Lessons Learned in the Design and Use of Stainless Steel as an Alternate to Carbon Steel Bolts and Tie Rods

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Abstract

Flanged and mechanical coupled joints are often a necessary component of water transmission pipelines. These joints utilize threaded materials, or fasteners, in the form of bolts, studs and harness rods which must be designed for a number of stresses. Threaded carbon steel is commonly used as a fastening material but in a buried application can be prone to corrosion even with protective coatings. Stainless steel fasteners are sometimes used in lieu of carbon steel with the expectation that stainless steel is inherently less susceptible to corrosion. Nevertheless, stainless steel bolts and tie rods can still corrode under certain conditions. Furthermore, stainless steel fasteners generally have less strength than carbon steel. This can become problematic when specified for applications such as flanges and harness rods because the general design framework of common American Water Works Association (AWWA) standards and design manuals assumes the strength of carbon steel.

This paper compares the relative merits of carbon and stainless steel material when used in threaded form for bolts, studs, and harness rods to connect carbon steel water pipe components. Corrosion aspects of both carbon and stainless steel are considered as are strength differences between the two materials and how it relates to design. Examples are provided to illustrate the potential conflicts that can result when stainless steel fasteners are incorporated into an AWWA design framework.

INTRODUCTON

Thrust is a common condition of pipeline design. Thrust results when internal hydrostatic pressure reacts laterally against the pipe wall at places such as elbows, laterals, and tees. Thrust also occurs where flow is stopped at bulk heads and closed valves. In most conventional pipe design, hoop stress due to internal pressure is generally greater than axial stress; thus the pipe cylinder wall thickness usually will be sufficient to handle any thrust condition if properly designed for internal pressure.

Where pipe sections connect together, the transmission of thrust across the joint must be considered. Welded joints in steel pipe have significant strength to carry tension loads, and in a typical buried pipeline, bell and spigot lap joints utilizing a single filet field weld are usually sufficient to restrain the thrust being transmitted along the pipe wall.

However, non-welded, gasketed joints are often a necessary component of pipeline design. These include bolted sleeve-type couplings (often called mechanical couplings) and flanged ends which utilize threaded materials in the form of bolts, studs and harness rods. Because these joint systems are mechanically fastened in lieu of welded, a number of stresses, such as bolting, bending and shear, need to be considered. As it relates to thrust, however, the ability of the fastener to carry tension is the primary design concern. In general, the combined cross sectional area of the fasteners must have sufficient strength to withstand the lateral thrust being exerted between the adjoining pipe sections. To this end, the diameter, number and strength of the bolts or harness rods are all design variables that should be considered.

In practice, flange drilling patterns for waterworks service have been standardized since the 1940s and remain the basis of *AWWA Standard C207 Steel Pipe Flanges for Waterworks Service, Sizes 4 In. Through 144 In. (2013).* The number and diameter of bolts for each nominal flange diameter and pressure class have been essentially set for decades. Harness design for bolted sleeve-type couplings also underwent some standardization starting in the 1960s with the first edition of *AWWA Manual M11 Steel Pipe—A Guide for Design and Installation (1964)*. The current 2004 edition of AWWA M11, Chapter 13, Table 3-5, provides the number and diameter of harness rods needed to restrain mechanical couplings from nominal diameters 6 inch to 96 inch in 50 psi increments up to 250 psi. Both AWWA C207 and AWWA Manual M11 call out the use of bolting material conforming to *American Society for Testing Materials (ASTM) A193, Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications* (2015). AWWA C207 and AWWA M11 specifically reference Grade B7 bolts which are derived from carbon-based steel with some alloying elements. More importantly, the inherent strength of carbon steel Grade B7 bolts is assumed in AWWA C207 and AWWA M11.

While generally used intermittently in longer pipeline applications, buried flanges and harnessed mechanical couplings do present a challenge from the stand point of corrosion control. Bare carbon steel will often corrode when placed in contact with soil so a coating system is generally desirable. While the back face of a flange or the harness ring and middle section of a mechanical coupling can be provided with a high quality, factory-applied coating, the associated tie rods, bolts and nuts have a variety of sharp angles and irregular surfaces which can be challenging to coat after installation. A number of products exist to coat threaded materials in the field after joint assembly. These include hand-applied polyethylene tape in accordance with *AWWA Standard C209 Cold Applied Tape Coatings for Steel Water Pipe, Special*

Sections, Connections and Fittings (2013) and wax-based tape in accordance with *AWWA Standard C217 Petrolatum and Petroleum Wax Tape Coatings for the Exterior Connections and Fittings for Steel Water Pipelines* (2009). Brush-applied bithumastic based material can also be used.

The degree to which carbon steel fasteners can be adequately protected from soil-induced corrosion with field coating materials remains a concern of many designers. As an alternate, stainless steel fasteners, which are also included under ASTM A193, are sometimes specified in lieu of carbon steel. However, this approach is not without issue. First, stainless steel is not immune from corrosion, particularly in the type of buried environment associated with flanges and harnessed mechanical couplings. Second, the underlying designs of both AWWA C207 and AWWA M11 assume the yield and tensile strength of carbon steel; commonly available stainless steel rods can have significantly less design strength than carbon steel. The 2013 revision of AWWA C207 went so far as to say *"(d)ue to potential corrosion issues and differences in material strengths between stainless and carbon steel, stainless-steel fasteners are not covered."* Thus, project specifications that require design be in accordance with AWWA C207 and AWWA M11 while also requiring stainless steel fasteners can be problematic. The inherent design safety that is assumed under AWWA C207 and AWWA M11 carbon steel fasteners may be compromised with the use of stainless steel unless additional measures are taken by the designer.

CORROSION PROPERTIES AND LIMITATIONS OF STAINLESS STEEL

Stainless steel is a broad group of iron-based alloys containing at least 10.5 percent or more chromium to provide its basic corrosion resistance. Alloying elements such as nickel, manganese, molybdenum, and sulfur are also commonly included to control a variety of other characteristics such as strength and machinability. Dozens of stainless steels are commercially available but series types 304 and 316, consisting of 18 percent chromium and 8 percent nickel, are probably the most widely specified for water service applications. AWWA has published standards covering stainless steel pipe and flanges as well.

Electrochemical corrosion. Almost all structural metals have the potential to electrochemically corrode. Electrochemical corrosion involves both a chemical reaction and flow of an electrical current, and, as discussed by AWWA M11, there are many mechanisms under which electrochemical corrosion can be induced. In simplest terms, two dissimilar metals in contact with each other and placed in an electrolyte will produce an electrical current between them, provided there is a return path to complete the circuit. At the location on a metal surface where the current discharges, the metal will chemically react with the electrolyte producing a corrosion byproduct.

The strength of the current is determined by the relative separation of the two metals in terms of their galvanic potential. There are many widely published tables of the galvanic series including AWWA M11, Table 10-1. In general, metals that are low on the galvanic series are considered active (or anodic) and more prone to corrosion; metals high on galvanic scale are considered noble (or cathodic) and less prone to corrosion. In a galvanic corrosion cell created by the proximity of two dissimilar metals in an electrolyte, the more active metal will act as the anode and corrode as it discharges electrical current, while the more noble metal will act as the cathode and be protected as it collects electrical current to complete the circuit.

Coatings and cathodic protection. Bonded coatings, such as *AWWA Standard C222 Polyurethane Coatings for Interior and Exterior of Steel Water Pipe and Fittings* (2008) or *AWWA Standard C210 Liquid-Epoxy Coating Systems for Interior and Exterior of Steel Water Pipelines* (2007), are highly efficient and serve to electrically insulate the underlying carbon steel surface from any surrounding electrolyte. This greatly reduces the overall anodic properties of the carbon steel. Nevertheless, highly localized current discharge is still possible at small pinholes and discontinuities in the coating thereby producing corrosion. Cathodic project systems serve to mitigate this by directing any current discharge to designed anodic points. The inclusion of sacrificial anodes such as zinc or magnesium is one such common cathodic protection measure for coated carbon steel pipeline systems.

While flanges and harness rings can be adequately coated in the factory and shipped to the jobsite holiday-free, installation may still result in inadvertent coating damage. Coating in the bolt holes can be relatively thin and prone to damage; edges around the bolt holes can be easily chipped as well. Stainless steel is considered highly noble to most other structural metals including carbon steel. Thus, stainless steel fasteners should act as a cathode and be protected in any galvanic reaction with the adjoining carbon steel flange or harness ring exposed surface. What this scenario overlooks, however, is the effect a bonded coating has on the carbon steel components. If damage happens, the relatively small area of exposed carbon steel becomes anodic which acts to protect the much larger cathodic surface area of the stainless steel fastener. While possibly mitigated by a cathodic projection system, this relative disparity in surface area has the potential to induce highly aggressive and concentrated corrosion of the exposed carbon steel in contact or near proximity to the stainless steel fastener

Stainless steel corrosion resistance. The corrosion resistance of stainless steel largely results from passivation, whereby a durable film of chromium oxide forms on the surface of the stainless steel. The chromium oxide barrier, which is as thin as only a few molecules, prevents the transmission of oxygen molecules to the stainless steel surface which, in turn, could readily react with the iron in the metallic grain structure of the alloy. Carbon steel also readily forms an outer layer of oxidation which in some circumstances can serve to protect against further corrosion. However, the oxidation that forms on carbon steel is not generally durable and can readily flake away leaving the surface more vulnerable to attack.

While stainless steel is generally thought to self-passivate when in adequate contact with oxygen, contaminates embedded into the surface can be extremely detrimental. At the spot where the passivation layer is prevented from forming (for example, due to a shard of carbon steel pressed into the surface from formation rolls), the area becomes anodic. In turn, the anodic spot can react with the surrounding passivated surface, which remains cathodic, creating a potential corrosion cell. Thus most types of processed stainless steel, including bolts, will undergo a cleaning process, sometimes referred to a "pickling and passivation," to assure the protective chromium oxide barrier forms. True pickling and passivation involves washing the stainless steel into a solution of nitric acid to remove solvents and contaminates and to make the surface more reactive to oxygen. Other washing processes, which may not involve acid, are now also commonly used.

Stainless steel bolts and rods are durable and do not require any exceptional precautions in terms of routine handling and installation. In working with stainless steel components, good practice is to avoid deep scratches, keep the material clean, and minimize direct contact with carbon steel. The action of bolting up stainless steel is not considered detrimental to the passivation; standard threading tolerances are not close enough between the flaying surfaces to remove the chromium oxide or prevent its reformation if necessary. However, over torquing or applying excessive force to the bolt to draw two components together has been observed to cause damage. Also, the use of even moderately damaged threads can produce enough sheer in the bolting action to impinge the bolt and nut together; without a separating layer of passivation, the bolt and nut can seize together, sometimes referred to as cold welding. In turn, this could prevent the disassembly of the bolt if needed in the future. Similarly, passivation also can be damaged by sand and grit in the threads.

STRENGTH CHARACTERISTIC OF STAINLESS STEEL VS. CARBON STEEL FASTENERS

Steel is a form of refined iron with carbon providing it principle strength and hardness. Elements such as manganese, phosphorus and sulfur are also included to achieve, or control, other specific characteristics such as the ability to form, machine or weld. Along with its chemical composition, how the steel is transformed into its shape can determine other strength properties. Strain hardening by cold drawing round bar stock under tension and reducing its cross sectional area is a common practice for strengthening bolt materials. Inducing heat and then controlling the cooling process can also significantly modify the strength characteristics of the steel.

Comparative strengths. Two properties are generally considered as a measure of steel strength. Yield strength is the amount of force needed to achieve permanent deformation; tensile strength is the amount of force needed to physically separate a specimen under tension. Elongation is another common value and measures how far a prepared specimen can physically stretch between its initial yield point and ultimate tensile break. Because stainless steel includes a significant displacement of iron with chromium and nickel, stainless steels as a whole will not characteristically have the same yield and tensile strength as carbon steels. A comparison of commonly specified fastener materials is provided in Table 1:

Table 1: Strength Property Comparison, Carbon Steel and Stainless Steel Bolts

ASTM A193 Bolt Material	Tensile Strength Minimum, ksi	Yield Strength Minimum, ksi	Elongation Minimum , %
B7, Carbon Steel	125	105	16
B8 & B8M, Stainless Steel	75	30	30
Class 2 B8, Strain Hardened Stainless Steel	110	95	15

FLANGE CONNECTIONS USING STAINLESS STEEL VS. CARBON STEEL FASTENERS

The implication of strength differences between carbon steel and stainless steel fasteners can be significant if not fully taken into account when designing flanged connections and harnessing for restrained mechanical couplings. For non-strain hardened, tensile strength of stainless steel is only 60 percent of carbon steel; yield strength is only 28 percent. Even for strain-hardened stainless steel, tensile strength is 88 percent of carbon steel; yield strength is 90 percent.

Flange design. Flange joints are a gasket and bolt system. In simplest terms, the flanges must have sufficient strength to transfer thrust and other stresses from the pipe shell across two perpendicular mating surfaces fastened together. The cross sectional area of the bolts must have sufficient strength to carry any thrust load across the joint. If the two sides of the flange joint are not uniformly supported, bending and sheer stress may also have to be carried by the fasteners. In some situations, thrust resulting from thermal expansion and contraction also may have to be accommodated. Obviously, flange connections also rely on a gasket for water tightness. The bolts must provide enough compressive force, or seating stress, to create a reaction between the gasket and flange faces to create a durable seal. Even if the flange joint is not carrying any thrust, the fasteners will be under significant tension to provide sufficient seating stress.

AWWA C207 does not provide a specific design for flanges but AWWA M11 Chapter 12 does discuss flange installation procedures as it relates to torque values and resultant bolt loading. The empirical record strongly supports the performance of AWWA C207 flanges, and there are also reasonable underlying studies of flange design confirming the practices of the AWWA C207 standard. By necessity, the water industry has settled on basic flange dimensions, which date to the 1940s with historical precedents extending even further. Standard flange dimension with bolt circle diameter, number of bolts and bolt diameter are provided for nominal pipe diameters in range from 4 to 144 inch under Tables 2 and 3 of AWWA C207. The current AWWA C207 standard covers only flat face, plate-type flanges as these are the most widely used in the water industry.

AWWA C207 designates flanges by working pressure class and includes a standard allowance for transient conditions. Table 1 of AWWA C207 allows for three types of gasket materials with the allowable gasket type dictated by the pressure class of the flange and the working pressure of the pipe. Red rubber gaskets have seating stress requirement of 200 psi and are limited to pipe working pressure up to 150 psi for 24 inch and larger diameter. Compressed fiber gaskets and polytetrafluoroethylene-based gaskets have a significantly higher seating stress of 4,800 psi and are reserved for working pressures greater than 150 psi for diameters larger than 24 inch.

Flange bolts. AWWA C207 covers only the use of bolts conforming to ASTM A193 Grade B7 which is a carbon steel alloy. AWWA M11 Chapter 12 Tables 1 and 2, which provide torque requirements for flange bolts and studs, are also based on carbon steel. Given that AWWA C207 prescribes gasket type, number of bolts and bolt diameter for a given nominal pipe diameter operating under stated working and transient pressure limits, the designer has a high degree of assurance the AWWA C207 flange joint will safely function within its intended application. Nevertheless, it is not uncommon to find project specifications which state flanged joints shall be in accordance with AWWA C207 but then also include a requirement that the flange bolts be stainless steel. This is problematic for several reasons--and it is not simple matter of semantics as sometimes argued. The strength of ASTM A193Grade B7 bolts are integral to conformance to AWWA C207--as much so as the dimensional requirements of the flange or number and diameter of bolts required.

Flange bolt strength implications. When generically specified, type 304 stainless steel bolts are somewhat of a broad category under ASTM A193. The least expensive bolts from 304 stainless steel material are A193 B8. Sometimes bolts produced from type 316 stainless steel, designated as B8M, are acceptable as they have the same strength properties as B8. As noted above in Table 1, the yield and tensile strength properties of B8 and B8M bolts are significantly less than B7 carbon steel. There is also a notable difference in strength in stainless steel bolts when going to the strain-hardened Class 2.

For low pressure flanges, the use of lesser-strength stainless steel fasteners may not be significant as the combined cross sectional area of the bolts will provide adequate strength for the thrust condition. It is relatively simple to calculate the amount of thrust at the flange joint, which for example could be generated by a closed valve, and dividing by the number of bolts to determine the amount of stress carried by each bolt. In terms of yield and tensile strength, the safety factor afforded by carbon steel B7 bolts is clearly significant and may still be considered ample for stainless steel bolts at lower pressure applications. However, as pressure class increases, the safety factor with stainless steel bolts is demonstrably less, particularly with B8 and B8M bolts.

Thrust loading is not the only consideration when substituting stainless steel bolts for carbon steel. The gasket seating stress requirement is much greater with higher pressure class flanges. This in turn affects torque values; stainless steel bolts must use a much higher percentage of yield strength to achieve gasket seating. Under certain conditions, stainless steel bolts may be overstressed in order to get the gasket to seat. The possible effects of bending, sheer, thermal expansion and simple poor field installation can also be concerns with a flanged joint; using stainless steel bolts of lesser strength will certainly diminish the inherent safety factors built into AWWA C207 for these conditions. Relying on the greater strength provided by Class 2 B8 stainless steel bolts (which are stain-hardened) in lieu of Class 1 has its own limitations, including material availability in larger-sized fasteners.As a whole Class 2 B8 bolts still have less ductility than the B7 bolts assumed under AWWA C207. This adds another element of uncertainty as to how stainless steel bolts will perform under extreme stress events.

CARBON STEEL VS. STAINLESS STEEL TIE RODS FOR RESTRAINED COUPLINGS

Bolted sleeve-type and split sleeve couplings, or mechanical coupled joints, have many applications in water pipe design and are covered by *AWWA Standard C219 Bolted Sleeve-type Couplings for Plain End Pipe* and *AWWA Standard C227 Bolted Split-Sleeve Restrained and Nonrestrained Couplings for Plain-End Pipe.* As a gasketed joint, mechanical couplings can accommodate minor axial movement, generally 3/8 inch or less by AWWA C219 Standard, and also can be angularly deflected. One common application of mechanical couplings is to use them in series such that pipe differential settlement can be accommodated at wall structure penetrations. Bolted sleeve-type and split sleeve couplings also can be used to join two pipes of differing outside diameters together.

Bolted sleeve-type couplings function by tightly compressing two gaskets against adjoining plain pipe ends by use of follower rings drawn together against a middle ring. Split sleeve couplings function by compressing a gasket in the coupling gasket groove against the pipe wall. While the gasket compression is suitable for providing water tightness under pressure conditions, the coupling has minimal ability to transmit thrust. Thus, mechanical couplings are generally restrained by means of a harness system. In order to transfer thrust from the pipe cylinder across the mechanical coupling, two plate rings are typically shop-attached near each pipe end and stiffened with perpendicular gusset plates. Bolted rods are then connected through the rings to carry the axial load. Figure 1 shows a pair of harnessed mechanical couplings outside a structure to accommodate potential differential settlement. Tie rods may also be necessary for other types of gasketed connections such as a dismantling joint used next to a valve as illustrated by Figure 2.

Figure 1: Paired Harnessed Mechanical Couplings at Structure

Figure 2: Dismantling Joint Restrained with Tie Rods Connected Through Adjoining Flanges.

Tie rod design. AWWA M11 Tables 13-5, 15-5a and Figure 13-20 provides the basic design for joint harnesses and is based on the diameter and number of rods deemed suitable to transmit the thrust across the joint. AWWA M11 Table 13-4 provides tie rod sizes and counts for pipe diameters ranging from 6 to 96 inch and working pressures up to 250 psi. These standardized tables have origins dating to the 1960s with the earliest versions of AWWA M11.

Per AWWA M11 Chapter 13, the rods are assumed as A193 Grade B7 or equal which is a carbon steel alloy. The maximum allowable bolt stress is limited to 40,000 psi. AWWA M11 does not specify whether this stress is based on a percentage of yield strength or a percentage of tensile strength of the bolt. However, these values can be readily back calculated from AWWA M11 Table 13-4. In general, about 1/3 of tensile strength and 40 percent of yield strength is utilized with A193 Grade B7 bolts.

Project specifications will sometimes state that joint harnessing shall be in accordance with AWWA M11 but then also require stainless steel tie rods in lieu of A193 Grade B7. Unlike AWWA C207 flanges, some leeway exists to modify AWWA M11 harness design either by increasing the number of stainless steel rods or the rod diameter. Nevertheless, there is no clear guideline as to what meets the intent of AWWA M11 harness design when using stainless steel tie rods.

Basing the allowable design stress on the tensile strength there is a notable increase in the number of stainless steel rods necessary to restrain a mechanical coupled joint. Table 2 provides a comparison between carbon steel B7 and stainless steel B8M tie rods assuming a factored tensile strength for the allowable design stress for 150 design pressure restraint across a range of common pipe diameters:

Table 2: Design Comparison B7 and B8M Tie Rods at 150 psi Design Working Pressure

Pipe OD (in)	Tie Bolt Diameter (in)	B7 Tie Rods	B8M Tie Rods	Difference B7 vs B8M
24	7/8	4	6	2
36	1-1/4	4	8	4
48	1 – 5/8	4	8	4
96	1-7/8	12	18	6

Important to note in this example, at their intended design pressure of 150 psi, the stainless steel B8M tie rods are stressed to approximately 1/3 tensile strength but 84 percent of yield. By comparison, the carbon steel B7 tie rods are stressed to approximately 1/3 tensile strength and only 38 percent of yield. Because of the high utilization of yield strength with stainless steel tie rods, this leaves little safety factor if the rods are misaligned or eccentrically loaded as would be the case if the mechanical coupling deflects. Certainly the safety factor is significantly reduced when compared to hoop stress design of AWWA M11 which only utilizes 50 percent of steel yield strength for working pressure conditions and 75 percent of yield for transient and test conditions.

In order to hold the increase of stainless steel tie rod count, the use of larger diameter tie rods is possible. However, a significant tradeoff results as substantially larger harness rings and gusset plates must be provided. If allowable stress is based on yield, the stainless steel rod count could effectively double, creating a situation where the harness rings and gusset plates realistically cannot be designed to provide enough room to physically accommodate the number of rods. Strain hardened stainless steel tie rods such as Class 2 B8M do provide higher strength, but still are effectively only 90 percent of the yield and tensile strength of B7 carbon steel. Thus, some caution still needs to be exercised in design when lesser strength tie rods are still being utilized.

CONCLUSION

Stainless steel has inherent corrosion resistant properties. This opens it to consideration as an alternate to carbon steel which is far more vulnerable to corrosion in typical water service applications. Nevertheless, stainless steel can corrode under many common circumstances when used as a fastener for flanged joints or tie rods for harnessed mechanical couplings. AWWA C207 flange and AWWA M11 joint harness designs are significantly standardized and assume the high strength found in carbon steel bolts, studs and tie rods. Stainless steel fasteners have less strength than carbon steel. This becomes problematic if using the reliability of AWWA C207 or AWWA M11 designs as the basis of a specification but still seeking the corrosion resistant properties of stainless steel.

AWWA C207 expressly states that stainless steel fasteners are not covered under the standard due to potential corrosion issues and material strength differences with carbon steel. A designer using stainless steel bolts for AWWA C207 flanges must be willing to concede that the flanged joint will not have the same inherent and assumed safety factors that it would with carbon steel fasteners. AWWA M11 harness design affords more leeway for incorporating stainless steel tie rods in lieu of carbon steel. Nevertheless, the safety factors incorporated into AWWA M11 design using carbon steel fasteners are largely inferred. Some caution needs to be exercised in switching to stainless steel fasteners and still assuming that the safety and design intent of M11 is being met.

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