



INNOVATIONS FOR LIVING™

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Composites and the Future of Society:  
**PREVENTING a LEGACY of  
COSTLY CORROSION** with  
**MODERN MATERIALS**

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## EXECUTIVE SUMMARY

Corroding infrastructure is costing developed nations trillions of dollars annually in repair and replacement costs. Common examples include ruptured water and sewer pipe, and collapsing bridges. Also failing prematurely are oil pipelines and equipment in industrial facilities. A recent estimate of the worldwide direct cost of corrosion – for prevention as well as repair and replacement – exceeded \$1.8 trillion (1.4 trillion euro; 12.2 trillion Yuan), or 3 to 4 percent of the Gross Domestic Product (GDP) of industrialized countries.<sup>1</sup>

New material solutions such as fiberglass-reinforced polymer composites have been developed since much of the current corroding infrastructure was installed. An estimated 25 to 30 percent of the annual cost of corrosion can now be avoided if optimum corrosion management practices are employed.<sup>2</sup>

A study of corrosion in China in 2001 estimated the annual cost at 498 billion Yuan (US\$ 61 billion).<sup>3</sup> China's GDP that year was 9.6 trillion Yuan.<sup>4</sup> That put China's cost of corrosion even higher than the industrialized nations at 5.2 percent of GDP.

If present construction practices are continued, in 17 years when China is expected to have the world's largest economy, the country's annual cost of corrosion could be more than \$1 trillion (6.8 trillion Yuan).<sup>5</sup> By employing optimum corrosion management practices including greater use of composites, China's annual savings could then be as much as \$347 billion (2.4 trillion Yuan).

Rapidly developing nations such as China must avoid repeating the costly repair and replacement cycle of industrialized nations by adopting these advanced materials and construction methods.



<sup>1</sup>Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control by Gunter Schmitt, May 2009, The World Corrosion Organization

<sup>2</sup>Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control by Gunter Schmitt, May 2009, The World Corrosion Organization

<sup>3</sup>Chinese Industry Corrosion Status and Market Development, presentation by En-Hou Han, Institute of Metal Research, Chinese Academy of Sciences

<sup>4</sup>PeopleDaily.com

<sup>5</sup>The Long-Term Outlook for the BRICs and N-11 Post Crisis, Jim O'Neill and Anna Stupnyska, Goldman Sachs, Dec. 4, 2009



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## Defining Corrosion

Corrosion is a term used to describe the deterioration of a material as it reacts with its environment. In everyday language applied to metals, the process is known as “rusting.”

Corrosion is a natural process that occurs because materials such as refined metals want to return to a more stable compound. During corrosion, an engineered material actually disintegrates into its constituent atoms as a result of chemical reactions with its surrounding environment. Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area, more or less uniformly corroding the surface.

Electrochemical oxidation of metal occurs in reaction with oxygen in the presence of water or air moisture. Formation of an oxide of iron (rust) is a result of electrochemical corrosion. Other forms of corrosion include the reaction of iron and chlorine in an environment deprived of oxygen, such as on metal rebar used in underwater concrete pillars.

Given sufficient time, oxygen and water, any iron mass eventually converts entirely to rust and disintegrates. Surface rust provides no protection to the underlying iron.

## Environments Conducive to Corrosion

There are many environments that are especially hostile and conducive to corrosion including fog and humidity, saltwater and alkaline or acidic soils. Nations with a large land mass typically have a variety of these conditions.

The response of carbon steel to soil corrosion depends on the nature of the soil and other factors such as the availability to moisture and oxygen. Soils with high moisture content, high electrical conductivity, high acidity and high dissolved salts will be most corrosive.

Corrosive conditions also know no national boundaries. Acid rain generated in one country pollutes the environment and causes corrosion damage far beyond that country’s borders – even beyond the borders of its neighbors.

Unfortunately, these conditions exist in much of the world today, including China. The People’s Republic of China is so large that its atmosphere ranges from the extremes of very hot to very cold, and from desert dry to sticky humid. Acid rain is also a significant factor.

Soil conditions in China vary widely from acidic to alkaline, and there are large coastal areas where salt is found in the ground. Water properties range from saline to seawater and freshwater.<sup>6</sup>



<sup>6</sup>Chinese Industry Corrosion Status and Market Development, presentation by En-Hou Han, Institute of Metal Research, Chinese Academy of Sciences



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The following map shows the relative severity of corrosive conditions in China.

- Extremely Severe
- Severe
- Moderate
- Mild
- Negligible



Source: Corrosion, Vol. 55, No. 1, page 66

## The Cost of Corrosion

Corrosion has a huge economic and environmental impact on virtually all facets of the world's infrastructure, from highways, bridges and buildings, to oil and gas, chemical processing, and water and wastewater systems.

A comprehensive study of corrosion in the U.S., published in 2002, estimated the annual cost of corrosion at \$276 billion. The annual cost of corrosion in the U.S. today has been estimated at more than \$300 billion. Similar costs have been estimated by studies conducted in the United Kingdom, Germany and Japan.<sup>7</sup>

The 2009 cost of corrosion in water/wastewater systems alone in the U.S. was estimated to exceed \$50 billion.<sup>8</sup> An earlier study estimated the average annual corrosion-related cost in the U.S. for natural gas, crude oil and hazardous liquids transmission pipelines at \$7.0 billion, which the study divided into the cost of capital (38 percent), operation and maintenance (52 percent), and failures (10 percent).<sup>9</sup>

In the Persian Gulf region, where the sea is salty and much of the soil has high saline content, the cost of corrosion was estimated in 2006 to be \$10-15 billion per year.<sup>10</sup>

In China, a study estimated the annual cost of corrosion in 2001 at 498 billion Yuan (US\$ 61 billion).<sup>11</sup> China's GDP that year was 9.6 trillion Yuan.<sup>12</sup> That put China's cost of corrosion even higher than the industrialized nations at 5.2 percent of GDP.

If present construction practices are continued, in 17 years when China is expected to have the world's largest economy, the country's annual cost of corrosion could be more than \$1 trillion (6.8 trillion Yuan).

The good news is that an estimated 25 to 30 percent of the annual cost of corrosion can be avoided if optimum corrosion management practices are employed.<sup>13</sup>

<sup>7</sup> G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Payer, "Corrosion Costs and Preventive Strategies in the United States," FHWA-RD-01-156, U.S. Department of Transportation, Federal Highway Administration (2002)

<sup>8</sup> Nace Corrosion 2010 Wrap-Up report, www.nace.org

<sup>9</sup> CorrosionCost.com

<sup>10</sup> Bahrain Society of Engineers president Mohammed Khalil Al Sayed, opening ceremony of the 11th Middle East Corrosion Conference, Feb. 2006

<sup>11</sup> Chinese Industry Corrosion Status and Market Development, presentation by En-Hou Han, Institute of Metal Research, Chinese Academy of Sciences

<sup>12</sup> PeopleDaily.com

<sup>13</sup> Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control by Gunter Schmitt, May 2009, The World Corrosion Organization



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By employing optimum corrosion management practices including greater use of composites, China's annual savings could then be as much as \$347 billion (2.4 trillion Yuan).

Rapidly developing nations such as China must avoid repeating the costly repair and replacement cycle of industrialized nations by adopting advanced materials and construction methods.

## Composites and the Fight against Corrosion

There are many ways to fight corrosion including the use of costly metals and coatings, surface treatments and other special procedures to protect structural material. In many situations, a better solution can be achieved by using modern composite materials. This report focuses on the broad range of composite materials called fiberglass-reinforced polymer (FRP).

FRP composites are safe and reliable solutions, able to face corrosive conditions in various types of environments and have outperformed traditional materials for many years.

Composites offer:

- High strength
- Light weight
- Durability
- Cost savings

Markets making extensive use of FRP composites include:

- Chemical
- Petroleum & Mining
- Power & Energy
- Marine
- Water & Sewage
- Industrial



Courtesy NOV Fiber Glass Systems

With more than 50 years of field experience, FRP is now proven technology. Tanks and pipe constructed with corrosion-resistant composites have consistently provided extended service life over those made with metals. And FRP is now regularly used to replace expensive stainless steel and high-nickel alloys.

FRP composites consist of engineered polymer resin and fiber reinforcement – about 95 percent of composites are reinforced with glass fiber – and can be enhanced with additives and core materials. The combination can produce some of the strongest materials for their weight ever developed.

FRP composites gain their strength from glass fibers set within a resin matrix. The fibers carry the load while the resin spreads the load imposed on the composite and both impact corrosion resistance. A wide variety of properties can be achieved by selecting an appropriate combination of glass and resin.

Pound for pound, glass fibers are stronger than steel. That is because glass fibers have a high specific strength. Specific strength is a term that relates strength to weight.

To understand this concept, compare a ¼-inch diameter steel rod to a ¼-inch diameter fiberglass composite rod. The steel rod will have higher tensile and compressive strength, but will also weigh more. If the fiberglass rod is increased in diameter to the same weight as the steel rod, it will be stronger!<sup>14</sup>

<sup>14</sup> Composites Industry Overview, ACMA Web site



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How long do composites last? The answer to that question is not known because there are many examples where composites have lasted more than 50 years and are still in service. Several of the original composite applications have not yet come to the end of their useful lives.

There are examples of boats, buildings and other composite structures built in the 1950s that are still in service. For example, the bodies of the original 1953 Chevrolet Corvette sports car are FRP and still structurally sound. There are also case histories of FRP ductwork being in service in chemical plants for over 25 years, operating in harsh chemical environments 24 hours a day, seven days a week.<sup>15</sup>

For more examples of composites used in the fight against corrosion, see Appendix B, *Examples of Composites Winning the Fight against Corrosion*.

## Developments in the Fight against Corrosion

- **E-CR glass** – The corrosion resistance of glass fibers is determined by their chemical structure and E-CR glass was manufactured specifically to resist acid and alkali exposure.



E-CR glass fibers are boron-free fibers with a modified structure to enhance their long term acid and short term alkali resistance. Their electrical and mechanical properties are similar to E-glass but they perform significantly better in most corrosive environments.

Owens Corning developed E-CR glass in the 1980s to provide significantly improved resistance to the corrosive effects of a range of environments. That benefit was confirmed with field use data comparing the acid resistance of E-CR glass to that of traditional E-glass indicating that E-CR glass provides significantly improved resistance to the corrosive effects of acidic environments.

E-CR glass fiber also has significant environmental benefits because it is made in a boron-free process that minimizes air pollutants at the source – in the manufacturing process – yet it offers the same recycling opportunities available with traditional E-glass.

In the late 1990s, Owens Corning introduced a new glass composition that offers the unique attributes of being both a boron-free E-glass, and a corrosion-resistant E-CR glass reinforcement in accordance with ASTM D578, ISO 20789, and DIN 1259-01. Trademarked Advantex® glass, the patented product offers superior performance in composites facing corrosive environments when compared to E glass.

For more about Advantex® glass fiber reinforcements, see Appendix C.

- **AR Glass Fiber for Concrete** – Special alkali-resistant (AR) glass fibers have been developed for use in concrete. These fibers are manufactured with Zirconia content in compliance with ASTM C1666/0 1666/M-07 and EN 15455.

AR glass fibers have been in use for 40 years in more than 100 countries worldwide to create some of the world's most stunning architecture while offering strong and durable performance in widely varying cement- and mortar-based applications, including new and restored building facades, industrial flooring, tunnel lining and utility poles.

<sup>15</sup> Composites Industry Overview, ACMA Web site



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AR glass fibers are unique as a concrete reinforcement. Glass fibers have the same specific gravity as the stone or gravel mixed in concrete so fiber dispersion of the reinforcement is easier to achieve than with other fibers. AR fiber contributes efficiently to tensile strength before concrete is able to crack, thanks its high elastic modulus and its affinity for and efficient bonding with concrete. AR glass fiber reinforcements can reduce the weight and thickness of concrete by a factor of 10.

AR glass fibers from Owens Corning are marketed as Cem-FIL® glass fiber.

- **New Resins** – Several resin manufacturers today offer a variety of new resins that offer superior corrosion resistance compared to general-purpose resins and have other performance advantages that are useful in the fabrication of corrosion-resistant products.

Polymer matrix resins fall into two categories: thermoset and thermoplastic. The difference is in their chemistry. Thermoset resin is comprised of molecular chains that crosslink during the cure reaction (set off by heat, catalyst or both) and “set” into a final rigid form. Molecular chains in thermoplastic resin are processed at higher temperatures and remain capable of being reheated and reshaped.

With their track record of performance, thermosets have become the matrix of choice in continuously reinforced glass fiber composites. Especially popular are unsaturated polyester resins, which are relatively inexpensive, easy to handle and have good mechanical, electrical and chemical resistance properties.

Adding glycol, acid, reactive monomers (commonly styrene) and other materials during forming can enhance polyester’s properties for specific applications. For example, additives and fillers are used to make polyester resin more chemical or corrosion-resistant, fire retardant, shrink-resistant and thermally stable.

Vinyl esters cost more than polyesters but are used in many of the same applications. Their performance surpasses polyesters in chemically corrosive environments (such as filament wound chemical tanks) and structural laminates requiring high moisture resistance.

Another popular thermoset resin is epoxy, which is used in structural and electronic applications. While epoxies are generally more expensive than polyesters, they have less shrinkage and higher strength/stiffness at moderate temperatures. They are also corrosion-resistant to solvents, alkalis, and some acids. Epoxy resins can be used in most composite manufacturing processes.

- **Design changes** – The most significant composite design change in the fight against corrosion is the shift to using E-CR glass throughout a laminate.

When E-CR glass fibers were first introduced, the reinforcements were more expensive than standard E-glass and composite designers often used them only in a resin-rich layer on the side of the laminate that would be exposed to acidic conditions. As E-CR glass fibers became more widely available and a better understanding of how acids can reach the interior of laminates, designers began specifying E-CR glass throughout the composite, from the corrosion barrier through the structural portion.

With current trends to more and larger applications in corrosive environments, and the cost of failure much higher, the performance of the true E-CR glass is becoming essential.

Composites have long been known for excellent durability compared to standard steel and aluminum but there is now a proliferation of applications where special corrosion resistant properties are required. Examples include flue-gas desulphurization equipment, underground water and sewage pipe, desalination plants and a variety of saltwater marine applications including tidal energy installations.



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Flue-gas desulphurization equipment costs millions of dollars and is expected to run continuously to protect the environment. The cost of failure can be very high so fabricators are using state-of-the-art material systems throughout their products to assure reliable, long-term performance.

The role of the fiber reinforcement in corrosion-resistant applications is also becoming better known. Composite designers understand that resin is the first line of defense against corrosion in a laminate. And while surface resin does provide the initial barrier, certain acids, alkalis and other destabilizing liquids and gases are able to penetrate the skin of a laminate.

Micro-cracking can occur when large composite parts are delivered and installed. For example, there can be an impact when a large heavy storage tank is set in place on a concrete pad. There can be other "hits" when large applications are moved from the fabrication site to the installation location, such as when a bulldozer picks up pipe using chains and puts the pipe in place, or lifts it off a truck bed and puts it in a storage area.

A handbook published in 2008, edited by Dr. Rod Martin and titled *Ageing of Composites*,<sup>16</sup> explains and quantifies how composites age in service conditions. The handbook says the chemical reaction between the glass and the solution depends on the composition of the glass. "It is well recognized that the higher the SiO<sub>2</sub> (silica) content of the glass, the better its chemical resistance in acidic media."

Advantex® glass fiber reinforcements from Owens Corning are made with a batch formulation that contains silica in an amount consistent with corrosion-resistant E-CR glass.

Using E-CR glass throughout a composite laminate makes sense considering the fact that 60 to 75 percent of a laminate by weight can be glass fibers, and the fibers are providing the structural strength in the application.

Using E-CR glass throughout a laminate being made for a corrosive environment is also consistent with ISO 2078, which indicates that E-glass is a general purpose reinforcement and E-CR glass is for use in acid environments.<sup>17</sup>

- **Process improvements** – While materials and application designs evolved and improved, the processes used to make composites were also benefiting from years of experience and new technology such as computer control.

Sophisticated process controls now cut and shape fiberglass fabrics to optimize the value of the reinforcement in the end-use application.

Resin injection, vacuum infusion and other recently developed impregnation processes have greatly improved part consistency, reduced the potential for resin voids, and reduced waste and emissions. Process automation has improved productivity and part-to-part consistency. All of these developments have made composites an attractive option in the fight against corrosion.



Courtesy Strongwell

<sup>16</sup> Published by Woodhead Publishing Ltd., [www.woodheadpublishing.com](http://www.woodheadpublishing.com)

<sup>17</sup> International Standard ISO 2078, Fifth Edition, 1993-02-01



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## Conclusion

The cost of corrosion in the developed world today is substantial. Without using new materials and fabrication processes to resist corrosion, rapidly developing countries such as China are destined to follow the same path as the developed world and face substantial costs in the future for repair and replacement, and resource waste.

In 2010, real infrastructure industry growth in China is expected to be 25 percent, reaching CNY 1.1 trillion (US\$168.5 billion). Infrastructure industry value is forecast to reach CNY 1.8 trillion (US\$ 310 billion) by 2014, with average annual real growth at 13 percent.<sup>18</sup>

It is imperative that these infrastructure funds be invested carefully and that projects use modern, corrosion-resistant materials so China can avoid creating another a costly legacy of repair and replacement.

“ *Rapidly developing nations can avoid repeating the costly infrastructure repair and replacement cycle of industrialized nations by adopting advanced materials and construction methods, including composites.* ”



Courtesy Strongwell

<sup>18</sup> China Infrastructure Report Q3 2010, Business Monitor International, May 2010



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## Appendix A

### Market Impact of Corrosion

Corrosion has a huge economic and environmental impact on virtually all facets of the world's infrastructure, from highways, bridges and buildings, to oil and gas, chemical processing, and water and wastewater systems. In addition to causing severe damage and threats to public safety, corrosion disrupts operations and requires extensive repair and replacement of failed assets.

Following are some of the markets most affected by corrosion.

#### Water and Sewer Pipe

In many countries, the cost of water and wastewater system failures is far greater than any other single sector of the economy.<sup>19</sup>

The largest category of corrosion cost in the U.S. is infrastructure for drinking water and sewer systems, accounting for 26 percent of the total.<sup>20</sup>

A significant water line bursts on average every two minutes somewhere in the U.S.<sup>21</sup> In Washington, D.C., alone a pipe breaks every day, on average.<sup>22</sup>

The total annual direct cost of corrosion for the nation's drinking water and sewer systems has been estimated at \$36.0 billion (2001).<sup>23</sup>

Century-old pipe in many cities around the world mean more than 10 percent of the water is lost to leakage.<sup>24</sup>

A European study found that 30 percent of the drinking water that leaves the waterworks may not reach the consumer because of corroded and broken water mains.<sup>25</sup>

Johannesburg Water sets aside 250 million Rand (233 million Yuan; \$34.2 million) per year for repairs and maintenance of its water and sewer networks.<sup>26</sup>

The city of Toronto is reportedly faced with 1,200 to 1,500 breaks in the aging water distribution system per year, and spending C\$12 million per year to deal with such breaks.<sup>27</sup>

Significant increases in the water bills of UK customers have been projected in view of reported upgrades to aging piping systems over the next five years (at cost estimates of £21 billion).<sup>28</sup>

<sup>19</sup> *Now is the Time*, George F. Hays, PE, director general, World Corrosion Organization

<sup>20</sup> *Corrosion Costs And Preventive Strategies In The United States*, report by CC Technologies Laboratories, Inc. to Federal Highway Administration (FHWA), Office of Infrastructure Research and Development, Report FHWA-RD-01-156, September 2001

<sup>21</sup> *New York Times analysis of Environmental Protection Agency data*

<sup>22</sup> *New York Times analysis of Environmental Protection Agency data*

<sup>23</sup> *Cost of Corrosion Study Unveiled*, NACE International, undated

<sup>24</sup> *National Geographic*, special issue on water, April 2010

<sup>25</sup> *Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control* by Gunter Schmitt, May 2009, The World Corrosion Organization

<sup>26</sup> *Open letter of Johannesburg Water (Communications and Marketing Dept.) to Sunday Times newspaper*, February 11, 2002

<sup>27</sup> *Toronto Star*, GTA Section, January 25, 2005, p. B3

<sup>28</sup> *Weekly Telegraph*, North American Edition, Issue 632, September 3-9, 2003



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## Oil and Gas Pipe

According to the Alberta Energy and Utilities Board (AEUB), corrosion is the leading cause of oil pipeline failures.<sup>29</sup> The Board, which oversees about 385,000 kilometers of high pressure oil and gas pipelines, says there are typically about 750 failures annually.

In a study conducted in 2006, 53 percent of the failures were due to internal corrosion. The next most common cause of failure was external corrosion at 12 percent.

In the United States, the total annual direct cost of corrosion on natural gas distribution systems alone is estimated at \$5-6 billion.<sup>30</sup>

## Chemical Tanks and Factories

Corrosion is one of the leading causes of storage tank and piping failures. There are 8.5 million tanks in the U.S. The annual cost of corrosion on storage tanks and piping is estimated to be \$7 billion.<sup>31</sup>

## Marine environments

Sea water, by virtue of its chloride content, is a most efficient electrolyte. The omni-presence of oxygen in marine atmospheres, sea sprays and splash zones at the water-line, and sometimes surprisingly at much greater depths, increases the aggressiveness of salt attack.

Uncontrolled corrosion of reinforcing steel and pre-stressing strands in marine structures can decrease the life expectancy of a structure to a fraction of its design life. Structures in direct contact with coastal waters experience corrosion activity around the tidal splash zone areas.

Atmospheric corrosion of metals exposed on or near coastlines, and hot salt corrosion in engines operating at sea or taking in salt-laden air, can be equally troublesome.

Many corrosion-resistant metals rely on an oxide film to provide protection against corrosion. If the film is loose, powdery, easily damaged and not self-repairing, such as rust on steel, then corrosion will continue unchecked. And even the most stable oxides may be attacked when aggressive concentrations of hydrochloric acid are formed in chloride environments.

A study published by the American Concrete Institute in 2007 reported that fiber-reinforced polymer (FRP) is effective in mitigating corrosion in a marine environment.<sup>32</sup> Researchers found that the measured metal loss in wrapped specimens was significantly lower than that in identical unwrapped controls exposed to the same environment. They concluded that if columns or piles were wrapped at the time of installation, their performance would be vastly superior because the FRP would serve as a barrier to the ingress of chloride and significantly delay the onset of corrosion.

"Despite higher material costs, (columns wrapped with) FRP may be more economical if they result in a reduction in re-repairs that is often the reality for corrosion repair."<sup>33</sup>

<sup>29</sup> Alberta Energy & Utilities Board, April 2006\

<sup>30</sup> Pipeline and Gas Journal

<sup>31</sup> The Impact of Corrosion on Storage Tanks and Piping, presentation by Gerry Koch, CC Technologies at the NACE Freshwater Spills Symposium, April 2004

<sup>32</sup> Effectiveness of Fiber-Reinforced Polymer in Reducing Corrosion in Marine Environment, Kwangsuk Suh, Gray Mullins, Rajan Sen and Danny Winters, ACI Structural Journal, Feb. 2007

<sup>33</sup> Effectiveness of Fiber-Reinforced Polymer in Reducing Corrosion in Marine Environment, Kwangsuk Suh, Gray Mullins, Rajan Sen and Danny Winters, ACI Structural Journal, Feb. 2007



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## Bridges

In the United States, the cost of corrosion related to bridges amounts to about \$8.3 billion per year.<sup>34</sup>

There were an estimated 583,000 bridges in the U.S. in 1998, mostly constructed with steel, reinforced concrete and pre-stressed concrete. Approximately 15 percent of those bridges were considered structurally deficient, primarily due to corrosion of steel and steel reinforcement.

Rust is one of the most common causes of bridge failure. Iron oxide or rust has a much higher volume than the original iron so its build-up can force apart adjacent components. That was the cause of a bridge collapse in the United States in 1983 when bearings rusted internally and pushed the road slab off its support.

Rust was found to be an important factor in another disaster in the U.S. in 1967 when a steel suspension bridge collapsed in less than a minute. In a third example in the U.S., a bridge was blown down by a tornado in 2003 largely because the bolts holding the structure to the ground had rusted away, leaving the bridge resting by gravity alone.

Similarly, corrosion of concrete-covered steel and iron can cause concrete to spall, creating severe structural problems. Corrosion-induced spalling is one of the most common failure modes of reinforced concrete bridges.<sup>35</sup>



## Pollution Control

Corrosion resistant FRP is used extensively in air pollution control systems for NO<sub>x</sub> and SO<sub>2</sub> reduction.

Over the next decade, owners of coal-fired power plants around the globe are expected to spend more than \$200 billion to add flue gas desulphurization (FGD) systems to existing and new combustion units. Most of this investment is expected to be in the US and China. Nonetheless, many emerging industrial nations, such as India and South Africa, are also investing heavily in air pollution control technologies.

<sup>34</sup> Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control by Gunter Schmitt, May 2009, The World Corrosion Organization



<sup>35</sup> Wikipedia, Corrosion



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## Appendix B

### Examples of Composites Winning the Fight against Corrosion

- Strongwell, a world-leading pultruder of fiber reinforced structural composites, recently reported that its DURADEK®<sup>36</sup> composite grating continues to perform well after more than 30 years in service on an oil platform in the Pacific Ocean off the coast of southern California in the United States. Nearly 10,000 square feet of the grating was installed in 1979. In 2010, the facility superintendent said, “The grating looks to be in great shape. The surface shows very little wear and tear.”<sup>37</sup>
- In 2008, Strongwell reported that its SAFRAIL™ square tube industrial handrail continues to perform well after more than 12 years of service in a coal preparation facility in Galatia, Illinois, United States. The coal preparation facility turned to composites because the plant’s environment results in significant deterioration of carbon steel within two years and stainless steel in less than six. When Strongwell visited the facility 12 years after installation of their composite handrails, there had not been a single corrosion-related problem and the metal structures and components around the fiberglass railing and platforms were failing.<sup>38</sup>  


*Courtesy Strongwell*
- An article presented at the International Conference and Exhibition on Reinforced Plastics (ICERP) in Mumbai, India in 2008, said inspections of FRP pipe at three power plants after more than 22 years of service indicate that the FRP pipe is still in excellent condition. In one project a 16.3 ft (5 m) diameter pipe was installed in Florida to discharge hot water from a power plant. The other projects are in New York State where pipe delivers water to power stations through 10 ft and 12 ft (3 m and 3.6 m) diameter penstocks.<sup>39</sup>
- Western Fiberglass Pipe Sales Ltd., Red Deer Alberta, has reported oil field pipe still in service after 40 years in the ground in Canada. The majority of the earliest FRP pipe installations are in southeastern Saskatchewan. The company also said it has replaced steel lines that have been in the ground as little as six or eight months due to corrosion.<sup>40</sup>
- In 2005, the University of Sherbrooke, Sherbrooke, Quebec, Canada, reported results of a field service study of five glass fiber-reinforced concrete bridges located from Nova Scotia in the country’s eastern Maritimes to British Columbia on the west coast. After eight years of service, researchers found that the “components of the reinforcements (fibres, resin and interface) did not show any significant changes. “The resin and the glass fibres did not show any sign of deterioration, such as microcracking or corrosion.”<sup>41</sup>

<sup>36</sup> DURADEK is a registered trademark of Strongwell

<sup>37</sup> PROFILE: Strongwell News and Applications, Summer 2010

<sup>38</sup> PROFILE: Strongwell News and Applications, Special Edition 2008

<sup>39</sup> FRP Pipe Meets Power Plant Requirements, by Ben Bogner and Bruce Curry of AOC LLC, presented at the International Conference and Exhibition on Reinforced Plastics (ICERP), Mumbai, India, February 2008

<sup>40</sup> Interview with Owens Corning, 2004

<sup>41</sup> University of Sherbrooke GFRP Durability Study Report, Brahim Benmokrane and Patrice Cousin, April 2005



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- Traditional wood products are also switching to composites to extend their useful lives. One example is cooling towers for power plants. Cooling towers have traditionally been constructed with metal and wood. But with wood supplies getting tight and expensive, designers are turning to other materials. Reinforced plastics offer a good substitute because they are strong, moisture resistant and long lasting.



Courtesy Strongwell

- Power distribution and lighting poles have long been made with wood, but that situation is changing now that engineered poles made with fiberglass-reinforced polymer or concrete are showing they can outlast wooden poles and offer other important performance benefits in safety, cost and ease of use. The share of market for alternative materials is now approaching 40 percent and expected to continue growing rapidly in the next five to 10 years.<sup>42</sup>
- In 1947, the U.S. Coast Guard built a series of 40-foot patrol boats using polyester resin and glass fiber. The boats were used until the early 1970s when they were taken out of service because their design was outdated. Testing was done on the laminates after decommissioning and it was found that only 2 to 3 percent of the original strength was lost after 25 years of service.

<sup>42</sup> A New Generation Lighting & Distribution Pole, William T. Gay, Composite Materials Technology LLC, and Peter H. Mokhiber, CMT Worldwide



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## Appendix C

### Advantex® E-CR Glass Fiber Reinforcements

Advantex® glass fiber reinforcements from Owens Corning were introduced in 1997 as the solution to a wide range of customer needs. The benefits include a common technology platform that is being implemented across Owens Corning product lines and around the globe. It provides customers with a uniform basis for glass fiber specification offering the same products anywhere in the world.

Owens Corning Advantex® glass was formulated to be a boron-free E glass and to possess significantly improved resistance to the corrosive effects of a range of environments. Advantex® glass is both an E-CR glass and an E-glass, in accordance with ASTM D578, ISO 20789, and DIN 1259-01.

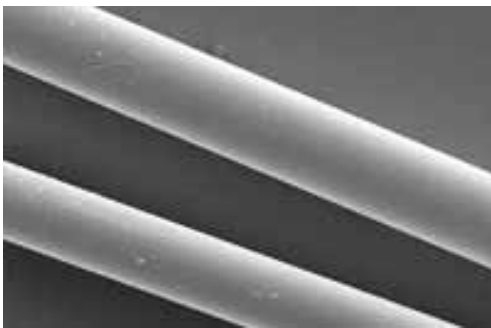
When it was introduced, Advantex® glass was expected to provide superior corrosion resistance in acidic environments. That benefit was confirmed with field use data comparing the acid resistance of Advantex® glass to that of traditional E glass indicating that Advantex® glass provides significantly improved resistance to the corrosive effects of acidic environments.

Field experience also showed that the product performs well in any aqueous environment, including water and alkaline solutions. Advantex® glass products also have a higher softening-point temperature than traditional E-glass – an advantage for some applications.

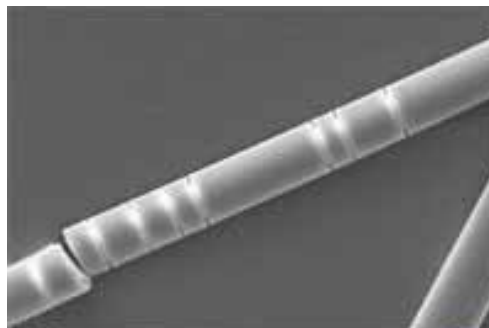
Advantex® glass fiber also has significant environmental benefits. The product is made in a boron-free process that reduces boron mining and minimizes air pollutants at the source – in the manufacturing process – yet it offers the same recycling opportunities available with traditional E-glass.

Owens Corning has tested composite rods in a 5 percent salt water solution under stress and had results indicating that composite made with Advantex glass have a projected lifetime in excess of 50 years, compared to only a few months under the same harsh conditions for composites made with traditional E glass. Stress-corrosion tests in hydrochloric acid were even more dramatic with the Advantex glass composite samples still expected to last more than 50 years and the E glass composite rods having an expected lifetime of only four days.

Following are microscopic views of what happens when Advantex® glass and E glass are subjected to four hours in five percent Hydrochloric acid at 95° C.



Advantex® glass



E-glass

For more about Advantex glass fibers, visit: [www.owenscorning.com/composites/aboutAdvantex.asp](http://www.owenscorning.com/composites/aboutAdvantex.asp)



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## Appendix D

### An Inside Look at Corrosion in Laminates

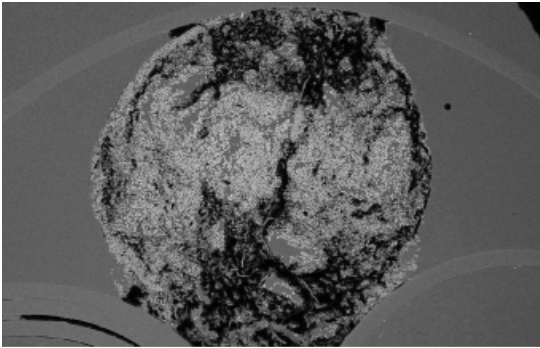
In another recent study at the Owens Corning Science and Technology Center in Granville, Ohio, U.S., researchers confirmed that boron-free Advantex® E-CR glass fibers demonstrate superior corrosion resistance compared to E glass when used in composite structures exposed to sulfuric acid.<sup>43</sup>

Most composite materials intended for corrosion resistant applications are designed to protect the structural fibers within the architecture of the part. This study focused on what happens if corrosive materials gain access to the structural portion of a laminate.

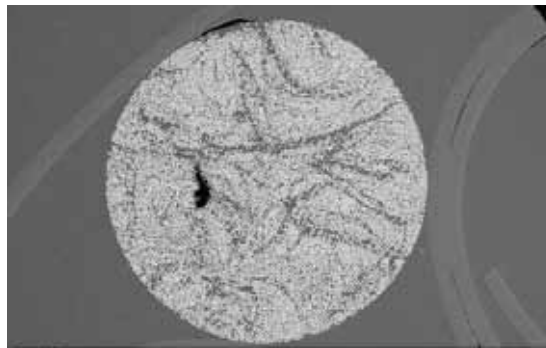
The study combined both corrosion and stress testing to predict the relative performance of E-glass compared to Advantex® glass under these dual conditions. The study showed the mechanism by which corrosion occurs over time in stressed laminates using both SEM (Scanning Electron Microscopy) and EDX (Energy Dispersive X-ray) spectrometry.

The study examined the corrosion of glass fiber-reinforced composite rods that were exposed to a ~1% strain for a brief period of time and then immersed in a 10 percent sulfuric acid solution under no-load and room temperature for an extended period of time. After regular intervals the rods were removed and examined for the effects of corrosion.

The photos below show E-glass and Advantex® glass composite rods after six month exposure in 10 percent sulfuric acid.



*E-glass rod, six months 10% H<sub>2</sub>SO<sub>4</sub>*



*Advantex® rod, six months 10% H<sub>2</sub>SO<sub>4</sub>*

The E-glass sample shows gray fibers along the entire perimeter of the rod and considerable damage on the left-hand side of the photo. Deformation of the rod has occurred as the E-glass deteriorates.

While the mechanism for the corrosion of E-glass had been inferred through previous leaching studies, this study showed E-glass deterioration visually and the mechanism by which it occurs. Corrosion testing composite laminates after they have been stressed provides a compelling reason for using Advantex® E CR glass reinforcement throughout a structure.

<sup>43</sup> An Inside Look at Corrosion in Composite Laminates, by Kevin Spoo and Marie Kalinowski, Owens Corning, April 2010



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