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High Strength Steel Wire for use in Cable Stayed Bridges

Due to the "rapid development of new production," structural steel is creating stronger, and safer construction (Fangxin 2014). The advancements of high-strength steel wires have allowed for cable-stayed bridges to gain recent popularity. Typically, these bridges are composed of a deck, weight-bearing pylon erections, and high strength steel "fundamental elements" (Chacar 2001). Due to this design's "optimum use of structural materials" and "low maintenance costs," cable-stayed bridges will rise in demand (Sarhang 2012).

Steel has an interesting science because of its diverse composition. Generally, steel is composed of many different alloys, or "controlled quantities of carefully selected impurities," which are added to enhance properties (Domone 2010). Carbon is an essential alloying element, as it increases hardness, tensile strength and hardenability. Chromium can improve corrosion resistance, while nickel can improve ductility. Alloys such as sulfur and silicon can cause create undesirable properties of brittleness and cracking.

Because of this mixed nature, high-strength steel follows a "packed," "repeating, three-dimensional" crystalline pattern (Domone 2010). This simple structure is a result of non-directional bonds, and has a changing atomic structure. At room temperature, steel forms in a body-centered cubic structure while this structure changes to face-centered cubic at extremely high temperatures. These varying forms, or allotropes, are "of fundamental importance to the metallurgic practice" (Domone 2010). High-strength steel can experience high values of stress with little values of strain (Domone 2010). When compared with regular steel, high-strength steel cables can have a "about five times higher" yield stress values (Chacar 2001).

With many types of steel, the processes involved in making high-strength steel require "careful control to ensure the demanding specifications" (Hobson 2008). As the most popular method, hot rolling begins by casting liquid steel into blooms. These semi-finished products can then be cast to billets, which are reheated, rolled, and cooled. Steel is drawn into wires to meet desired dimensions and specifications. This cooling portion is significant to the final properties of the steel, as it begins to produce a pearlitic microstructure. A fine pearlitic microstructure is "essential" in order for the steel to develop proper ductility and strength values (Hobson 2008).

Sometimes, additional heat treatment can be used to "achieve the required mechanical properties" (Domone 2010). Different types of heat treatment processes are applied to create types such as normalized, normalized-rolled, thermomechanially rolled, quenched, and tempered. Product variation occur because of various temperatures, rolling methods, and cooling techniques. Resources are being invested into new methods, with the aim of increasing manufacturing productivity, reducing environmental impacts.

To handle the brittle nature of high-strength steel, quenching and re-tempering is used. Steel is cooled through a quenching flash process, improving material hardness and strength. However, this increased strength occurs at the expense of a brittle microstructure. To combat this undesirable structure, the steel is then reheated through a reheating process, creating a more soft, ductile metal. Another way to improve torsional ductility includes immersing drawn wires into salt baths. These salt baths improve ductility by allowing for “carbon atoms to cluster and grow,” which increases the spherical shape of the pearlite created during cooling (Hobson 2008).

With recent manufacturing advancements, a few of the common cable types includes parallel-bar, parallel-wire, stranded, and locked-coil strand. Parallel bar cables, following ASTM A722 classification, are the most popular design for high-strength steel cables (Weserman 1994). The design follows a hexagonal format, where bundles of high tensile strength strands are assembled with fillers such as wax or grout. This classification can have ultimate tensile stress values of 670 MPa and a Young’s Modulus of 165,000 MPa (DiBernardo 1998). Parallel wire cables, following ASTM A421, are composed of 7 mm wires, and commonly vary in arrangement from 20 to 500 wires (Weserman 1994). Typically, parallel wire cables are arranged in hexagonal shapes, which provide strength through uniform tension. This rigid nature prevents twisting in cables, an occurrence that can dramatically decrease material stiffness and strength. This cable can have ultimate tensile stress values of 1,860 MPa and a Young’s Modulus of 190,000 MPa (DiBernardo 1998).

Stranded cables use pre-stressed strands instead of the popular 7mm wire used in parallel wire cables. This cable classification can have ultimate tensile stress values of 1,600 MPa and a Young’s Modulus of 200,000 MPa (DiBernardo 1998). Unlike previous arrangements, locked-coil strand cables following ASTM A586 benefit from a twisting pattern (Weserman 1994). These cables tend to be coiled in nature, with different layers following helical patterns. This design benefits from a higher modulus of elasticity, and better corrosion resistance due to the close arrangement nature. This classification can have ultimate tensile stress values near 1,500 MPa and a Young’s Modulus of near 170,000 MPa (DiBernardo 1998).

As the “main source of nonlinearity,” cables can create stress relaxation problems (Sarhang 2012). Sag and tension are two analyzed properties, as cable-stayed bridges are often frequented to constant impact loading and large stress changes. Fatigue failure can be “sudden and brittle” and can “occur after many years of satisfactory service” (Domone 2010). To combat sudden failure, research has studied aerodynamics as it relates to structural flexibility, moving towards “lightweight structures with high material stresses” (DiBernardo 1998). Galvanizing methods have been known to increase elongation to fracture and rotational ductility. Other ways of reducing stress relaxation in cables may relate to the design of the actual cable stayed-bridge. It is important to consider the “optimum distribution of post-tensioning cable forces,” when determining the efficiency of designs (Sarhang 2012).

Cable-stayed bridges are composed of harp, fan, or semi-fan arrangements. A harp design includes cables that are nearly parallel through various point attachments. However, this appealing design is inefficient for long bridge spans. Fan designs include stay cables attached to a single point on the top of each pylon. As the most popular design, semi-fan includes cables that are more steeply arranged on the upper portion of the pylon.

When comparing the different styles, research indicates that semi-fan styles have the “least post-tensioning cable forces,” while the harp arrangements have the “most post-tensioning forces” (Sarhang 2012). While increasing the number of stay cables reduces “post-tensioning cable forces,” this design should be monitored “due to the limited space to accommodate more cables at the top of the pylon” (Chacar 2001). It is possible that cable fatigue may be a result of other factors such as “corrosion, wind excitation,” and “any external factors effecting the cables” (DiBernardo 1998). Alternative materials, such as carbon reinforced plastic (CFRP), has been known to be a superior way to handle creep and relaxation.

Corrosion, or the “deterioration of a material by reaction to its environment” can have significant impacts (Chacar 2001). Since bridges are often above water, aqueous corrosion, or the “electrical transfer of charges between the cable and the environment” must be considered (Chacar 2001). To protect against this degradation, various design and protection techniques can be used. Such alterations include the use of large wires, which avoids surface corrosion vulnerabilities. Designing steel with high values of chromium, nickel, and molybdenum creates a stainless-steel grade 316, which offers strong corrosion resistance, visual aesthetics, and low maintenance. Protection techniques, such as grouting, coating, galvanizing, and fretting, enhance isolation by preventing electrolyte current flow. If corrosion is present, magnetic flux testing is often used as a detection method.

The Nipigon River Bridge failed on January 10th, 2016 where it “heaved nearly 60 centimeters into the air” (Walters 2017). Review of this failure sited issues such as bolt failure, improper bearing attachments and cable shortenings. To correct the bridge, a permanent retrofit design accounted for vertical bar placement and longitudinal and rotational cable movement. The Millennium Pedestrian Bridge in London, England experienced similar swaying issues upon its opening on June 10th, 2000. Almost immediately, this cable-stayed bridge wobbled and swayed as “thousands of pedestrians streamed over it” (Strogatz 2005). Within a few days, the bridge failed due to the low cable stiffness and deck damping. As repair, viscous dampers were placed “between the cables and the decks at the piers” and cable tensions were increased (Dallard 2001).

As the first cable-stayed bridge in Minnesota, the Martin Olav Sabo Bridge experienced failure in 2012 just 5 years after opening. This failure resulted from the disconnection of two cables, due to cable vortex shedding and vibrations from wind. Options such as increased fasteners, complete cable connections, and proper cable diaphragm plates were explored to correct this failure. The Sunshine Skyway Bridge, located over the Tampa Bay, experienced similar integrity issues due to design choices. The original cantilever bridge was easily cracked due to insufficient support when a 600-foot cargo ship struck the bridge. This failure resulted in a bridge remodeling that used a sleeker, stiffer, more appropriate cable-stayed design.

Examining past failures allows for engineers, designers, and laborers to understand how to create long-lasting structures. Improving integrity, increasing wire strength, designing against stress relaxation, and avoiding corrosion are all useful tactics in improving cable-stayed bridges. Understanding information surrounding material structure, manufacturing processes, cable organization, and mechanical properties ensures the research and development of the influential high-strength steel.

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