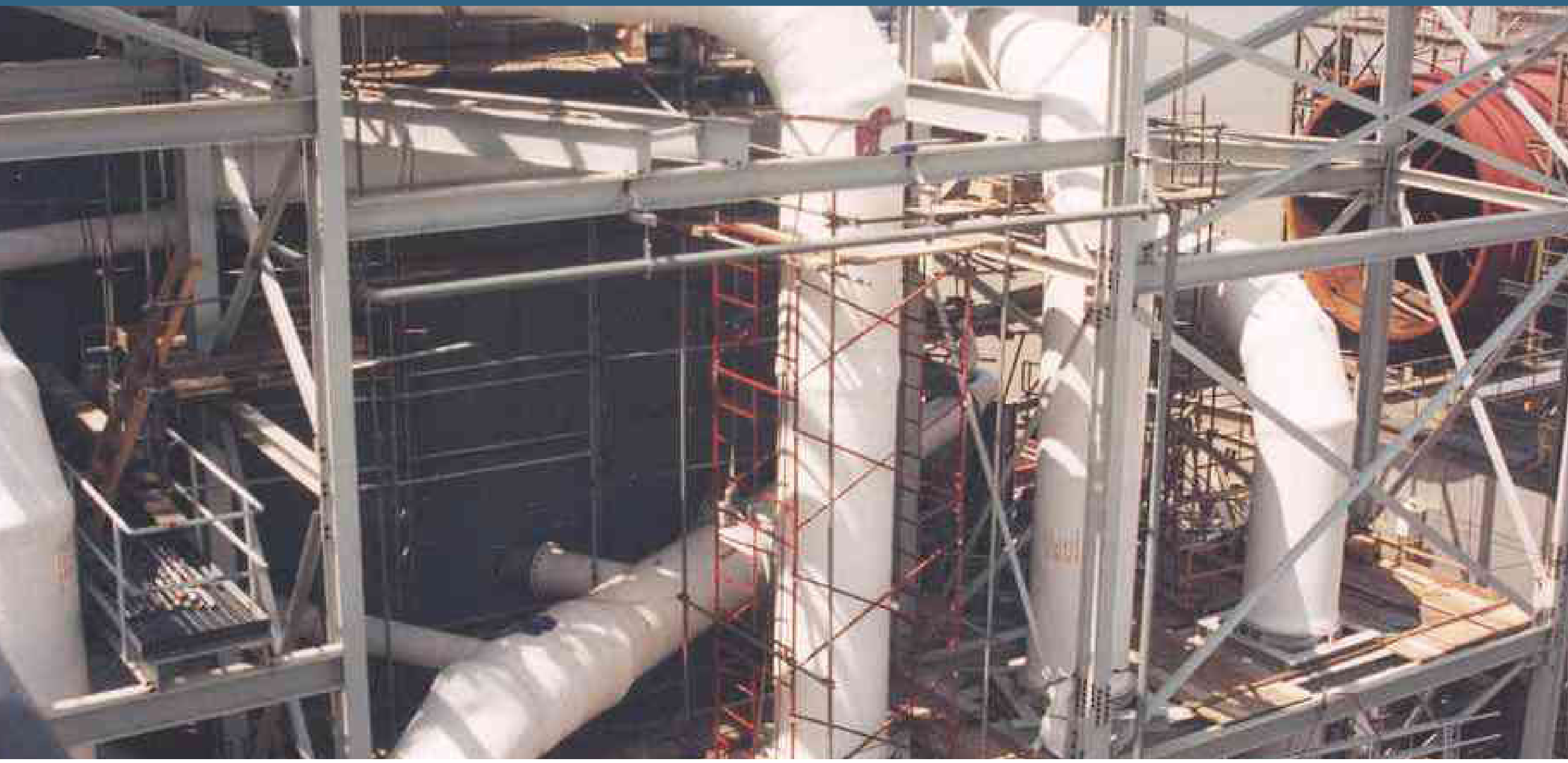

Avoiding the Pitfall of Applying Metallic Steel Piping Design Standards to Non-Metallic Fiber Reinforced Plastics (FRP) Piping Systems

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Use of Fiber Reinforced Plastics (FRP) piping is now becoming a common replacement for steel piping across multiple industries, including in wafer fabrication, chemical, data centers, power, and mining operations, due to the material's inherent corrosion resistance and associated weight and cost benefits.

However, industrial fabricators and operators are finding that, when ASME B31.1 and B31.3 steel pipe design standards are applied to FRP, the materials can become compromised. Some of these failures include cracking, kinking, fracturing or debonding.

Designing, fabricating, or bonding/joining industrial FRP piping systems requires understanding the differences between steel piping metallic design standards and FRP's non-metallic design standards and manufacturing process.

For example, steel can undergo plastic deformation (stretching beyond its elastic limit without immediate failure, though still experiencing stress and strain), whereas FRP piping remains essentially elastic up to failure—experiencing stress and strain when stretched and potentially snapping brittlely without warning.

Therefore, the American Society of Mechanical Engineers (ASME) developed non-metallic design standards (thermoplastics - HDPE, PTFE, etc, thermosets - FRP, GRP, etc and the properties for both to be used in design) that address the unique design differences and challenges of thermoset and thermoplastic materials.

Metallic Versus Non-Metallic Materials

Unlike metallic, isotropic materials, (i.e., steel composition in pressure vessels and storage tanks) that exhibit uniform behavior and strength in all directions, non-metallic, anisotropic materials in fiber reinforced plastics (i.e., FRP), do not.

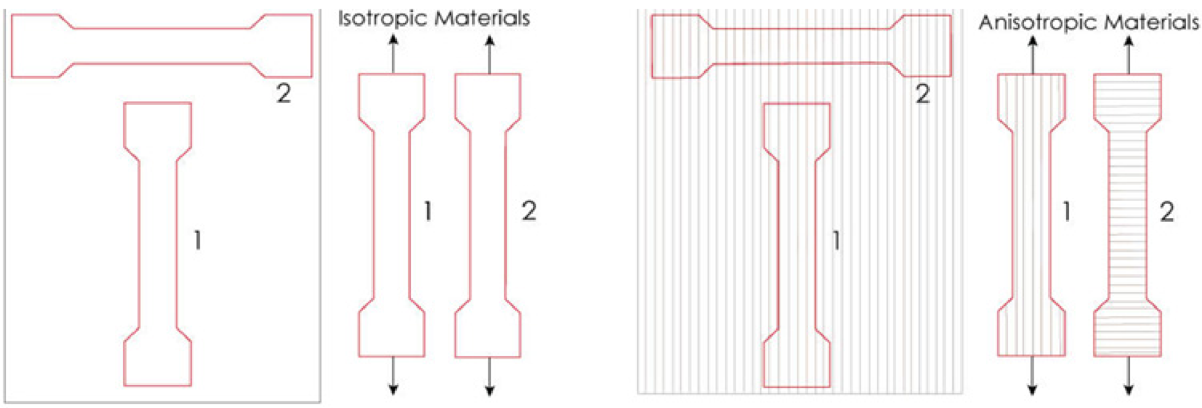
Anisotropic materials are composed of properties that vary when measured in different directions. Fiber reinforced materials can demonstrate great strength when force is applied in the same direction as the fibers, and much less strength when force is applied in the opposite direction. [1]

that underwent hydrotesting per ASME B31 criteria (1.5x design pressure).

Pipelines of different length were laid down at 9-10 locations. Hydrotesting was then conducted at all locations. At each location, the joints started leaking (figure 2).

The pipe manufacturer laminated the joints to fix the issue and the leaks stopped, but in an unusual and unforeseen turn of events, the pipeline also failed through the wall of the filament wound pipe.

Fig. 1 Anisotropic (fiber reinforced plastic) material strength versus isotropic (metal) material strength [1]



Therefore, designing non-metallic materials like FRP per steel pipe design manuals (i.e., ASME B31.1 and B31.3), can result in the following failures:

- Microfractures in new FRP piping, tanks, and pressure vessels
- Piping support load distribution
- Flange brittle failure
- Secondary bond delamination
- Peel failure of bond lines

This document will focus on the differences between steel and FRP materials for use in industrial engineering designs.

Example of a Failure in Applying Steel Design Standards to Non Metallic FRP Materials

Critical piping joints can fail when an engineer or piping designer apply a "metal mindset" to non-metallic materials. For example, multiple joint failures occurred on a 2.75 mile, 20-inch nominal pipe size (NPS) pipeline

To make matters worse, the location of the leakages could not be detected due to the fact that most of the pipeline was underground.

A study published in the International Research Journal of Engineering and Technology (IRJET) analyzed the failure, emphasizing microstructural and micromechanical failure modes, while omitting discussion on design basis laminates, methodology, and the design factors applied.

Fig. 2 Leaking Joints in a FRP pipeline

What the study revealed was that the "GFRP composite pipes failed due to leakage during hydro test while laying out in the site due to defective manufacturing process, and usage of improper polymer/resin material and non-uniform sand content along with non-prescribed fiber loading which might have initiated the failure of pipes during hydro test."[2]

Potential Pitfalls of Designing FRP to Steel Standards

Hydrotesting

According to legacy members of B31 Code Standards Committee, hydrotesting to flange limits was a method used to "settle-out" metallic piping on the supports. Local residual stresses are often present at welded joints when one surface cools more rapidly than the other.

By hydrotesting just below yield of the parent piping material, any local residual stresses are pushed beyond yield thereby encouraging metallic piping to "settle" onto the supports.

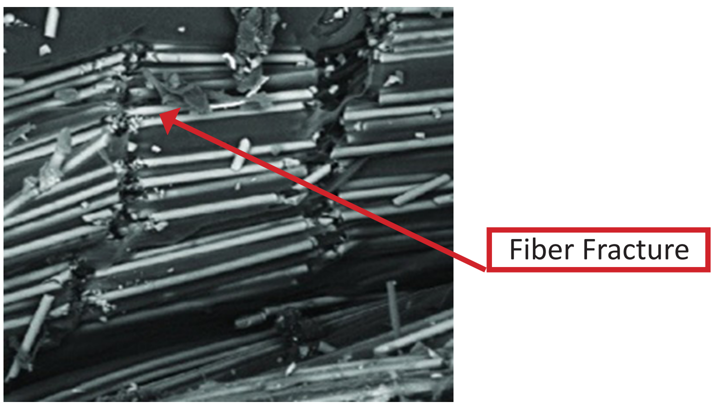


Fig. 3 Microfracture of Glass Fibers

As FRP does not yield, the same benefit cannot be realized. Hydrotesting to 1.5 times the flange limits can cause microfractures in the piping—specifically in the resin-rich (and weaker) corrosion barrier and the external surface coat.

A leak test at the intended piping's design pressure is a preferable alternative to hydrotesting FRP.

A compromised corrosion barrier is not detectable by the naked eye, exposes the structural fiberglass layers to process fluids and can lead to premature structural failure of the pipe.

Joining

Steel piping is typically joined using welded, threaded, or mechanical (Victaulic) connections. While mechanical fittings can be used in FRP systems, socket glue joints or secondarily bonded overlays are more commonly used.

Factors that affect the performance of joints include a properly prepared surface, clean environment and substrate, and a temperature/humidity controlled environment. Depending upon the system pressure, chemical exposure, and/or ancillary loads on branch joints, an internal joint may be necessary.

Fig. 4 Glue Joint Piping

Fig. 5 Preparing to install an inside nozzle joint

Joining steel pipes only requires a welding process that can be automated. FRP, on the other hand, requires skilled labor as it is a manually intensive process due to its customizable and unique designs and multiple layers of resin and fiber application.

Tolerances

Joints for non-commodity FRP pipe are typically made using a secondary overlay. Each layer of fiberglass and resin applied can cause tolerance stack.

Fig. 6 FRP Flange/Nut Interferance

If not anticipated, it can result in collisions between bolted connections as noted below. This issue is overlooked by metallic standards.

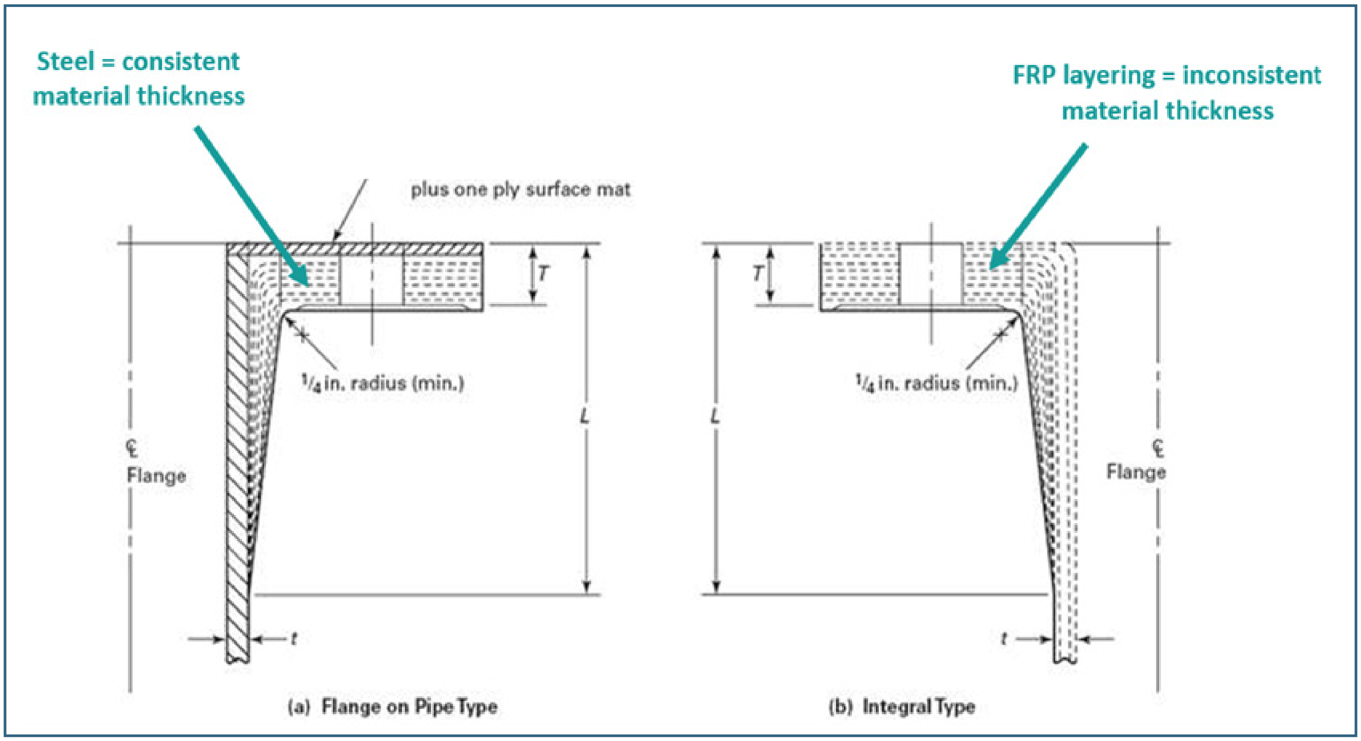


Fig. 7 Standard FRP Flange and Hub Construction

Brittle Failure

Much like cast iron fittings, FRP pipe is subject to brittle fracture. In the case below, a pump backflush resulted in excessive forces being applied by expansion joint control rods in a concentrated manner to the backside of a fiberglass flange.

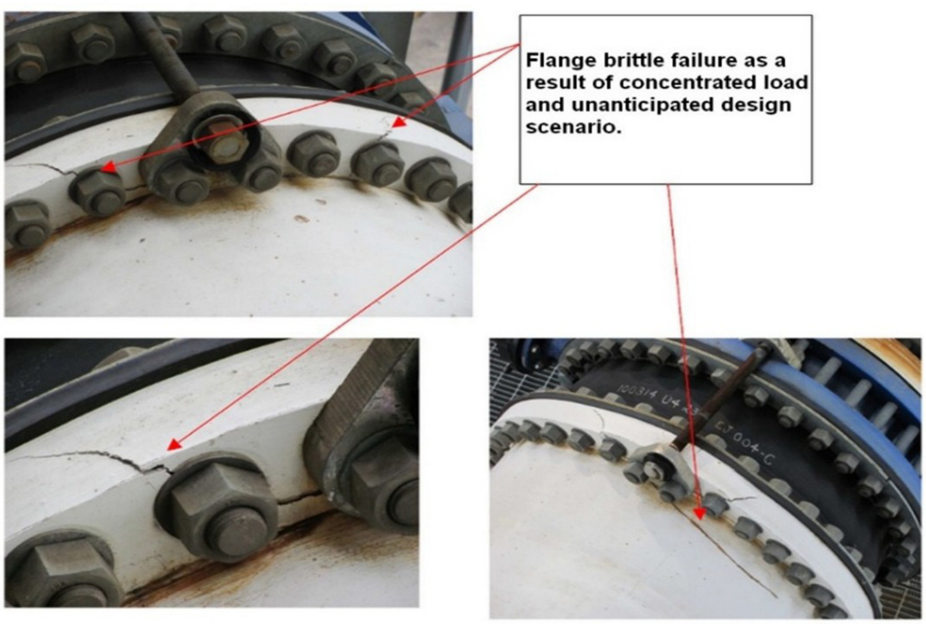


Fig. 8 Flange Brittle Failure

FRP Design Approach

The material properties, such as tensile strength, modulus of elasticity, density and thermal conductance for metal alloys have been well established for many years. As a composite material, fiberglass pipe laminates exhibit properties that are dependent upon the process used and glass and resin types. Historically, there are several methods used to determine material properties:

Rules Method: If planning to use standard filament winding or hand-layup techniques with common materials, a designer may use allowable stresses listed in ASME NM.3.3 Non Metallic Materials, Part 3 Properties.

Empirical Long Term Testing Method: Using ASTM D2992, cyclic biaxial pressure testing is conducted on the pipe sample and then a design factor is applied based upon the service conditions. This is a common method for commodity pipe.

Empirical Short Term Testing Method: Using ASTM D1599, biaxial pressure testing is conducted on a pipe sample to immediate failure. This is common for custom laminates where HDB testing would be cost and time prohibitive; however a penalty is paid for the reduced testing requirements.

Theoretical Method: Biaxial stress analysis is completed using finite element analysis or micromechanics/ lamination theory to demonstrate that the stress state is within permissible limits. Similar to Empirical Short Term Testing Method, this is common for custom laminates where HDB testing would be cost and time prohibitive; however an allowable stress penalty is paid for the reduced testing requirements.

Summary

Understanding the unique properties and applications for FRP in industrial environments is crucial to maintaining its reliability and safety. Engineers need to understand the nuances of working with FRP including not only the design approach but also the operational environment and constructability challenges.

Applying traditional ASME B31.1 and B31.3 steel piping standards to FRP piping systems often leads to critical failures due to the material's anisotropic nature and unique failure modes, such as microfractures, brittle fractures, and joint delamination.

ASME NM.1, NM.2, and NM.3 non-metallic design standards now provide a robust framework for designing, fabricating, and testing nonmetallic piping systems. By adopting these FRP-specific guidelines, engineers can ensure safer, more reliable piping systems tailored to the distinct properties and challenges of FRP materials.

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