Two climbers headed up a two-pitch sport route on the Fire Wall, above Tonsai Beach on the Phra Nang Peninsula of Thailand. At the two-bolt anchor, the leader pulled up slack to belay his partner, and as an afterthought, he reached up to clip the first bolt of the next pitch as a redirect to belay his partner.

When the second reached the belay, both climbers leaned out on the anchor to inspect the next pitch. Immediately both anchor bolts broke. The pair swung off their stance and hung suspended, 90 feet off the ground, by the single second-pitch bolt the leader had clipped as a redirect. That bolt didn't break.

A climber on the Upper Town Wall at Index, Washington, was tackling a seldom-climbed 5.12 route named *Calling Wolfgang*. After climbing through some gear-protected terrain, he continued past several bolts. Now about 65 feet up, he clipped the third bolt he encountered, intending to hang and clean some holds. As he leaned back on the bolt, however, it broke. He fell about 15 feet until his weight came onto the bolt below, which also broke. Fortunately, the next bolt held, arresting the climber's fall only 15 feet off the ground.

What caused these accidents? When new, these anchors could hold thousands of pounds, but now they had failed under body weight. None of the failed bolts looked all that bad, at least at first glance, and one was almost new. The story behind these near-catastrophic bolt failures is more complicated—and more common—than you might expect.

Free-for-all engineering

You read it all the time: The climber is responsible for his own safety and should evaluate every protection bolt he clips. True in theory, but in practice, most climbers don't. Unless a bolt is so rusted that it looks like a relic, it's generally considered good.

Yet bolting sport routes is a completely unregulated practice, carried out mostly by practitioners who are not only untrained, but often are functioning on dangerously tight budgets. Skimping on materials can save $100 or more per route—a week's living expenses at Miguel's or Rifle Mountain Park. At the same crag, some anchors will be "by the book," while others are creative combinations of bolts, chains, and hangers chosen to save cost, and some are poorly placed due to lack of knowledge. Some anchors are exposed to unusual corrosive forces that have surprised even trained specialists.

"The result is a high degree of variability in strength and lifespan of the anchors out there," says Bill Belcourt, Director of Research and Development at Black Diamond Equipment. "It is apparent there is no standard practice or training for placing bolts, and this is a big problem that is compounding daily as more routes are being developed and existing anchors age." Many feel we have outgrown the "wing-it" phase in our equipping and should become a little more standardized and responsible.

Alan Jarvis of the UIAA Climbing Anchors Working Group, certainly feels that way and compares climbing to other instances where bolt failures can cause dangerous accidents. "The construction and oil and gas industries use a lot of fasteners, as they call bolts," says Jarvis. "The engineers specify what anchors to use and plan for a defined lifetime. Fifty years is considered normal. On big projects they have a quality-control system in place to inspect critical anchors after installation, as well as during their lifespan."

"In climbing, however, quite often the person who decides on the anchor doesn't know that much about materials or corrosion. They are not materials specialists. They are not certified or specially trained, as welders on pipelines, etc., are. Nobody inspects the bolts after or during installation, or during their lifetime. And there is no pre-determined lifetime, or replacement program."

Now, just over 20 years since bolt-protected climbing took hold in the U.S., the first-generation routes in most parts of the country have become unsafe. Many crags have already begun re-equipping, and the hardware is well into its second round of wear. In remote locations lie classic routes that are unclimbable due to inadequate hardware. It doesn't have to be this way.

Should climbers be inspecting the bolts they clip? Of course. But how? Can you tell by looking at a bolt if it's safe? Perhaps more importantly, how can a route developer or anchor-replacement volunteer choose a bolt that will be good for 50 years?

Metal-urgency

It's easy to spot a very rusty bolt, but the most dangerous kinds of corrosion are less obvious. Inexpensive carbon-steel bolts rust predictably—quickly or slowly depending on the environment—and get weaker and weaker as the steel gradually flakes away as rust. On the other hand, corrosion-resistant hardware such as stainless steel, doesn't rust as noticeably. But it can be attacked in other ways—sometimes rapidly.

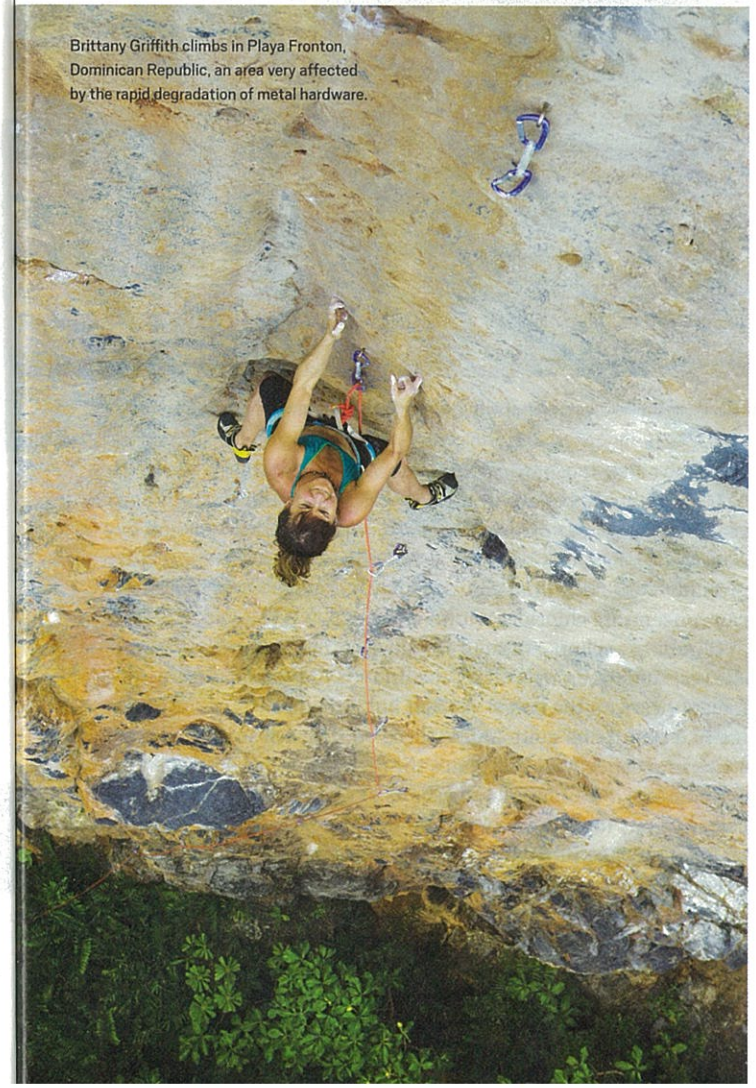
Most anchor hardware is made of steel, which mainly consists of iron, plus a mix of other things. Iron rusts when it reacts with oxygen. Water speeds up the process, too: Oxygen in dry air tends to stay in the air, while oxygen plus water plus iron equals rust.

Saltwater accelerates rust even more. Dissolved salts become positive and negative ions, so they make saltwater a much better conductor of electricity than freshwater, which speeds up the chemical reactions of corrosion. Heat also increases the speed of corrosion. All else being equal, climbing bolts will rust faster in Alabama than in New Hampshire. Acids—even mild ones such as acid rain near industrial areas—will significantly increase corrosion. Groundwater affected by decaying vegetation becomes acidic, like vinegar, and will rust bolts faster—sometimes much faster.

There are many kinds of steel, but the simplest ones are over 95 percent iron, plus a small percentage of carbon. Pure iron is actually softer than aluminum, and carbon gives "carbon steel" its strength and hardness.

Of the hundreds of kinds of steel, some are designed to hold a sharp cutting edge, some to be malleable, others made to flex and spring back into shape. You can completely alter the properties of steel by changing the carbon content, heating and then cooling it in a certain way, or by mixing it with other metals. Steel is amazingly versatile, but its main drawback is and always has been its susceptibility to rust. It's the only metal that corrodes so badly in typical environmental conditions.

The main reason is that rusts—iron oxides—have the unusual property of being soft and powdery. They flake off, taking the metal with them, so the surface just dissolves away. Rust is oxygen-permeable, so the inner metal continues to oxidize. This is unusual for metal oxides, as most others form a hard, resilient film on the surface that protects the base metal from corrosion. Fortunately, by mixing other metals into the steel, you can create alloys that will form a much more protective surface layer.



Brittany Griffith climbs in Playa Fronton, Dominican Republic, an area very affected by the rapid degradation of metal hardware.

The best-known steels of this type are "stainless" steels, a large family of over 100 alloys that share the characteristic of containing at least 10.5 percent chromium. Somewhat counterintuitively, chromium makes steel "stainless" because it is even more reactive with oxygen than iron. But instead of forming a flakey rust, stainless steel develops a thin surface layer of chromium oxide that keeps the steel from rusting. It's self-healing—if you scratch or gouge the steel, new chromium oxide forms to protect it.

Chromium makes steel brittle, however, so most stainless also contains nickel, which counteracts chromium's brittleness and adds its own corrosion resistance. Nickel is also what makes stainless significantly more expensive than carbon steel.

There are many grades of stainless, but the most common one for climbing-anchor hardware in the U.S. is SAE 304, sometimes called 18/8 because it contains 18 percent chromium and 8 percent nickel. "Marine-grade" or SAE 316 stainless is similar, but in addition contains 2 percent molybdenum, a pricey metal that makes 316 more resistant to the crevice and pitting types of corrosion that can plague stainless steel in "aggressive" (highly corrosive) environments. In the U.S., 316 stainless costs 35 to 40 percent more than 304, but in Europe, where 316 is favored, the cost difference is less. Many European-made stainless hangers, including those donated by Petzl to *Climbing's* Anchor Replacement Initiative program (***climbing.com/ari***), are 316.

There are other steels with significantly more corrosion resistance than 304 and 316. Some are prohibitively expensive, but some could be viable for climbing anchors. One such group are the so-called HCR (high corrosion resistance) steels, which contain more molybdenum and nickel, and their molecular structure is enhanced by other elements such as nitrogen. One widely used HCR steel is 254 SMO. With 6 percent molybdenum and 18 percent nickel, 254 SMO is significantly more expensive than 316, but it is very resistant to the special kinds of corrosion—pitting, crevice corrosion, and SCC—that can plague climbing anchors in aggressive environments.

In the construction industry in Europe, outdoor safety-critical steel anchors must be either 316 or HCR; the less expensive 304 is not considered adequately corrosion-resistant.

Nickel and molybdenum make stainless steels expensive, and there is a cheaper way to keep steel from rusting: plate it with zinc, a process sometimes called galvanizing. This can be done either by dipping the steel in molten zinc, or, more appropriate for climbing-anchor hardware, applying the zinc through an electrical process. Zinc costs about the same as aluminum (one-eighth as much as nickel), and electroplating requires little zinc anyway. Like the chromium in stainless steel, zinc oxidizes readily, forming a protective layer that keeps oxygen away from the iron.

Stainless steel has its corrosion resistance built in, but plated steel doesn't: Zinc-plated steel will slowly lose its zinc to oxidation. In wet climates, it doesn't take long for the zinc to be used up. No zinc, no corrosion-resistant veneer.

Most of the carbon-steel bolts still used at U.S. climbing areas—the Rawl/Powers "5-piece" sleeve bolts, for example—are zinc-electroplated. Plated-steel bolt hangers are significantly less expensive than stainless and are widely used in the western U.S.

Of course, no discussion of corrosion-resistant metals would be complete without mentioning titanium, "metal of the Titans." Titanium is pricey, but not obscenely so, and has a higher strength-to-weight ratio than steel, as well as excellent corrosion-, fatigue-, and crack-resistance. Titanium bolts are becoming the standard at tropical climbing areas, and the first UIAA-certified titanium anchor is now on the market.

Currents, crevices, and cracks—special types of corrosion

Not all corrosion is as gradual or easy to detect as rust. One equipping mistake that speeds up corrosion is to mix two kinds of metal in the same anchor—a stainless steel hanger on a carbon-steel bolt, for example. Such setups may suffer from "galvanic corrosion."

As the name implies, galvanic corrosion involves an electric current. Metals each have their own "electrode potentials"—the potential to become either a positive or negative pole of an electric couple. If the potential of two adjacent metals isn't the same, a small current, carried by electrons, flows between them. Seeking a sort of equilibrium, the metal donating the negatively charged electrons will also begin to lose positively charged metal ions, causing the metal to dissolve.

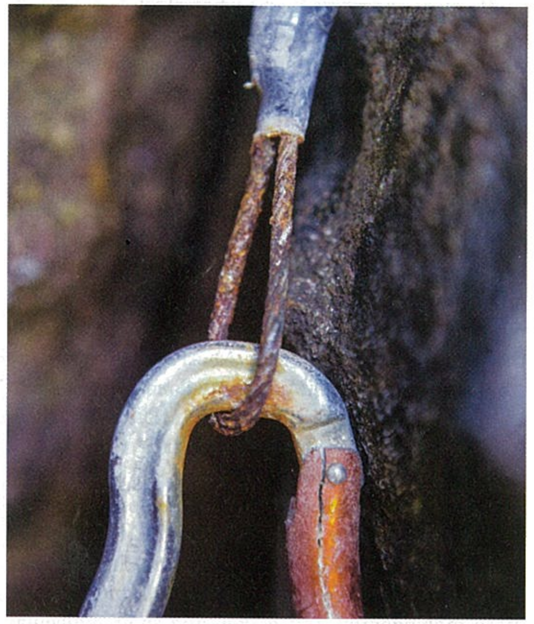
Galvanic corrosion won't occur in dry conditions or in distilled water; to "complete the circuit" you need an electrolyte such as saltwater. In climbing anchors, any mineralized water trapped between a bolt and its hanger will function as the electrolyte.

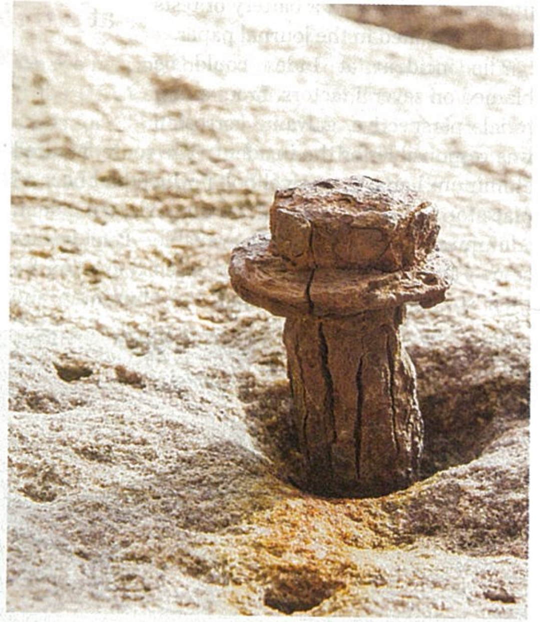
Various combinations of mild steel, zinc-plate, aluminum, and stainless can experience galvanic corrosion. Installing a stainless hanger on a carbon-steel bolt will compromise the bolt itself, while a zinc-plated hanger on a stainless bolt will compromise the hanger.

Crevice corrosion is also relevant to climbing anchors. It is caused by the concentration of corrosive minerals, especially chlorides. Crevices in or around the metal tend to trap mineralized moisture. If the crevice periodically dries out, it can concentrate dissolved chlorides and create a microenvironment so aggressive that it can overwhelm the oxides on stainless steel.

It's commonly believed that only crags near the ocean are at risk for aggressive corrosion because of the chlorides carried by seawater. In fact, chlorides are also carried by rain and especially groundwater. The initial amounts may be small, but evaporation can concentrate chlorides within crevices.

Climbing anchors are rife with crevices, including the threads, sleeves, and wedging collars, behind washers, and where the hanger bears on the bolt stud. Bolt holes themselves create crevice-like conditions quite unlike those on the rock surface. Water soaks into sandstone, percolates through limestone, and even in dry climates like Colorado, the shafts of rock climbing bolts typically live out their years in a state of dampness. If they dry out completely once in a while, that's actually worse, since it serves to concentrate corrosive salts. This highlights advantages to glue-in bolts: 1) they have no crevices, and 2) the epoxy protects the metal from the corrosive microenvironment inside a bolt hole.





From the sea stacks of Scotland (images one, two, and four) to the beaches of the Dominican Republic (image three), saltwater accelerates the rusting of all types of metals, including aluminum and various kinds of steel.

Crevice corrosion affects all steels, but it is particularly disturbing in stainless steel. A stainless steel bolt/hanger combination will almost never show surface rust. The bolt may look fine, yet be badly corroded in critical, invisible areas such as the threads.

Pitting is another special kind of corrosion. This one you often can see, since it takes place on exposed surfaces such as the face of a bolt hanger. It is essentially a microscopic version of crevice corrosion. Stainless steel's chromium oxide layer contains minute flaws that can become tiny pits. Once a pit starts, it can create its own microenvironment with an aggressive chemistry that allows corrosion to proceed.

Pitting is still an active field of study among metallurgists, but it is definitely linked to mineral inclusions. Sulfur, for example, is often purposely added to stainless steel to make it easier to machine (SAE 303 is one example—avoid it!). Sulfur inclusions, however, when exposed on the surface of the steel, create a break in the chromium oxide layer where pitting can begin.

One final kind of corrosion of real consequence to climbers is stress corrosion cracking. "SCC" is technically more than just corrosion. It's a double-whammy interaction between chemical corrosion and mechanical stress. In the wrong conditions, SCC can rapidly destroy stainless steel climbing hardware.

SCC is a devious, hard-to-predict process with a history of making catastrophic surprise appearances. Beginning in the early 1990s, it has been responsible for an epidemic of climbing-anchor failures at tropical crags worldwide.

If a metal is susceptible—and stainless steel is—several factors must be present for SCC to occur. One is stress within the metal. This is universal in climbing anchors. Mechanical bolts are put under tension when they are tightened. The bolt/hanger metal retains internal stresses from the "cold-working" processes of manufacturing—punching the hole and putting in the bend, for example.

The last necessary ingredient for SCC is an aggressive environment. Here's where prediction gets complicated, because the microenvironments within and around a climbing anchor can become aggressive in many subtle ways. SCC was originally associated with industrial sites such as boilers and desalination plants. High heat, lots of salts. Yet SCC was later found to occur at much lower temperatures—around indoor swimming pools, for example.

SCC is only associated with very high concentrations of chlorides. Unfortunately, both the geology of certain cliffs and the microenvironments within bolt holes can help create the aggressive conditions needed for SCC to occur. It can make the face of a stainless steel bolt hanger look like shattered glass.

The incidents analyzed

If you hadn't guessed already, the incident in Thailand relayed at the beginning of this story was a case of SCC. One of the anchors that broke was a ½-inch stainless steel bolt that had been placed only 18 months before.

This was just one of many stories climber Sam Lightner recalls from the early days—the mid to late 1990s—of chronic anchor failures in the tropical climbing paradise of Thailand. "It was a strange thing," says Lightner. "Some walls seemed OK, and some were eating the steel fast. We now realize it had to do with temperature. The walls that face the sun for a good bit of the day get incredibly hot, increasing the speed of the chemical reaction. Some of the walls that never saw the sun took many years to visibly show the problem."

Climbing-anchor SCC was also later discovered to involve factors that had never been documented by materials specialists. The mechanism was discussed in detail in a 2008 paper by climber and metallurgist Angele Sjong, published in the widely read Journal of Failure Analysis and Prevention.

At that time, Sjong (wife of the well-known climbing athlete and coach Justen Sjong) worked at the renowned engineering consulting firm Exponent, in the California Bay Area. Though she had never been to Thailand, she had heard from climbing friends about the terrible corrosion problems there. When Greg Barnes of the American Safe Climbing Association brought her a broken bolt hanger, she agreed to do a quick analysis.

When Sjong looked at the specimen under the scope, she couldn't believe the severity of the corrosion. "It was a crowded day in the lab," she says, "and I said, 'Hey, check this out!' Everyone was stunned." Exponent is one of the most respected failure-analysis firms in the world, but none of the experts had seen ambient-temperature SCC like this. One senior analyst said, "We should look into this." Sjong launched a literature review and a battery of tests that culminated in the journal paper.

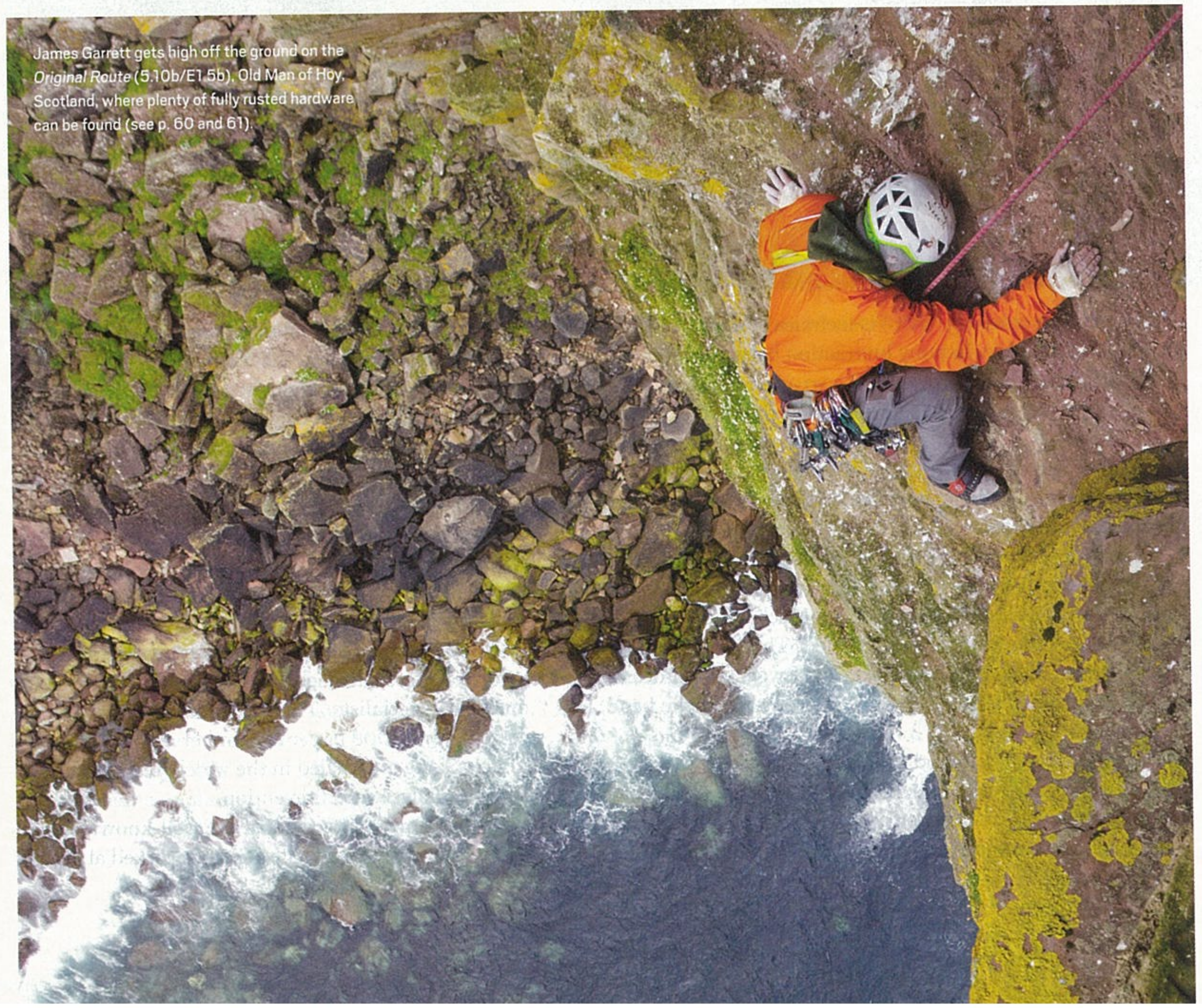
Learn how developers in the tropical climbing paradise of Cayman Brac have worked successfully to overcome anchor corrosion at ***climbing.com/bracwin.***

The incident at Index could be blamed on several factors. From a materials perspective, galvanic corrosion was responsible for the incident: The route featured aluminum hangers on steel bolts, which had been in place for almost 20 years at the time of the incident. Aluminum hangers are still available—Petzl makes some—and are favored for deep cave exploration for their strength and light weight, but aluminum and steel make a very active galvanic couple. With almost 70 inches of rain per year, Index is wet enough to keep the galvanic "battery" going, dissolving enough aluminum near the hanger/bolt attachment point that the hanger sheared off under body weight.

But there is also a social factor. The route was established around 1990, amid the "first generation" of sport-style bolting that swept across the U.S. During those Lycra-clad days, bolting wisdom was all over the map, and with angry trad climbers often ready to chop the routes, the whole concept of bolt longevity was basically off the radar. The equippers were functioning at the normal standard of the day: Routes were equipped with random hardware that was either imported, purchased at the local hardware store, or homemade—sometimes all of the above—and mixed and mismatched.

The human side

An improvisational, skimp-and-save philosophy lingers to this day, and there is still a dangerously lean knowledge base about climbing-anchor longevity. Even among knowledgeable route developers dedicated to "best practices," there is still plenty of disagreement. Is stainless steel necessary in drier environments such as Lander, Wyoming, or Indian Creek, Utah? Coastal climbing areas obviously need corrosion-resistant hardware, but how resistant: Is titanium necessary for non-tropical areas such as Kalymnos, Greece, or Mickey's Beach, California? Open questions, all of them.



James Garrett gets high off the ground on the *Original Route* (5.10b/E1 5b), Old Man of Hoy, Scotland, where plenty of fully rusted hardware can be found (see p. 60 and 61).

In November 2012, the Access Fund held a conference in Red Rock, Nevada, called the Future of Fixed Anchors. One reason was the amount of time and money now going into re-bolting efforts. "The old bolts from the beginning of the sport climbing era are in need of replacement," says Brady Robinson, the AF's Executive Director. "Some people are doing a great job replacing them, and others are, frankly, botching it."

Kenny Parker is chairman of the Anchor Committee for the New River Alliance of Climbers (NRAC) in West Virginia, one of the earliest and most effective anchor-replacement efforts in the country. Yet Parker claims that money and man-hours haven't been the biggest hurdles. "Even more than doing the actual work," says Parker, "the biggest challenge has been pulling together the community around a process and a plan." In other words, consensus.

Parker suggests that the average original sport route in the New River Gorge (annual rainfall about 50 inches) proved to have a life expectancy of about 10 years. In drier areas such as Rifle, Colorado, most routes lasted 10 to 15 years. It's clear that our original attempts to create sport routes in the U.S. also created a massive maintenance problem just a few years down the road.

"In 100 years, I for one don't want every popular route to have five holes at every clip," says Robinson, "evidence of generations of climbers' efforts to upgrade the anchors with the times. We can do better."

Alan Jarvis of the UIAA agrees. "I think that the most important thing here is to establish a specific lifetime for anchors," he says, strongly suggesting 50 years as a baseline. "It doesn't have to be 50 years, but it needs to be specified. Once you agree on a specified working life, then everything else falls into place."

International standards for corrosion resistance

So let's say you're an equipper and buy into the concept that re-bolting a route every 15 or 20 years doesn't cut it. How can you know what hardware to use at your area to get a 50-year lifetime? The UIAA is in the process of rolling out guidelines that will help.

"Let's say you've heard that Bolt A is more corrosion-resistant than Bolt B," says Jarvis. "Is it even true? And do you really need that? Who knows? The UIAA is working to have a classification system based on the corrosion resistance of an anchor."

The specific tests will be some version of standard tests used in other industries. Significantly, only complete anchors—one-piece glue-ins or complete bolt/hanger combinations—will be tested. A bolt or a hanger alone will not be eligible for classification. In a nutshell, here's what the system will look like:

Class 1 anchors will have to endure severe testing conditions and prove themselves extremely resistant to normal corrosion, crevice corrosion, pitting, and stress corrosion cracking. Anchors in this class are what places like Thailand will need. The UIAA safety commission decided on the specific tests for this class during their meeting in Chamonix in June 2013.

Class 2 means moderate to high corrosion resistance. "This is likely what other coastal areas need," says Jarvis, "where there is some risk of SCC, but not as extreme as in tropical areas." It will be interesting to see what tests the UIAA comes up with for this class, and what metals will pass, since, despite its susceptibility to SCC, 316 stainless is widely used for anchor replacement in such areas, and there is significant resistance to upgrading to much more expensive alternatives such as titanium.

Class 3 anchors will have "moderate" corrosion resistance. There will be no tests for SCC. Anchors in this class should be suitable for the bulk of climbing areas that have no special corrosion concerns, and it will be the minimum level of corrosion resistance recommended for outdoor climbing. Since this standard is being generated in Europe, it seems very likely that anchors in this category will have to show corrosion resistance equal to 304, and possibly 316 stainless. If so, this requirement is sure to cause some controversy in the U.S.

Class 4 anchors will have no specified corrosion resistance and be aimed at indoor use.

Manufacturers will not give any specific lifespan warranty after these tests. Rather, it is a tool for consumers. "If one matches the right anchor class with a given climbing environment," says Jarvis, "then a 50-year (or more) lifetime should be achievable."

The future

We are nearing the end of seat-of-the-pants bolting. If the UIAA stays on course, it will soon have standards for climbing anchors that—barring placement errors or mismatches between hardware type and environment—should allow us to choose anchors that will last 50 years. The Access Fund is currently assembling a web page of "best practices" for anchor placement. The question is, how quickly will bolters upgrade their habits?

"Land managers are beginning to move toward telling climbers how to place or replace bolts, and which kinds to use," says Robinson. "If we don't have any consensus in our community and without hard science to back up our actions, how are we going to prevent bureaucrats from dictating bolting practices?"

Historically, cost has been a very important criterion for choosing climbing anchors. That will probably never change. But actually, it doesn't need to. Anchors made from corrosion-resistant metals cost more up front, but if they last three times as long as cheaper anchors, in 50 years the climbing community will have saved money—and a lot of re-bolting effort.

That logic works well for community-funded re-bolting efforts, but not so well for first ascensionists, who, in the U.S. at least, almost always buy bolts with their own money. Spending to ensure 50 years of service can seriously slow down their effort.

"The Access Fund can't just step in and tell people what to do," says Robinson. "The hope is that long-lived bolts, and bolts that can be replaced without drilling new holes, will become more and more common. Great technologies are here or are on the horizon, but it only helps us if people use them."

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