interface to oppose that load with an equal frictional force. But friction can only do so much, because friction is relying solely on collar barbs inside of the hole. Some wedge bolt designs, particularly the geometry of the barbs on the collar, (e.g. Raumer) (Orndorff 2022), result in comparatively high pounding force to push the bolt into its hole. This exacerbates the problem of equating pounding force with preload.

Industrial experience and a mechanical analysis of this application of bolts allows us to make some very strong claims about wedge bolts. Most importantly, a bolt's nut must be properly torqued to achieve the preload that prevents the bolt from feeling any later-applied load. Correspondingly, it is virtually impossible for a bolt having preload to pop out of the hole. There is no mechanism by which nut torque can exist in a good bolted joint without the bolt having preload.

Preload is, within reason, the only thing that matters for a properly installed bolt. Preload can't exist if the hole diameter is too large or if the rock is horribly weak. It's also useful to consider the things that don't really matter in judging whether a bolt placement is good. The number of threads protruding through the nut is no indication that the nut was tightened. A hole that wasn't blown clean and contains rock dust might stop a bolt from being torqued and preloaded, but if you were able to apply 28 foot-pounds of torque, the bolt is preloaded and it will hold, dust or not. The brand of drill affects how tired your arm gets and your ability to make a good hole but has no bearing once the nut is torqued. We all have our favorite brands of bolts, but all ⅜ stainless bolts with 16 threads per inch create the same preload for a given amount of torque. The preload is a function of thread pitch, the steel-on-steel coefficient of friction, and the elastic modulus of the steel, which does not vary by brand. Bolt preload, regardless of bolt orientation, ensures that when you apply a load to it there will be no change in the stress state of either the bolt or the rock it is in.

Bolt preload, regardless of bolt orientation, ensures that when you apply a load to it there will be no change in the stress state of either the bolt or the rock it is in.

Measurements of metal creep, the relaxing of the preload stress in a bolt, vary widely depending on conditions. Where vibration is not a factor, a 10% loss of preload is commonly reported within a few days (e.g. MIL-HDBK-60, 1990; Chesson, 1964). Caltrans data showed some instances of loss of over 25% (attributed to steel creep, not concrete weathering – Honarvar, 2017) in 30 years.

Fig. 8. Training with a torque wrench or similar setup helps learn what 28 foot-pounds feels like when applied with a hand wrench.

Given the importance of preload, it makes sense to learn what 28 foot-pounds feels like on the wrench you use to place bolts. A torque wrench fixed to a bench, against which a trainee uses a hand wrench as would be the case in the field, might be a good addition to rigging training. Given the extensive misunderstandings regarding bolt installation, it is likely that a large fraction of existing bolt placements have no preload. Periodically retorquing the nuts on existing permanent rigging seems prudent and is absolutely essential when rescue work makes use of existing rigging.

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William Storage is an engineer with extensive experience in design and failure analysis of bolted joints and has served as expert witness in many aircraft crash accident analyses and court cases involving threaded fasteners and bolted joints. He has installed hundreds of wedge anchors for mountaineering and caving in the US, Canada, and Mexico.

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