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Secure Connections

Choosing the Wrong Fastener Can Have Catastrophic Consequences

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There are certain circumstances where a standard fastener—properly manufactured, and rated for the design load—can be predicted to have a high probability of failure. It's not that the fastener is defective, but that it is not designed to handle certain situations. There are issues beyond just working loads and fastener strength that need to be considered, issues that may be outside the knowledge of a contractor who is purchasing screws. In these instances, a specialty fastener must be specified, or else the security of the installation is being left to chance.

Case-hardened self-drilling fasteners have gained broad usage in construction over the past 20 years because they are fast and easy to install and, under normal circumstances, are reliable. If, however, the fastener is attaching a door, window, curtain-wall panel, roof system, or piece of heavy equipment, failure is not an option. This article deals with two conditions that endanger the integrity of conventional case-hardened self-drilling fasteners. Metal-to-metal connections—such as attaching aluminum door framing to structural steel, aluminum framing to galvanized steel studs, or attaching steel hardware to

aluminum framing—can create a vulnerability. Extreme loading caused by blast attacks, seismic events or high winds make structural demands that do not behave like conventional loads. Identifying a high-risk situation and selecting appropriate fasteners can mitigate risk and protect both public safety and the project.

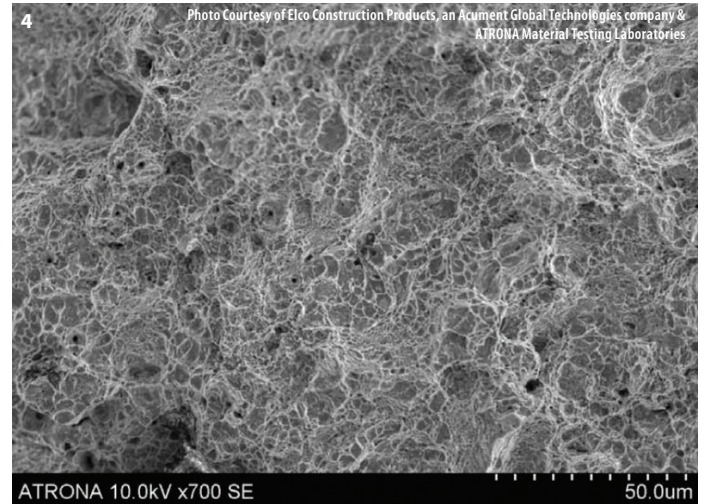
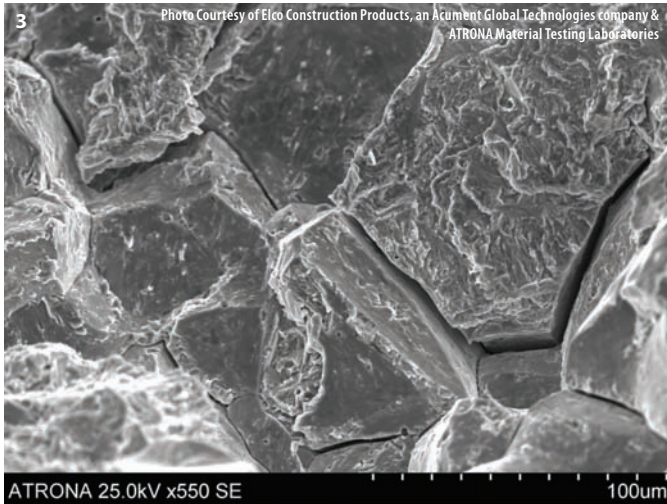
When Metals Attack

Making the right choice of fasteners depends partly on knowing the specific materials to be fastened. There are little-noted electrochemical phenomena at work, often invisibly, that can compromise the integrity of structural connections. Attaching aluminum to aluminum, aluminum to steel, even steel to steel can set the stage for failure of what are otherwise perfectly good fasteners. Loss of one fastener can transfer working loads to adjacent fasteners. Progressive failures can lead to failure of critical components and present a threat to building integrity and life safety.

One culprit in this kind of failure is Hydrogen Assisted Stress Corrosion Cracking (HASCC). The phenomenon can occur without warning and for no apparent reason in standard self-drilling and



1. Made of case-hardened 410 stainless steel, these self-drilling screws were used to attach aluminum to steel. They failed at the place where the screw shank was aligned with the interface between the two metals. Hydrogen generated by galvanic reaction at that interface caused embrittlement of the hardened casing of the screws.



2. A cross-section of a case-hardened screw thread. The wavy line is the hardened steel outer layer of the screw, HRC 52 or greater. The grainy area to the right is the softer, more ductile core, HRC 32-40. Hardened steel has been shown to be vulnerable to embrittlement by hydrogen generated in the service application.

3. Gaping grain boundary. A scanning electron microscope photo of a failed 410 stainless steel fastener shows the gaping grain boundaries associated with hydrogen-assisted stress-corrosion cracking. These dislocations of the metal's crystalline structure cause loss of ductility and tensile strength necessary to carry its design load.

4. Steel in its normal, ductile state displays a much more consistent texture, with no obvious gaps in its structure.

-tapping screws, causing the fastener to “spontaneously” fail. These failures can occur shortly after installation, months, or even years after installation. Screw heads pop off and the materials that they were connecting become separated, leaving the contractor, building owner and other responsible parties puzzling over what caused the failures and what the remedy will cost.

The risk can be minimized if a designer is aware of the conditions that cause HASCC and specifies fasteners that are immune to HASCC attack. These fasteners are manufactured by new metallurgical techniques including selective heat-treatment and fusing together two types of metals.

Catastrophic Failure

Recently, in a government facility in the US, screws installed over 20

years ago were found to be snapping apart for no apparent reason. Forensic investigators noted that the fasteners were standard, hardened steel self-drilling screws that complied with applicable building code requirements and accepted industry manufacturing standards.¹ Further, the fasteners were not visibly corroded, and simply appeared to have broken in half. It was determined that the fasteners had recently been exposed to the weather for a short period of time due to roof wind damage. This exposure may have been the factor that initiated some damaging process, but the direct cause of failure was not obvious.

According to independent metallurgical analysis, the fasteners were weakened by HASCC. Scanning electron micrographs (SEM) revealed distinctive patterns of hydrogen attack in addition to complete ductile failure across the

inner 20% of the fastener that had not yet suffered HASCC.

HASCC attacks hardened steel parts such as self-drilling screws. The screws' drill-point and lead threads act as cutting tools, and therefore must be harder than the metal they are cutting into. Typically, this has been achieved by case-hardening the fastener, a process in which a low-carbon steel part is heated in a high-carbon environment to infuse extra carbon into the outer layers of the part. The result is a fastener with a hard "shell" over a core of softer, more ductile steel. The hardened shell that cuts the hole is brittle. The softer steel core provides strength to bear a load once the fastener is fully driven.

Millions of self-drilling and self-tapping screws are used every year in North America alone. They have become the fastener of choice for erecting curtainwall, and attaching architectural elements such as door or fenestration units that have metal attachment frames. The problem of HASCC in relationship to self-drilling, self-tapping screws has been identified only recently. Two decades of experience with this type of screw have finally provided enough incidents and enough data for the cause of the problem to be identified.

The Hydrogen Threat

HASCC typically occurs in metal-to-metal connections where two dissimilar metals are in contact, and some form of moisture is present. It is actually two different processes—stress corrosion cracking and hydrogen embrittlement—which occur together as a result of an electrochemical process called galvanic reaction. (See sidebar: GALVANIC REACTION & CORROSION)

Stress corrosion cracking (SCC) refers to the tendency of corrosion to be more aggressive at stress points in metal. Some aspects of the phenomenon are still not completely understood, due to the wide variety of environments and applications involved, but it has been definitively observed.

Hydrogen embrittlement is a complete loss of ductility and tensile strength resulting from hydrogen atoms penetrating into steel and disrupting its crystal structure. The hydrogen atom is so small it can diffuse through "solid" metals such as hardened steel. As they move, hydrogen atoms lodge in microscopic voids in the crystal structure of metal. It is believed that lone hydrogen atoms try to join into pairs to form more stable H₂ molecules. The larger H₂ molecules

put pressure on the steel, splitting it open. This is particularly true at stress points in the steel, where the voids are more prominent. Stress both enhances and localizes the natural hydrogen diffusion process. The deformed metal loses tensile strength, becoming brittle and no longer capable of bearing its normal tensile load.

The problem is largely confined to hardened steel; softer steel (maximum Rockwell C34 hardness) is virtually immune. However, the harder the steel, the more vulnerable it is. Self-drilling, self-tapping screws and thread-cutting concrete screws are typically in the range of HRC 52 on the case (surface), and HRC 32-40 in the core, making them prime targets.

Understanding the source of the hydrogen is key to predicting vulnerability. It can sometimes

5. Hydrogen embrittlement concentrates at stress points in metal. This test setup for susceptibility to embrittlement failure induces stress in the test fastener in a way that mimics the type of loading often applied in real-world installations: screws are seldom inserted at perfect right angles, placing uneven stress on the screw head. The test screw is engaged through an aluminum plate, into a steel plate. When the screw is tightened, the steel shim puts the fastener in tension slightly off-axis. The test setup is then exposed to saltwater for a given period.

6. Screws in the actual test setup.

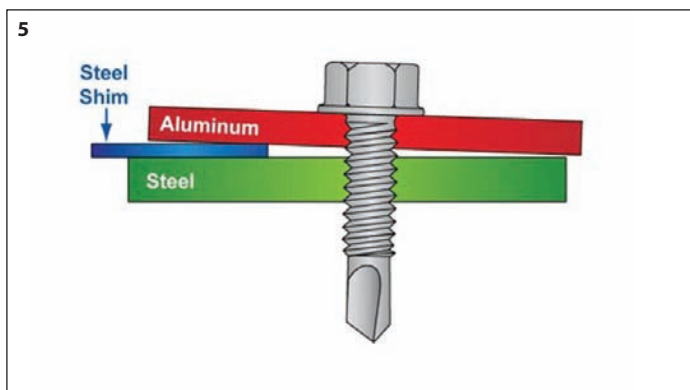


Illustration courtesy of Elco Construction Products, an Acument Global Technologies company



Photo Courtesy of Elco Construction Products, an Acument Global Technologies company

Galvanic Reaction & Corrosion

When two dissimilar metals come into contact in the presence of an electrolyte (a liquid that can conduct electricity), an electrical current flows from one metal to the other. Metals all have a propensity to give up electrons, and this propensity varies from one metal to another. The metal with a greater tendency to give up electrons creates a flow of electrical current towards the other metal. The phenomenon is called galvanic current, named after the 18th century physician and physicist Luigi Galvani, whose pioneering investigations helped unravel the mysteries of electricity. The galvanic relationship of specific metals is well documented in a table known as a galvanic series. This galvanic principle is the basis on which batteries are made.

In construction situations, however, the result is not always benign. When the metal lower in the galvanic series sacrifices electrons (the anode), it is corroded at a rate significantly greater than its natural tendency to corrode. The metal higher in the series, the cathode, is “protected” by the flow, and corrodes significantly slower than normal, or not at all. This process is known as galvanic corrosion.

At the same time, the elements of the electrolyte can be separated, collecting at the anode or the cathode depending on their charge.

Galvanic corrosion weakens the sacrificial metal. In a steel-aluminum connection, aluminum is weakened. Aluminum and zinc are close to each other in the galvanic series, but there is sufficient electro-potential difference between them to initiate corrosion. Because 18-8 stainless steel is high on the series, it is often used for fasteners exposed to corrosive environments.

Ironically, hydrogen that is often a by-product of galvanic reaction attacks hardened steel, the metal that is considered “protected” by the electrical flow in the aforementioned situations.

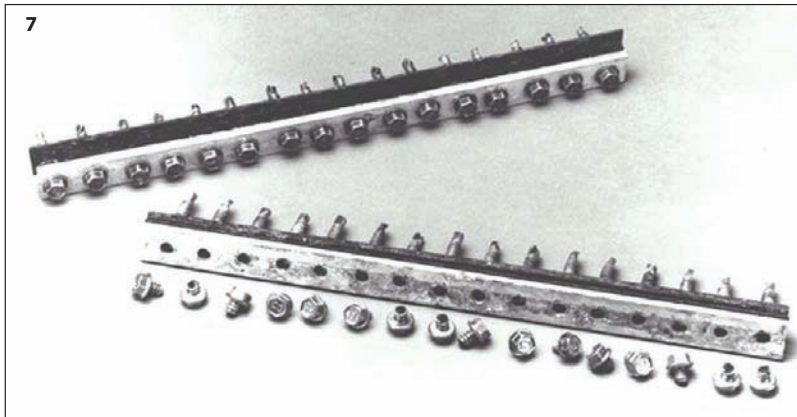


Photo Courtesy of Elco Construction Products, an Acument Global Technologies company



Photo Courtesy of Elco Construction Products, an Acument Global Technologies company

7. After 96 hours of exposure to salt spray, the case-hardened fasteners, in the bottom row, failed. The selectively heat-treated fasteners, in the top row, did not fail.

8. The junction of the screw head and shank is a concentration point for both residual stress from the manufacturing process and application induced stress. Hydrogen atoms invade stress points easily, causing HASCC failures.

enter metal parts during manufacturing processes, but this hydrogen is usually removed and dissipated by a post-baking process. Hydrogen can also be generated in the service environment, after installation, by galvanic reaction. It is this source that can be foreseen and designed for.

Predicting Vulnerability

The most common combination of metals causing galvanic reaction is aluminum and steel. Such a condition occurs, for example, where a door unit has aluminum flanges to attach to the steel structure, or where

a steel fastener is used to join two pieces of aluminum. An electrolyte must be present: it is usually water that has leaked into a structure or moisture that forms due to condensation. If moisture contacts the two metals, galvanic current can flow and cause the water to separate into hydrogen and oxygen molecules. Oxygen collects at the anode—in this case the aluminum. Hydrogen collects at the cathode, the steel, including the hardened steel fastener. (The galvanic corrosive effect can also weaken the aluminum over time, which can cause different problems with the strength of the connection.)

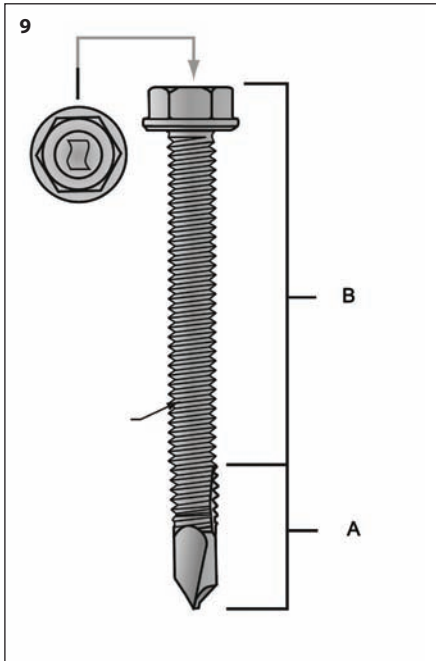


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9. Self-drilling fasteners that are resistant to hydrogen assisted stress corrosion cracking have three zones. Section A has to be hard enough to drill into steel and tap threads while Section B has to be strong and ductile enough to carry the intended load. The third section, the head, is marked with an embossment to allow visual identification of an installed fastener's type.

Galvanic reaction can occur even in steel-to-steel connections if one of the parts is zinc-coated. One of the steel members may be galvanized steel, (steel coated with zinc to prevent rust), or two similar pieces of steel may be connected by a zinc-coated fastener. All that is required is for the two dissimilar metals to be in contact in the presence of an electrolyte.

Under these conditions, hardened steel fasteners are vulnerable to infiltration by hydrogen and subsequent embrittlement at stress points.

Stress and Steel

One of the most common stress-points in a self-drilling screw is its head. This is due to both the manufacturing process and the



Photo Courtesy of Elco Construction Products, an Acument Global Technologies company

10. For applications where high corrosion-resistance is required, such as installations regularly exposed to moisture, a bi-metal fastener is used so that 300 series stainless steel is exposed to the elements.

way in which the screw is typically used. The shape of the screw is made by deforming the metal comprising the head to a diameter as much as 500% wider, causing it to retain residual stress.

Application-induced stress also concentrates at the junction between the screw shank and head. When the screw is driven all the way into the hole, the head is the part that resists further progress, putting it in a constant state of tension.

A third source of stress results from the practical fact that self-drilling screws are rarely installed at a perfect perpendicular to the surface that they bear on. When the screw is driven at a slight diagonal, one edge engages first, placing uneven stress on the head.

Hydrogen generated through galvanic reaction can invade these stress points, embrittling the metal. Micro-cracking appears, creating an attractive site for stress-corrosion. In an element under load, stress corrosion is progressive: the more the cracked site corrodes, the less metal there is to bear the tensile load, the greater the stress build-up at that point.

Failure Mechanisms

HASCC attacks the hard shell of the screw, but a crack need not go all the way through the fastener to cause failure. Corrosion through the hardened outer layer effectively reduces the diameter of steel available to bear the load. When the tensile load exceeds the tensile strength of the diminished cross-section, the fastener fails. In the case noted above, the complete ductile failure of the central 20% of the cross-section indicated that what was left of the fastener core, after the hardened case cracked, simply could not accommodate the working load of the original design. In some instances, fasteners broke at the connection point; at other locations, the screw head simply popped off due to stress concentration.

Preventing Failure

Theoretically, eliminating the electrolyte could prevent problems. If the fastener is completely sealed from any possible moisture contact, corrosion ought to be avoided. However, this is often not a practical possibility. Joint sealants, for example, can fail without notice. In the case of the facility mentioned earlier, the building was stable for



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almost 20 years. Then, investigators surmise, wind damage allowed moisture entry. A year later, the fasteners failed. In other situations, exposure to moisture during construction before a building is enclosed, and even common humidity levels and condensation within a building assembly, have been identified as the source of moisture.

A more reliable solution is to use fasteners that are invulnerable to HASCC. Two methods of fastener manufacture have been developed specifically to resist HASCC.

A fastener can be selectively heat-treated, not case-hardened, so that only the drilling tip and lead threads are hardened. The majority of the shank is softer steel that is

not prone to HASCC. This process uses Grade 5 steel, an alloy that has enough carbon already present to be hardened simply by heating. The tip of the part is passed through an induction coil that heats it and hardens it locally without affecting the rest of the shank.

When a selectively heat-treated fastener is installed, the hardened tip penetrates the anchoring metal and cuts threads in it, but then moves past the connection area as the screw is driven to full depth. The relatively softer steel portion of the shank, which is not vulnerable to HASCC, bears the load. The fastener performs as would a ductile Grade 5 bolt, the same type of bolt used for structural steel connections, assuring a high degree of reliability.

Another type of HASCC-resistant fastener is a bi-metal screw, a high-performance part suitable for applications where greater corrosion-resistance is desirable. In this case, a high-carbon steel is used, but only for the drill point and lead threads. The headed shank is made of 300-series stainless steel (also known as 18-8 stainless steel). The two pieces are friction-welded together. Then, the point and lead threads are selectively hardened by induction heating, similarly to the process of heat-treating a selectively hardened carbon steel fastener.

An additional treatment is applied to some fasteners to enhance their resistance to galvanic reaction. By coating the fastener with a multi-layer, aluminum-filled, cross-linked baked-on polymer, the outer surface of the fastener acquires high aluminum content. This corrosion-resistant finish makes the fastener more compatible with aluminum parts and is less prone to galvanic reaction.



11
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13
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11. Cladding, including glazing units and stone facades, often contain aluminum in the framework that attaches the unit to the building's steel superstructure. This contact of aluminum and steel sets up the risk of galvanic reactions that generate hydrogen and precipitate hydrogen assisted stress corrosion cracking. To preserve the integrity of the cladding's attachment to the building, fasteners that resist hydrogen embrittlement are recommended.

12. Screws resistant to HASCC are available in a wide variety of configurations for applications that include self-drilling and self-tapping in structural steel or in concrete.

13. The 88-story Petronas Towers in Kuala Lumpur, Malaysia in 1998. The façade contains literally millions of 300 series self-drilling fasteners with multi-layer zinc rich and aluminum-filled coating, chosen to prevent embrittlement from galvanic reaction between steel and aluminum and to mitigate the potential for sacrificial loss of aluminum in the cladding frame system.



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Expecting the Unexpected

Extreme loading is a condition where loads far in excess of the normal design load are temporarily applied to a structure, sometimes only for a few milliseconds. The source of the extreme load might be a blast shockwave, an earthquake, or a hurricane-driven gust of wind.


In places where the occurrence of an extreme load can be predicted, it must be designed for. Seismically active regions and locales subject to frequent hurricanes or tornadoes are well identified. In recent years, buildings that can be considered likely targets for attack, or are adjacent to likely targets, are also receiving special design consideration.

Current design strategy for extreme loading is to make the building absorb the load by deforming but remaining stable long enough to allow evacuation and the preservation of life safety. For threats such as blast shockwave or wind impact, the designer typically seeks to transfer load from the vertical elements of the building shell to the building framework, often using the horizontal floor diaphragms to spread the load over more of the structure. This means it is vital for the elements of the building envelope to stay in place and the fasteners that attach them to transfer load to the frame without failing.

Extreme loads are often impulsive in nature, that is, they hit like a hammer, applying the full force virtually instantly rather than gradually. This impulsive load can make materials perform in an atypical fashion. It can fracture a brittle material, such as the outer shell of a hardened steel fastener.

As noted above, when the hardened outer case of a fastener cracks, the load on the fastener must be born by the narrower ductile inner core. If a significant percentage of the fastener's cross-section is disabled, there is effectively a smaller fastener left to bear the load.

A fastener that is not case-hardened, such as bi-metallic or selectively-hardened fasteners, has full ductility through the entire cross-section of the shank where the fastener bears its load. Under extreme loading, it is far more likely to deform but remain in service, as compared to a more brittle part.

When designing for extreme loading, it is important to have a realistic design-threat as the baseline for determining loads. Expert consultants may be useful. Consideration of connections that must transfer load in this situation should include ductile specialty fasteners that can handle impulsive loading more effectively. 

FOOTNOTES

1. Society of Automotive Engineers SAE J78—Steel Self-Drilling Tapping Screws.

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