Fiber Reinforced Plastic Piping Systems and Pipe Supports for Reliable Performance

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ABSTRACT

Fiber Reinforced Plastic (FRP) piping and equipment have been an important part of pulp and paper processing for over 60 years. FRP is an excellent material of construction for the corrosive services of these processes. The composite construction of FRP materials can vary widely, depending on the manufacturer and fabrication method. Correspondingly, material properties and behavior of FRP systems can vary, influencing the piping design and the system arrangement. Ensuring mill safety and performance are paramount. The pipe support arrangement and design of pipe support elements are critical to the reliable performance of FRP piping systems. The behavior of FRP piping varies from that of other piping materials, such as metals. Additional attention to design concerns is necessary in meeting performance expectations.

We will discuss the best practices for design of pipe supports and pipe support arrangement of FRP piping systems. The author will provide examples of the Do's and Don'ts for FRP pipe support design and arrangement. Additionally, essential design considerations and lessons learned will be presented to optimize system performance and to maximize the reliable service life of FRP piping systems.

INTRODUCTION

As a naturally corrosion resistant material of construction, FRP can be found in many areas of pulp & paper mills, particular in the bleach plant area. FRP is a reliable material of construction for piping and equipment in acid and base chemical services, such as hydrochloric acid (HCl), sulfuric acid(H_2SO_4), chlorine dioxide (ClO2), sodium hypochlorite (NaOCl) and caustic (NaOH) solutions. A wide range of process equipment is constructed from FRP to meet these service conditions, including:

- Chlorine dioxide generators
- Chlorine dioxide storage tanks
- Bleach towers
- Effluent piping
- Upflow tubes
- Downflow tubes
- Vapor collection ductwork
- Vent stacks
- Washer hoods
- Seal tanks
- Process piping
- Sump and trough linings

FRP is a proven material used for process equipment within the pulp & paper mill. In this paper, we will be focusing on understanding FRP piping used in a variety of mill processes, including chemical transfer piping and vapor collection ductwork. While there are decades of success stories of FRP in service, the system design and arrangement of FRP piping systems is not always executed with consistency, which can lead to challenges to reliability and premature failure. We will discuss differences in properties and material behavior between composite

materials and metals in piping applications. There are also newly published ASME guidelines available for piping design and stress analysis of FRP piping. We will discuss the basic rules for best practices of piping system arrangement, as well as when FRP piping systems should be analyzed with a formal pipe flexibility/stress analysis program.

MATERIAL PROPERTIES

As a composite material, FRP is principally made up of thermoset resin and glass fibers. Compared to most metals, FRP is generally considered a nonductile material. FRP has a long elastic zone, but once it gets into the top of the stress-strain curve, the plastic deformation of FRP ranges from 2% to 6% elongation before failure. Comparatively, ASTM A-36 carbon steel elongates approximately 20% prior to failure, which represents more of a ductile behavior. Yet, FRP is notably flexible for what is considered to be a rigid piping material. As shown in Figure 1, FRP has a markedly lower modulus of elasticity as compared to carbon and stainless steels.
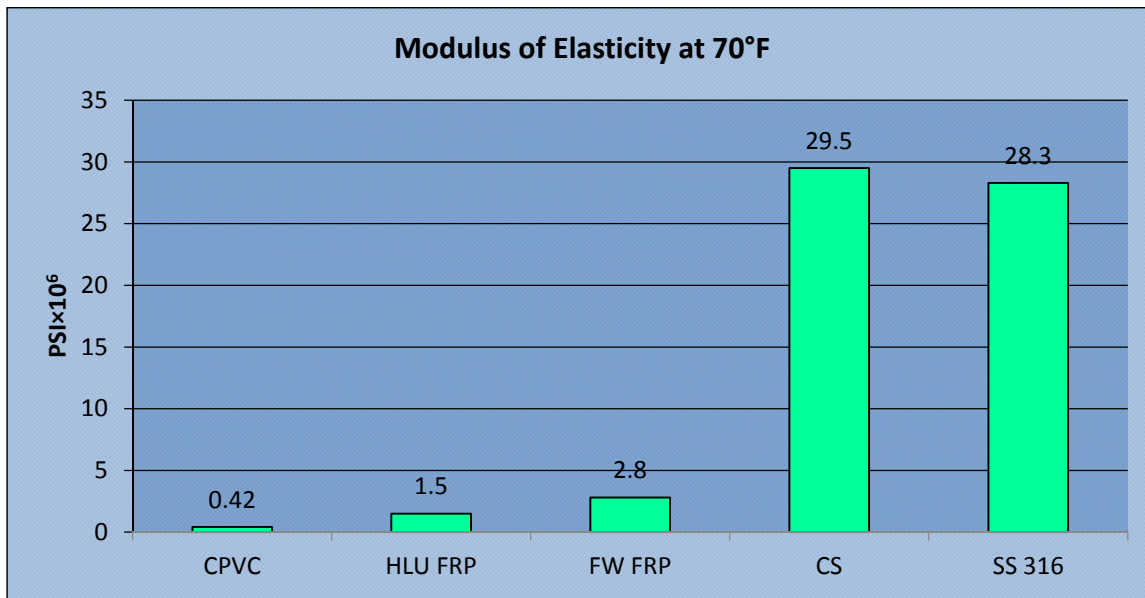

Figure 1: Comparative Data on Modulus of Elasticity of Piping Materials

It should be noted that since FRP is a composite material, its material properties are orthotropic in nature, meaning that the properties are different in the hoop and axial directions. The modulus of elasticity shown in this chart for filament wound (FW) FRP is the hoop modulus of elasticity, E_{hoop}. In the axial direction, the typical axial modulus of elasticity for 55$\square$ filament wound (FW) FRP pipe, E_{axial}, is about 1.5×10^6 PSI. The low elasticity value affords FRP greater flexibility under low loading, as compared to most steel materials. Hand lay-up (HLU) FRP is not helically wound, but rather hoop wrapped with chopped strand mat and woven roving. The woven roving provides most of the strength and stiffness in HLU pipe. The fibers of woven roving are oriented in a 0$\square$/90$\square$ weave with approximately the same fiber content in each direction. Similarly, the modulus of elasticity, E, and tensile strength, S, is approximately the same in both directions. We will discuss how these attributes affect piping flexibility and the stress analysis later in this paper.

Figure 2 illustrates the tensile strength of HLU FRP along with the axial and hoop tensile strength of FW FRP as compared to other piping materials. It can be noted that in examining the material tensile strengths, FW FRP has comparable hoop tensile strength to the yield strengths of carbon and 316 stainless steel. The orthotropic characteristics of FRP are evident when examining the axial tensile strength versus the hoop tensile strength of FW FRP. This is created by the fiber direction and density of the 55$\square$ wind angle, typically found in filament wound piping. The tensile strength of HLU FRP is notably lower than that of FW FRP, carbon steel or 316 stainless steel. The result of this reality is that HLU FRP must be about 50% thicker than FW FRP to achieve similar pressure rating in piping.
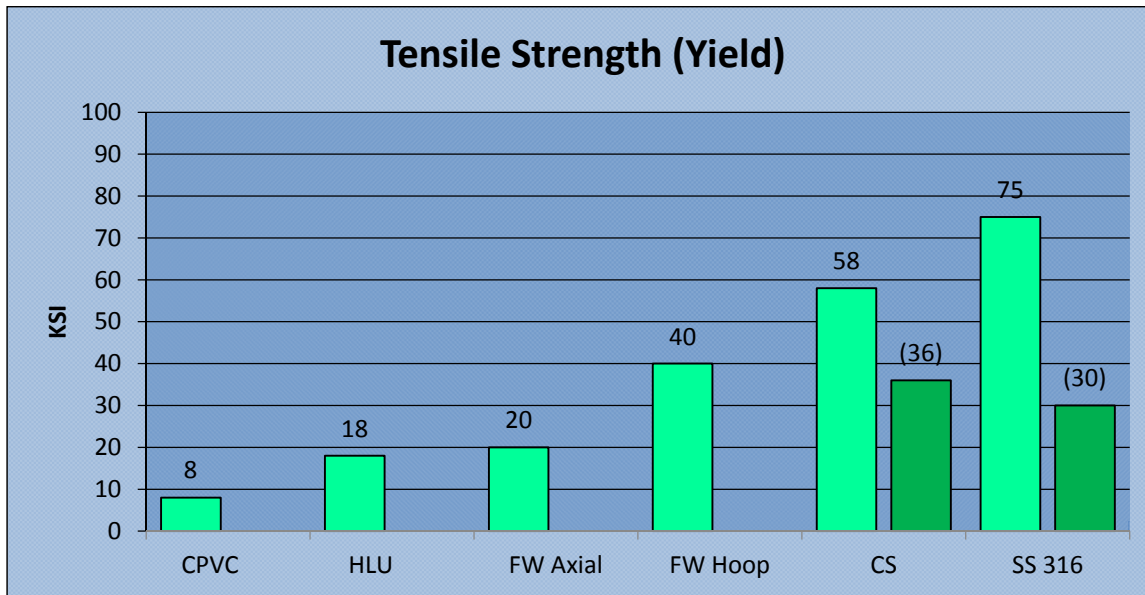
Tensile Strength (Yield)

KSI

- CPVC: 8
- HLU: 18
- FW Axial: 20
- FW Hoop: 40
- CS: 58, (36)
- SS 316: 75, (30)

Figure 2: Comparative Data on Tensile Strength of Piping Materials

Most plastics expand and contract at a higher rate than ferrous metals. Depending on the resin and glass content, FRP expands and contracts about 2.5 to 3 times that of carbon steel. Typical values for material coefficient of thermal expansion (CTE) are illustrated in Figure 3 below.
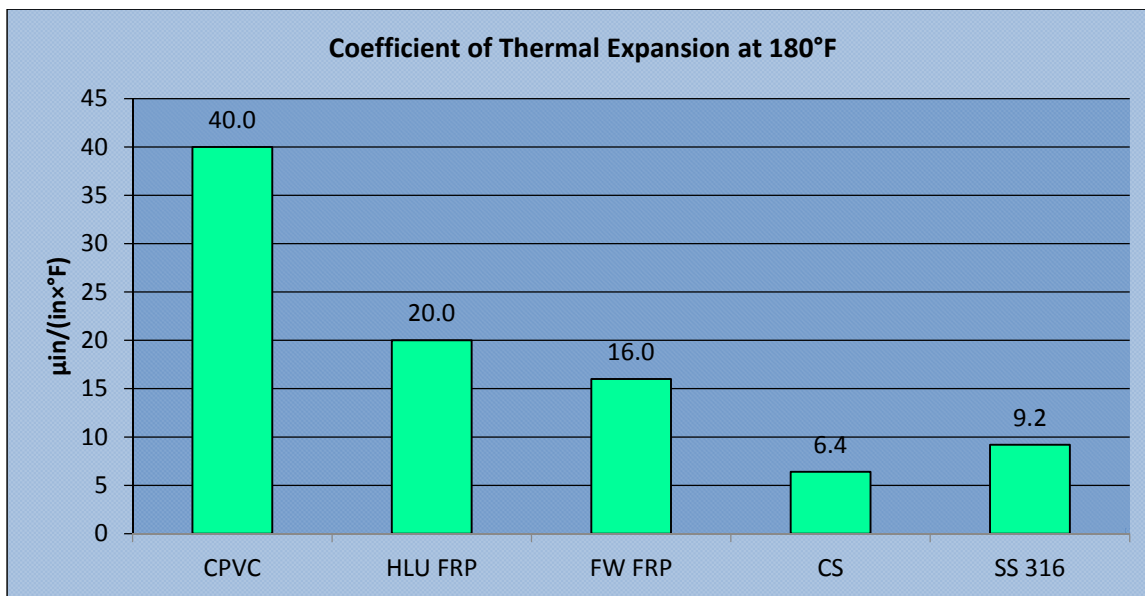
Coefficient of Thermal Expansion at 180°F

$\mu in/(in \times °F)$

- CPVC: 40.0
- HLU FRP: 20.0
- FW FRP: 16.0
- CS: 6.4
- SS 316: 9.2

Figure 3: Comparative Data on the Coefficient of Thermal Expansion for Piping Materials

A higher resin to glass reinforcement ratio will yield a higher CTE in a fabricated FRP laminate. The values depicted above are typical values for common resins used in FRP. Within the category of FRP materials, the CTE will vary depending on the specific resin system within a family of resins, i.e. polyesters, vinyl esters or epoxies. Additionally, the CTE will vary with the thickness of the corrosion barrier. Depending on the service, the corrosion barrier thickness can vary from 1/8" (3mm) to ½" (13mm). The resin to glass ratio of the corrosion barrier is approximately 75%. Having a high resin content, this can further influence the CTE of an FRP piping material. Among other concerns, managing the thermal expansion and contraction is a critical element in providing reliable FRP piping solutions.

PIPE STRESS ANALYSIS

After eight (8) years of development, in 2019 the American Society of Mechanical Engineers (ASME) published the first American National Standard to define comprehensive requirements for FRP piping, materials, design, fabrication, inspection and erection. This standard, developed by the ASME Nonmetallic Pressure Piping Systems (NPPS) Committee, is entitled "ASME NM.2, Glass Fiber-Reinforced Thermosetting Resin Piping". This standard follows the document structure of the ASME B31.3 Process Piping Code and defines the requirements for analysis as well as when analysis is and is not necessary. To summarize, it states that formal analysis is not required for a piping system that meets one of the following conditions:

1) The piping system duplicates or replaces, without change to materials, method of construction, system arrangement and operating conditions, a system operating with a successful service record. Simply stated, identical replacement in kind, assuming a proven record of reliable service.
2) The piping system is nearly identical in system arrangement, piping materials and operating conditions to an existing system that can readily be judged adequate by comparison with previously analyzed systems. This definition affords some limited judgement for the design engineer in the event parallel and other systems have a common criterion and construction, without having to perform a formal pipe stress analysis.
3) The piping system is laid out with an inherent flexibility that can be judged adequate for the given design conditions, or uses joining methods and expansion joint devices, or a combination of these methods, that are intended to absorb the majority of thermal expansion and contraction throughout the piping system and are selected and installed in accordance with manufacturer's instructions. This is a very broad and vague statement, as it is difficult for even the most trained FRP piping engineer to judge a piping system as inherently flexible and safe in operation with a high level of certainty without some level of piping system analysis. The most conservative view of this statement would be when design conditions are ambient in nature for very low pressures or gravity flow. That being said, it does afford the design engineer some level of judgement for a smaller or simplistic piping system arrangement.

After the standard defines when analysis is not required, it states that if these criteria cannot be met, then the system shall be formally analyzed. Further, the standard offers a range of analysis approaches, all structured and methodical in execution and documentation.

Where analysis is required, pipe stress/flexibility analysis using a formal pipe stress computer program is highly recommended. These analysis programs can be very accurate in predicting the performance and behavior of FRP systems. That being said, accuracy and reliability bear more on the competent training and expertise of the piping engineer/analyst, as the saying goes "Garbage In – Garbage Out". It is important to have a sound understanding of all of the design conditions and the piping construction. The following is a discussion and explanation of critical input data for a pipe stress analysis.

System Geometry – The goal is to replicate the piping system arrangement in the computer program in order to predict the system behavior. The first step in preparing to evaluate the piping system is modeling the piping system geometry in the program. The geometric inputs should include dimensional data for piping, fittings and all in-line components, such as valves, supports, flowmeters and expansion joints. Valve data inputs should include weights including actuators. Expansion joints need to be selected with FRP in mind. Since FRP has a lower modulus, E_{axial}, than steel, the expansion joints must be lower stiffness as well. Additionally, the pressure thrust area (cross section) of the expansion joint needs to be input separately as it is greater than the inner diameter (ID) of the pipe, creating large axial thrust loads.

Piping Materials – As noted earlier, material properties can vary between HLU and FW piping construction. To clarify further, there are typically three (3) categories of FRP piping materials.

- Type I
- Type II
- 55° Filament Wound (FW)

Each of these laminates produce different material properties. Type I is an all chopped strand mat laminate (no woven roving reinforcement). Many manufacturers will produce smaller diameter pipes, for example 1" to 3" in diameter, with an all chop strand mat structure for ease of manufacture. Since Type I laminates have a high resin to

glass content, about 70%, Type I laminates have a lower modulus of elasticity and strength. For vinyl ester resins, Type I laminates have a modulus of elasticity value, $E_{axial} = E_{hoop} = 1.0 \times 10^6$ PSI, with a typical tensile strength value, $S_{axial} = S_{hoop} = 9,000$ PSI. Type I and Type II laminates are considered quasi-isotropic materials, since the hoop and axial properties are approximately equal. The HLU data in the charts above, see Figure 1 and Figure 2, represents Type II laminate data, which is notably greater than the defined Type I data. Also found in Figure 1 and Figure 2 is FW data which varies again from Type I and Type II laminate properties.

There are three significant points to gain from this discussion:

1) Manufacturers should be prequalified to ensure that the methods of manufacturing performed by each is understood
2) Vendors should be selected based on common methods of manufacturing
3) The analysis approach should be paired with the approved vendors and their preference of laminate construction.

Beyond physical properties, there are other analysis related data that may vary depending on the piping method of construction and specifically selected resin and glass. Additionally, these factors will influence other values, such as Stress Intensification Factors and allowable stress values. The accuracy and integrity of the results are dependent on the accuracy and reliability of the material data. The new ASME standard, NM.2, for FRP piping has introduced substantive requirements for material testing, design basis and proof of design. This is a significant step forward toward design reliability and consistency. For new capital projects, this standard will provide a solid foundation for guidance to establish material testing requirements and validation of properties.

<u>Design Conditions and Load Cases</u> – The requirements and expectations for design conditions for FRP piping generally follow the same guidelines as other piping materials, meetings the requirements of the ASME Process Piping Code B31.3, with only a few exceptions. The design pressure, $P_{D \text{ or }} P_{MAX}$, may be defined as the maximum achievable system pressure and can be somewhat subjective. Sometimes design pressure is defined by the maximum dead head pressure of the pump in the system. However, the design pressure is almost always greater than the operating pressure, P_o. As an example, where an FRP system is expected to operate at $P_o = 110$ PSI, the system may be analyzed and designed for a design pressure, $P_D = 150$ PSI. design pressure and rated pressure are frequently confused. The rated pressure of a pipe is the pressure which the piping component is designed or built for and tends to be a customary size and not based on a system requirement. The design pressure relates to the piping system design and not the component design. Individual components are designed, tested and rated based on separate protocols and requirements, where design values are based on the service specific process requirements, which are applicable to the analysis of piping systems.

Design temperature, T_D or T_{MAX}, is similarly compared to design pressure, where it is the defined maximum achievable system temperature. Again, this should be greater than the expected operating temperature. The design temperature is frequently the governing or most influential design parameter for an FRP piping system, due to the notable coefficient of thermal expansion of FRP, so careful consideration should be defined.

One deviation in the analysis of FRP piping as compared to the analysis of process piping of metal materials of construction, is the approach to evaluating the system's thermal expansion and contraction. Typically, when performing a formal pipe stress/flexibility analysis of a steel piping system, for each load case, the temperature is evaluated from the minimum design temperature, T_{MIN}, to the maximum design temperature, T_{MAX}. As an example, if $T_{MIN} = 20\Box$F and $T_{MAX} = 180\Box$F, the evaluated temperature range of expansion would be from $20\Box$F to $180\Box$F, or a temperature gradient of $160\Box$F. When performing a formal pipe stress/flexibility analysis of an FRP piping system, this temperature range is divided at the installation temperature, usually assumed to be $70\Box$F. This means that the full temperature range is evaluated over two load cases, 1) a cold case and 2) a hot case. In our example, the temperature of the cold case would be evaluated from $20\Box$F to $70\Box$F, while the hot case would be evaluated from $70\Box$F to $180\Box$F. This approach assumes that the ambient condition is the installed condition, pre-stress. Since thermal expansion is a significant stress contributor for FRP piping systems, this approach allows the design engineer to independently evaluate the expansion and contraction loads, which can vary depending on the configuration of each piping system. This is considered a best practice approach for FRP piping analysis and is

included in the new ASME NM.2 standard. In ASME NM.2, the temperature condition is considered a fundamental sustained load case, and is not self-limited as is typically understood for steel piping.

Occasional loads are important design conditions for consideration in any piping design, whether steel or FRP piping. Evaluation of occasional loads are a requirement of both the ASME B31.3 Piping Code and the NM.2 Piping Standard. Typical occasional loads for consideration are wind, seismic and snow loads. Water hammer, or pressure surge, loads can be considered an occasional load, although that is a more rare occurrence. Possible water hammer concerns should be remedied by operational controls, as it is difficult or impractical to design FRP piping systems for worst-case surge events. The Piping Code requires that occasional loads be evaluated in parallel with the defined system loads. For example, the occasional load case:

Load Case: Deadweight + P_{MAX} + $WIND_X$

Occasional loads should be evaluated independently in the two principal transverse directions, such as X and Y directions, in combination with sustained loadings.

PIPING BEHAVIOR AND SYSTEM ARRANGEMENT

FRP is approximately 25% of the weight of carbon steel on a density basis. Due to the lower axial modulus of HLU or FW FRP, the span capabilities tend to be about 75% to 80% of that for carbon steel, so attention needs to be paid to the specific gravity of the contents when determining spans. FRP piping is comprised of two principal elements, 1) the corrosion barrier and 2) the structure. The corrosion barrier is constructed of three to six very resin rich layers, including surfacing veil(s) and chopped strand mat layers. The primary purpose of the corrosion barrier is to provide a chemical resistance barrier to protect the piping structure from the chemical attack of the contents.   The resin selection, layers and total thickness of the corrosion barrier are determined based on the chemical contents and the design conditions of the service. The corrosion barrier is not recommended to be considered a structural element since it is expected to be impacted by the chemical contents of the service, so the corrosion barrier thickness is generally not included in strength or pipe span calculations. For thermal expansion/contraction considerations, however, the corrosion barrier should always be included.

There are two fundamental approaches to piping and pipe support arrangement of FRP piping systems, 1) fully restrained systems (example shown in Figure 4) and 2) flexible system arrangements (example shown in Figure 5).
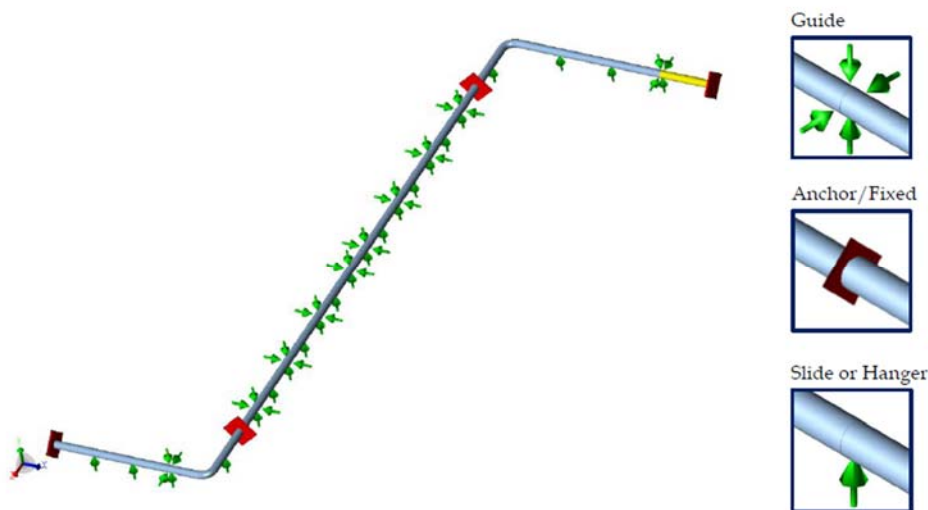

Figure 4: Example Pipe Support Arrangement of a Fully Restrained FRP Piping Design

The fully restrained system, with an example shown in Figure 4 above, is best suited for long runs without changes in direction where flexibility cannot be introduced by natural changes in direction or expansion joints.   In the fully restrained pipe support arrangement, anchor supports are located near fittings, such as elbows, at the ends of a long

straight run. The goal is to restrict the thermal expansion in the run and isolate the more sensitive fittings, such as elbow and tees, protecting them from potential overstress. This approach may be used in long header piping runs as well, locating anchor supports in between header tee branches to protect the branches from excessive movement.

The anchors in the fully restrained arrangement prohibit thermal expansion in the pipe run. The result of this is that the restrained pipe is significantly loaded in compression, realized at the anchor supports. The disadvantage of this arrangement is that the opposing loads developed at the anchor supports are transferred into the supporting steel structures. Large anchors loads can be developed from a single line or multiple lines in a pipe rack, which can lead to unanticipated challenges for the structural design team on a project. There are times when a fully restrained pipe support arrangement is necessary, although it should not be the first option, due to these concerns.
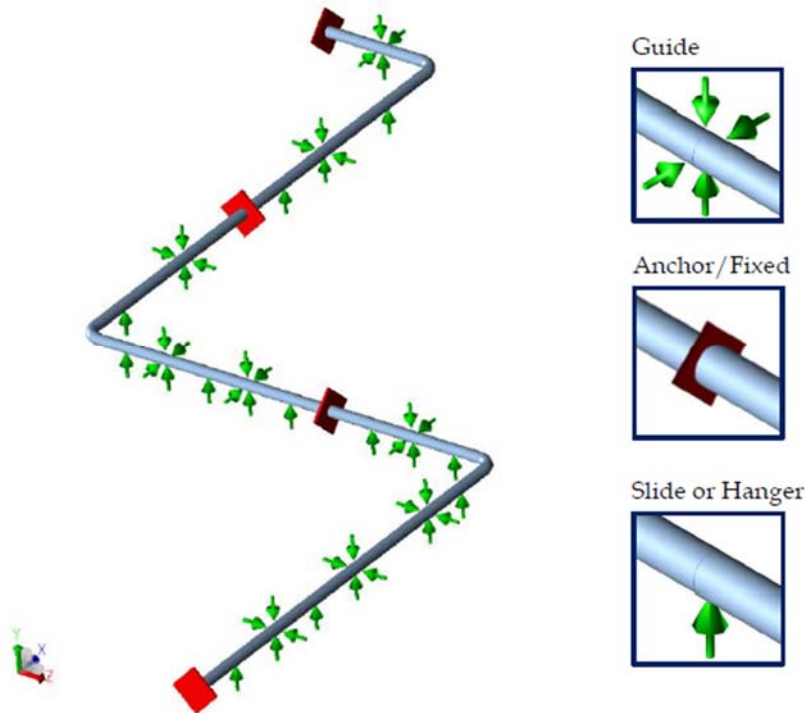
Figure 5: Example Pipe Support Arrangement of a Flexible FRP Piping Design

In a flexible piping arrangement similar to that shown in Figure 5 above, fewer anchor supports are required as compared to a fully restrained system. Anchor supports are located at neutral points in main piping runs, typically in the middle of the run. This allows the thermal expansion and contraction in that area of the piping system to be absorbed by the changes in direction, elbows, which tend to be more flexible than tee fittings. The lower modulus of FRP affords greater flexibility in the piping system. The changes in direction are supported to permit relatively free movement at the bends, which relieve or greatly reduce the effects of expansion loads. The flexible system approach, when executed properly, minimizes the loads in the piping as well as those transmitted through the pipe supports to structures. Where practical, the flexible piping arrangement can afford greater reliability and reduced stress conditions in FRP process piping systems, as well as reduced cost for structures.

Where a flexible system arrangement cannot be accommodated and a restrained piping system may not be desirable, expansion joints may be used to relieve and absorb excessive movements. If significant vibration from equipment is anticipated, the equipment should be isolated with expansion joints or flexible hoses so that loads are not transmitted to piping systems and other associated structures. Where expansion joints are implemented, anchor supports may need to be considered to manage unbalanced thrust loads.

PIPE SUPPORTS and OTHER CONSIDERATIONS

There are some fundamental considerations for defining pipe supports for FRP piping, which promote stability and reliability of the piping system. Below is a discussion of some key design rules.

1) Piping deflection is a concern of every piping system, regardless of the material of construction. For FRP piping, the maximum piping deflection between support locations should not exceed ½". In calculating the piping deflection, the corrosion barrier should not be included in the structural calculation but should be included in the total pipe weight.
2) Anchor supports should be located in each principal run of pipe. This will provide stability to the system from excessive movement due to thermal expansion, water hammer or vibration.
3) Valves and other in-line piping components, such as flowmeters, should be independently supported or the permissible span between supports should be decreased. Hanging heavy metal components from FRP flanges can overstress the pipe and has been shown to cause flange failures.
4) 90□ bends afford greater flexibility at changes in directions as compared to 45□ bends, which tend to be more rigid. 45□ bends do not tend to relieve piping loads and they typically transfer piping loads further down the line.
5) Clamp type pipe support elements should have an elastomeric lining inside the clamp to isolate the FRP piping from the support steel. Additionally, the elastomeric lining ensures a better fit of the clamp around the pipe, since most custom FRP piping has a controlled inner diameter versus a controlled outer diameter, as with most steel piping.
6) Due to the low modulus of FRP piping, pipe supports require wider clamps with greater bearing areas than those typically used for other piping materials. Depending on the type of support and load requirements, clamp widths can be 50% to 100% of the pipe diameter.
7) Point loads at support locations can potentially crack or fail the pipe. Pipe supports for FRP piping tend to be more robust than similar supports for steel piping.

CONCLUSIONS

FRP piping and equipment have been successfully used in pulp and paper service for decades. Its natural corrosion resistant characteristics make FRP an excellent material of construction for the chlorinated and other chemical processes in a pulp and paper mill. With this said, FRP is a composite material having orthotropic properties which requires unique design considerations that vary from the established piping design practices for steel piping. The lower modulus of elasticity of FRP affords increased flexibility to these piping systems, although the piping span capability for FRP is typically slightly less than that of metal piping systems. With a notably higher Coefficient of Thermal Expansion than most metals, loads and movements due to system thermal expansion and contraction can be significant and need to be closely managed. Most FRP piping and ductwork in pulp and paper processes where the design temperature, $T_{MAX,} \geq 150 \square F$ should be analyzed with a formal pipe stress program, in accordance with ASME B31.3 and ASME NM.2, to ensure a reliable FRP piping system. There are established rules and best practices for the support arrangement for FRP piping systems; guidance can be found in ASME NM.2.

REFERENCES

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2. ASME NM.2, "Glass-Fiber Reinforced Thermosetting-Resin Piping Systems", American Society of Mechanical Engineers, New York, NY, 2018.

3. ASME B31.3, "Process Piping, ASME Code for Pressure Piping, B31", American Society of Mechanical Engineers, New York, NY, 2018.

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Fiber Reinforced Plastic Piping Systems and Pipe Supports for Reliable Performance

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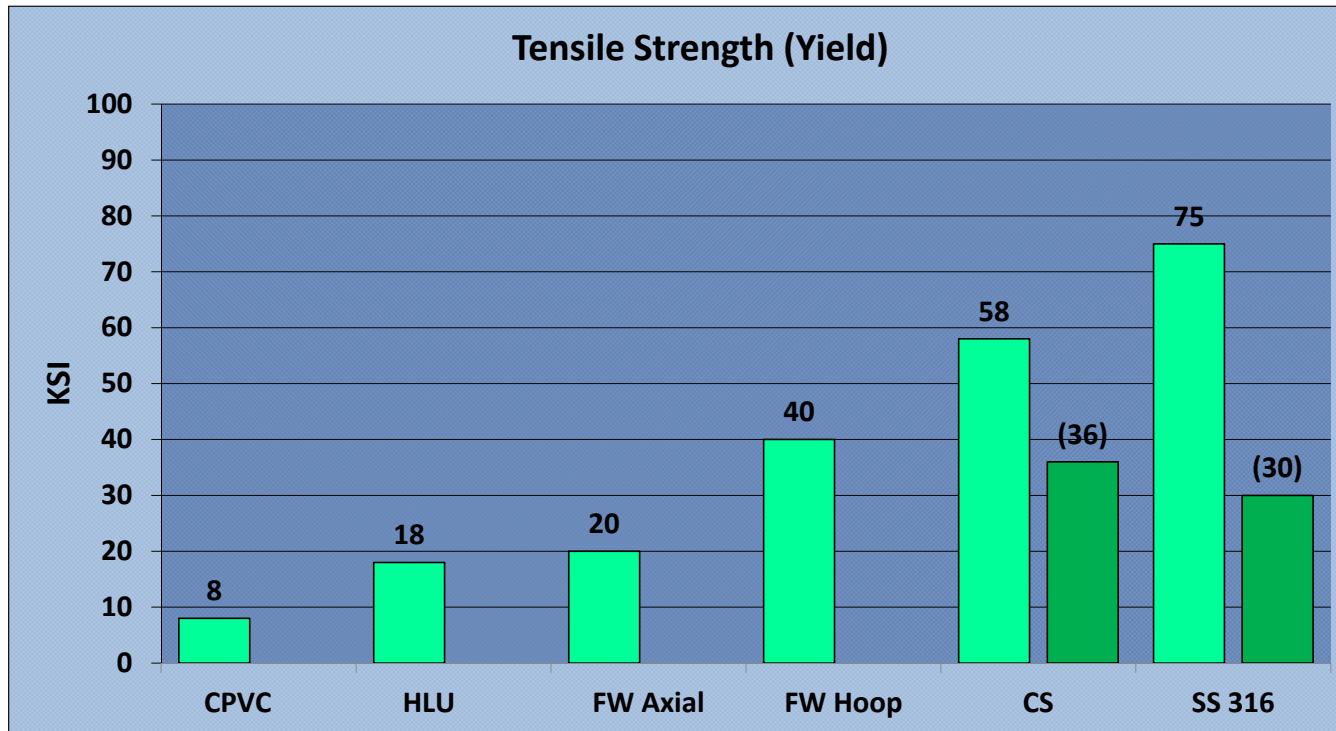
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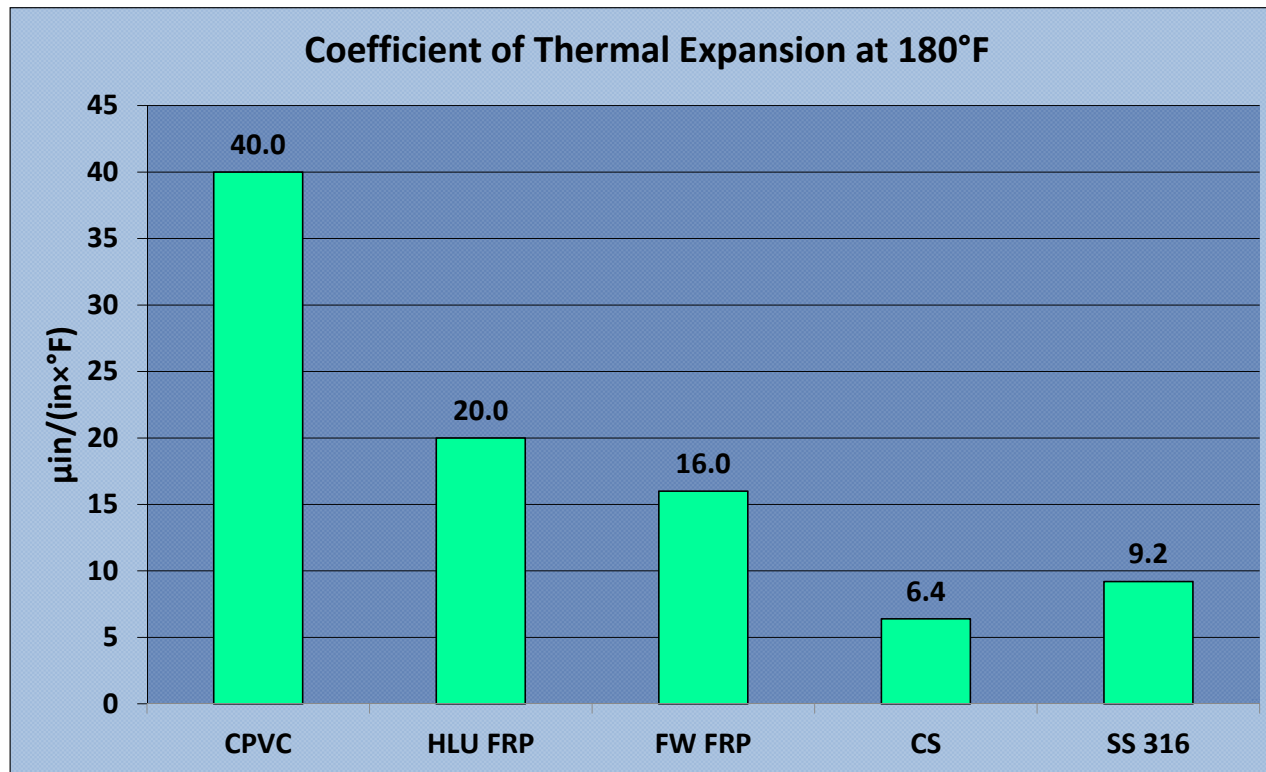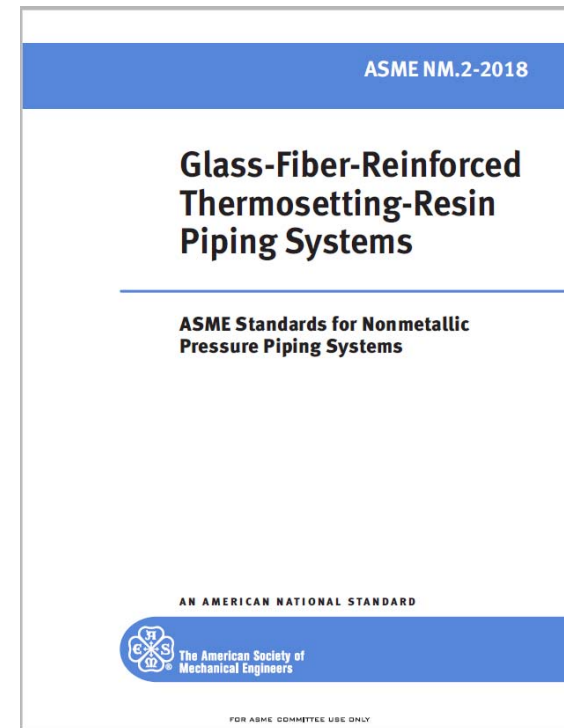# General Outline

- Introduction
- Material Properties
- Pipe Stress Analysis
- Piping Behavior and System Arrangement
- Pipe Supports
- Lessons Learned
- Conclusions

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Introduction - FRP in Pulp &Paper

- ClO_2 Generators
- ClO_2 Storage Tanks
- Bleach Towers
- Effluent Piping
- Upflow Tubes
- Downflow Tubes

- Vapor Collection Ductwork
- Vent Stacks
- Washer Hoods
- Seal Tanks
- Process Piping
- Sump and Trough Linings

FRP Piping Construction
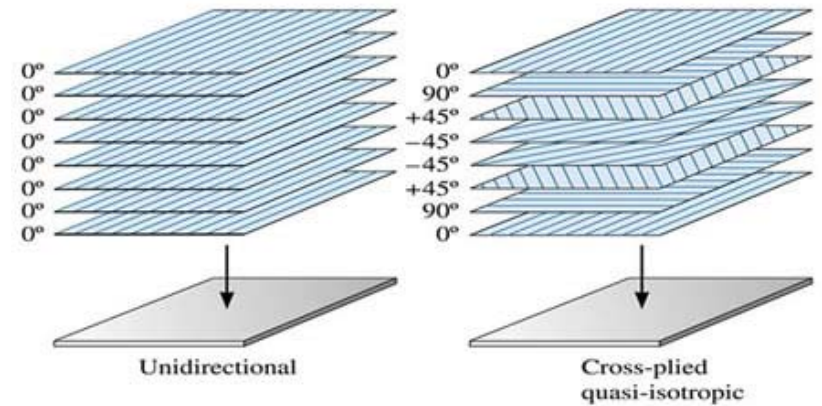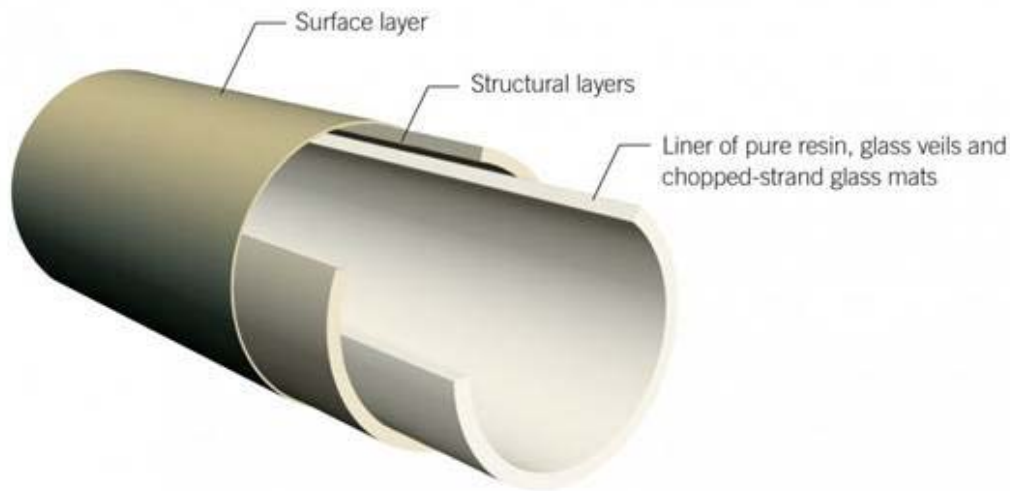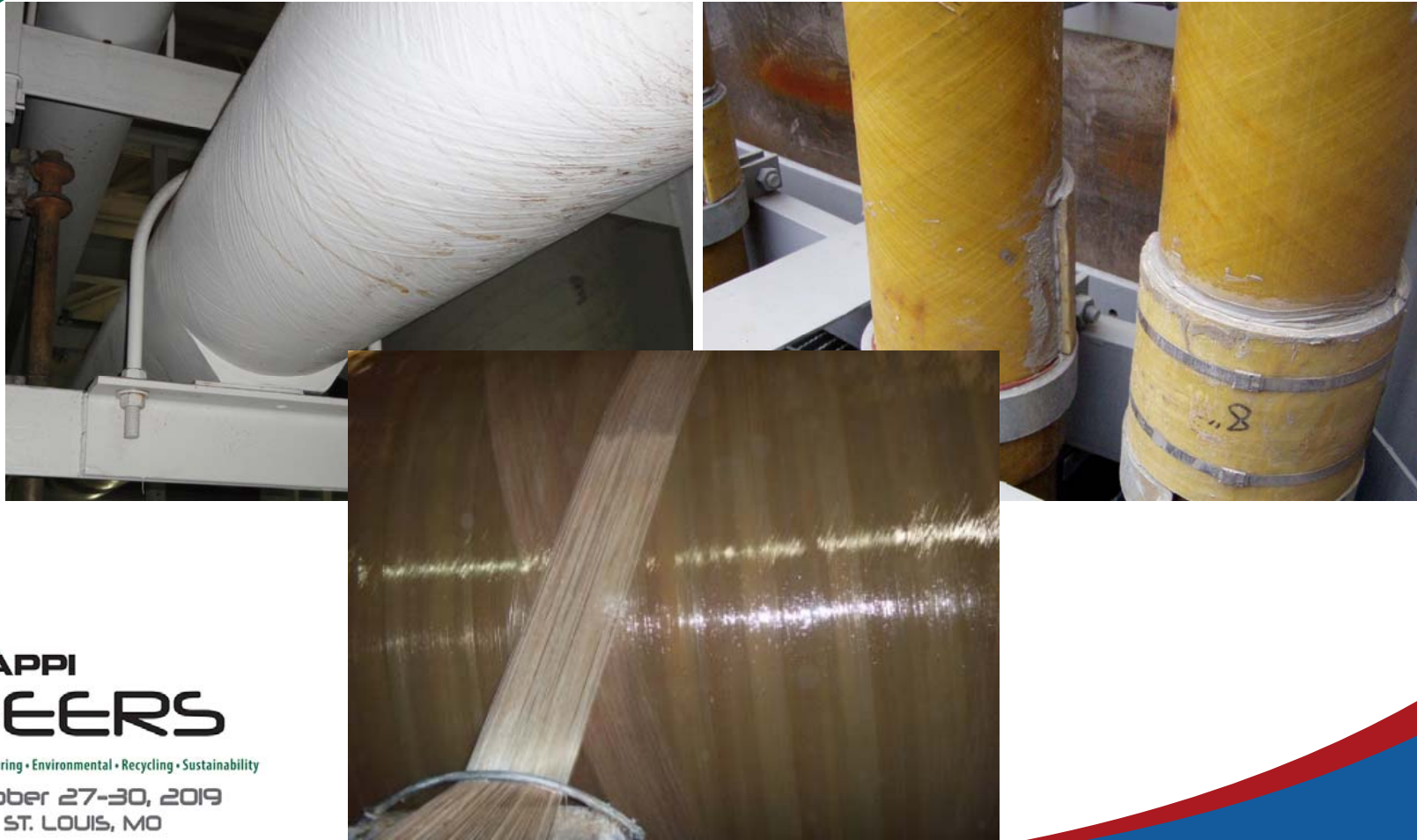
Surface layer

Structural layers

Liner of pure resin, glass veils and
chopped-strand glass mats

0°	0°
0°	90°
0°	+45°
0°	−45°
0°	−45°
0°	+45°
0°	90°
0°	0°

Unidirectional

Cross-plied
quasi-isotropic

Filament Wound Pipe

Hand Lay-up Piping

Material Properties

Modulus of Elasticity at 70°F

Material	PSI×106
CPVC	0.42
HLU FRP	1.5
FW FRP	2.8
CS	29.5
SS 316	28.3
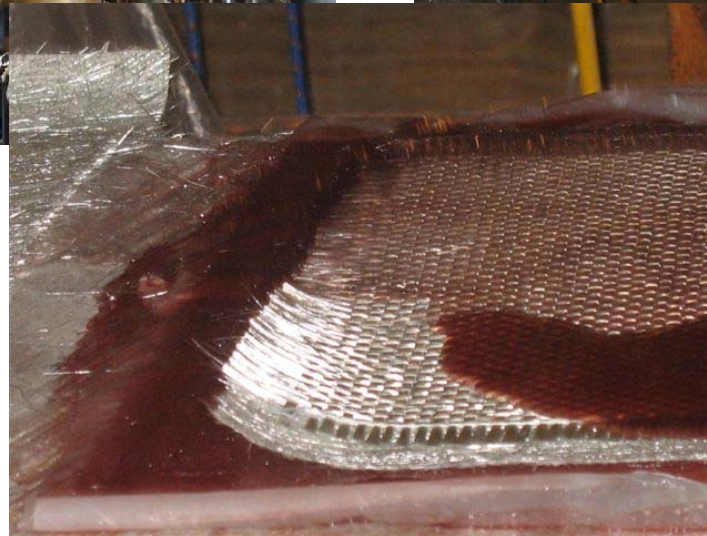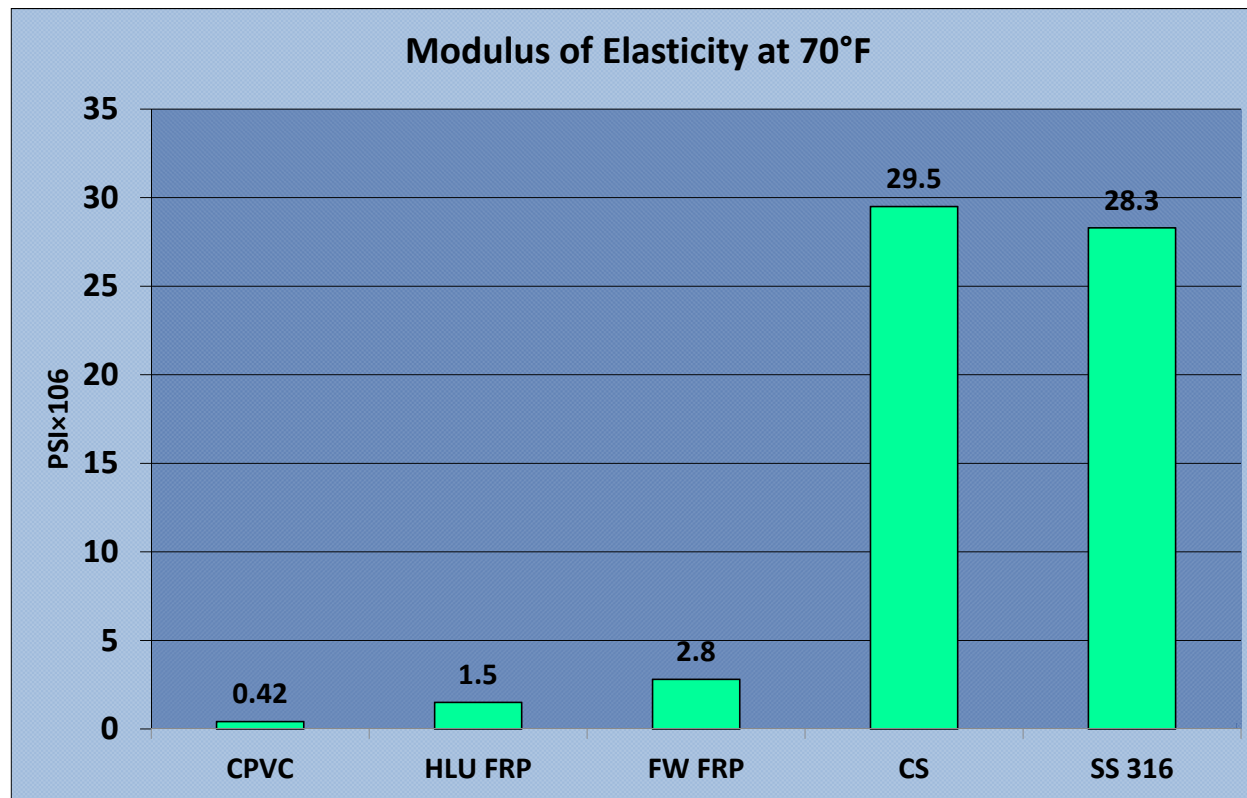
ASME NM.2-2018,
A New Standard for FRP Piping

- Chap 1: Scope and Definitions

- Chap 2: Design

- Chap 3: Constituent Materials

- Chap 4: Standards for Piping Components

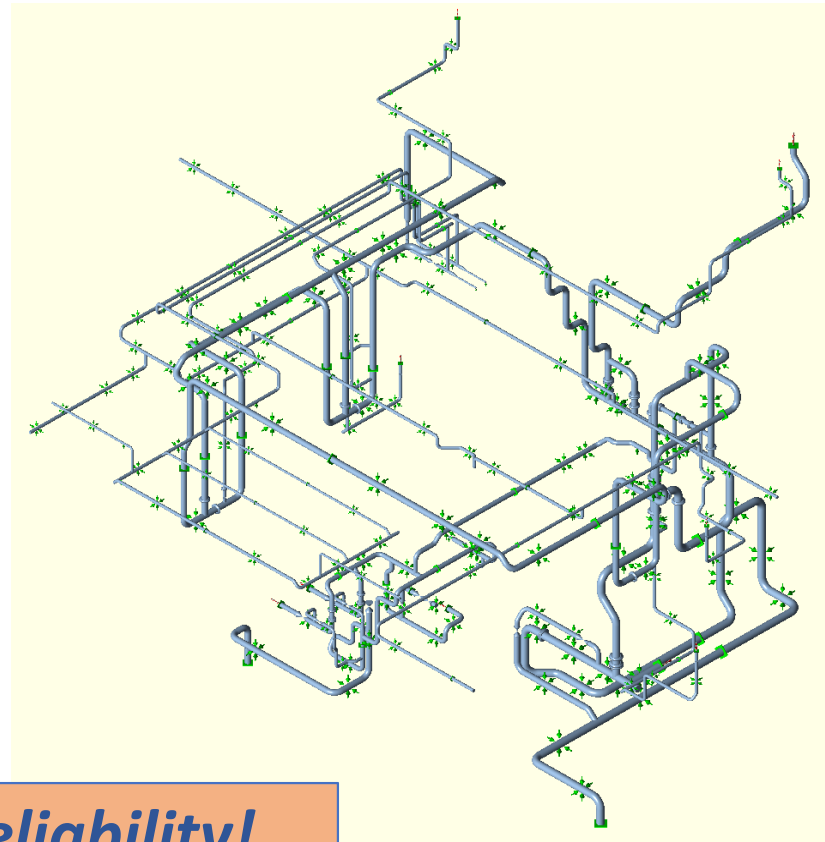- Chap 5: Fabrication, Assembly, and Erection

- Chap 6: Inspection, Examination, and Testing

ASME NM.2-2018

Glass-Fiber-Reinforced Thermosetting-Resin Piping Systems

ASME Standards for Nonmetallic Pressure Piping Systems

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Pipe Stress Analysis

Modeling

- Piping Geometry
- Material Properties
- Weights
- Design Conditions
- External Loads
- Multiple Load Cases
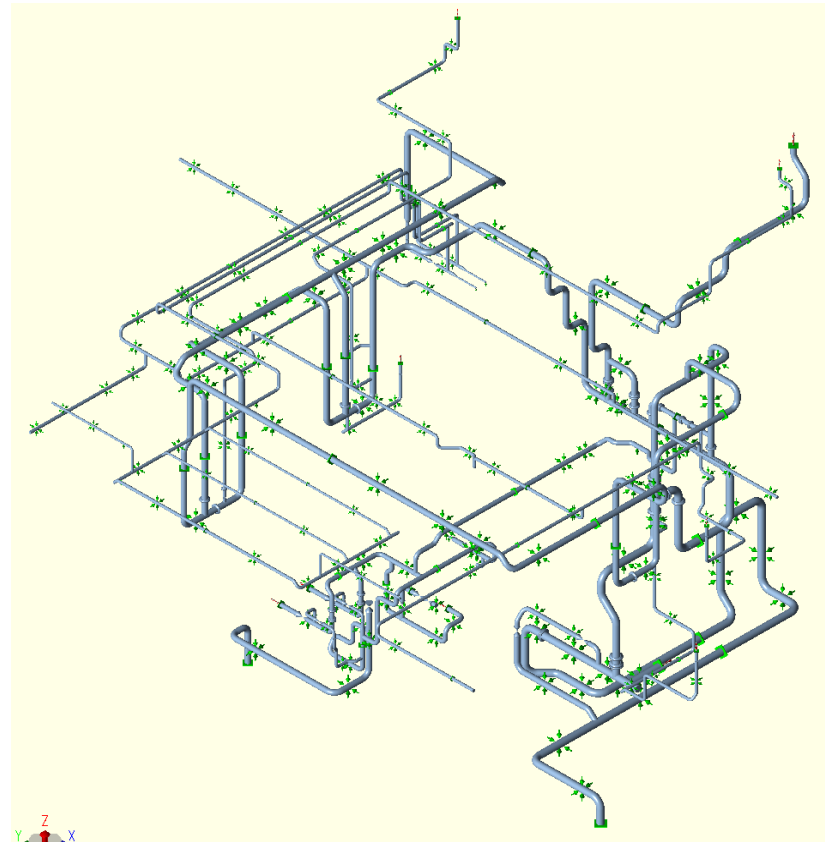
Need for Pipe Stress Analysis

- Analysis Validates the Piping System

- Identifies High Stress Areas

- Optimizes Arrangement
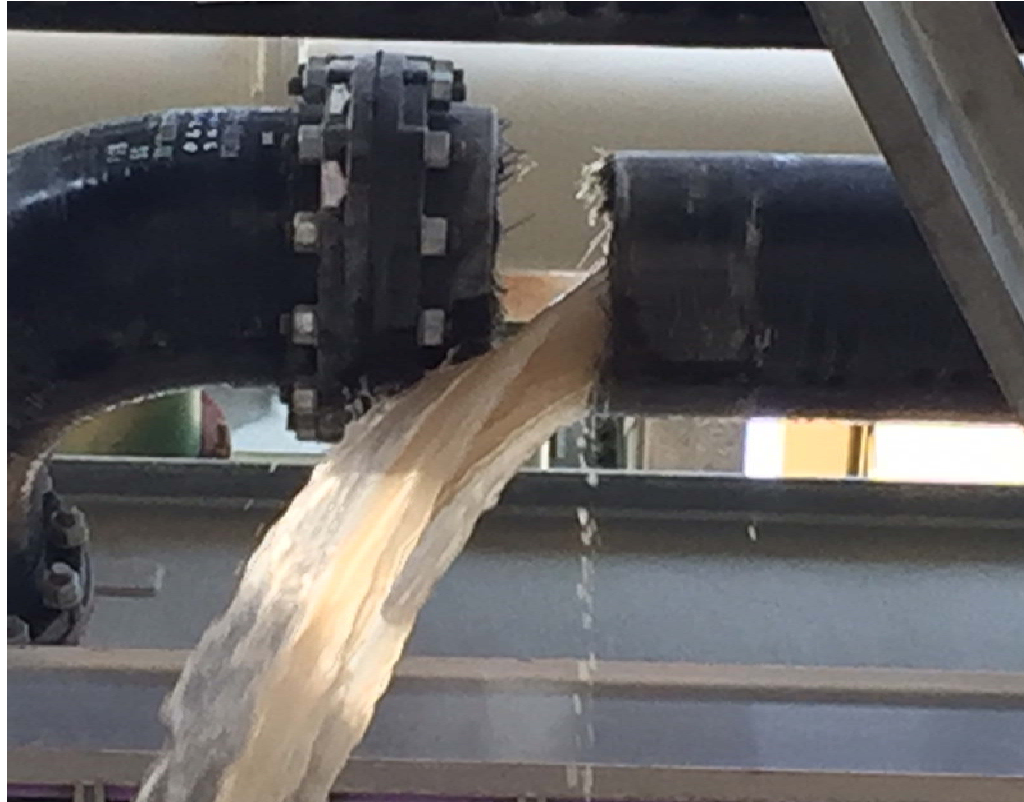 - For Supports
  - For Additional Reinforcements

Ensures Reliability!

Examination of Pipe Failures

Piping Failures
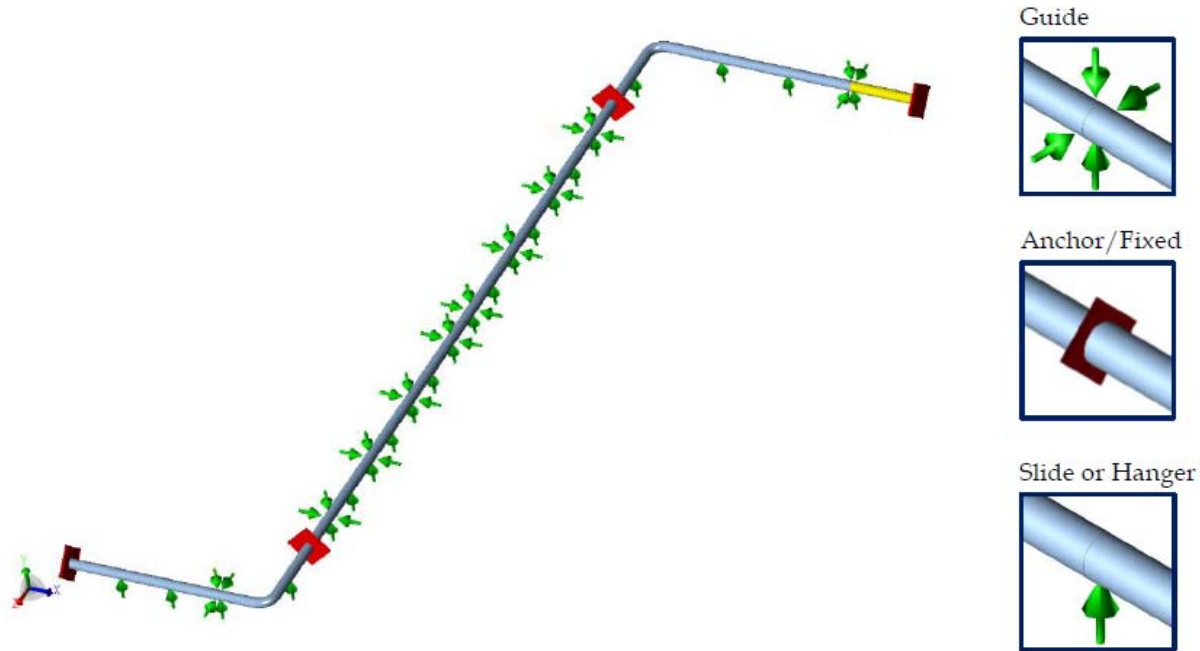
- Operational 7%
- Materials 7%
- Fabrication 23%
- Installation 26%
- Engineering 37%

Legend:
- Materials
- Fabrication
- Engineering
- Installation
- Operational
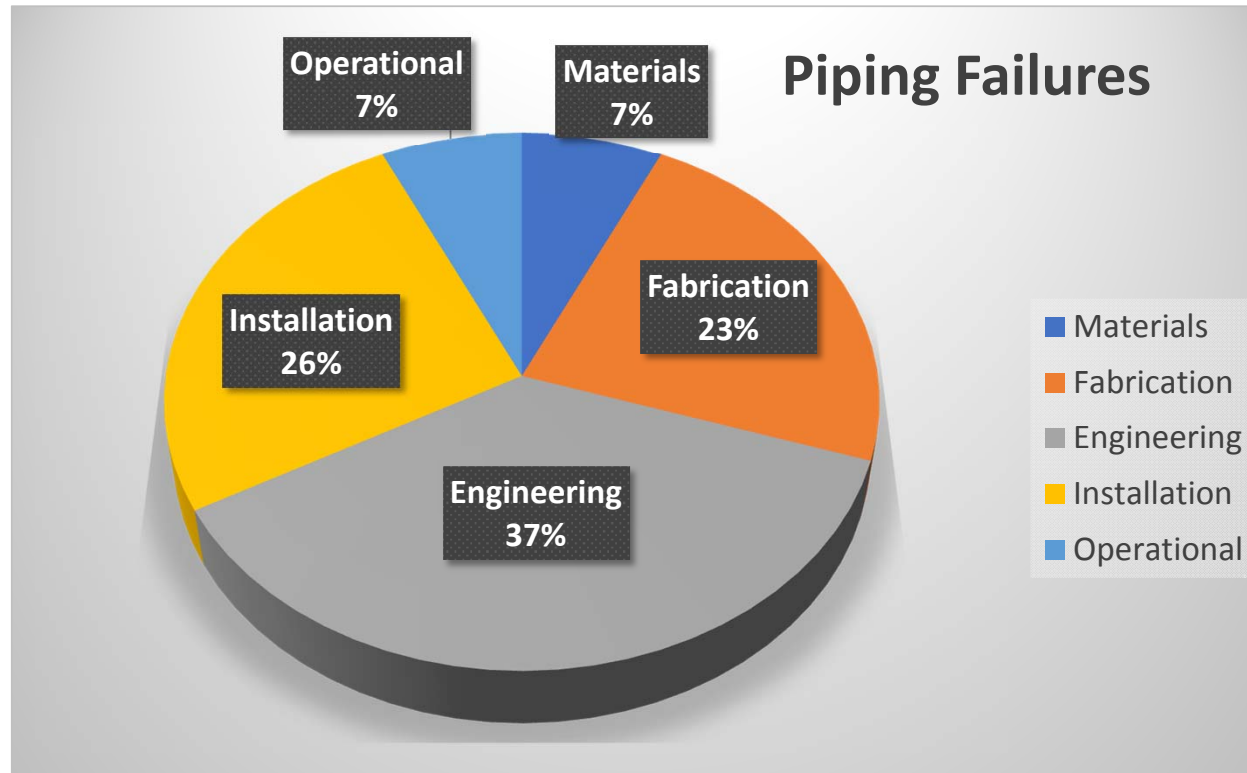
An Example: Displacement Stress

Considerations for Piping Arrangement

- Pipe Spans
- Pipe Supports
- Thermal Expansion
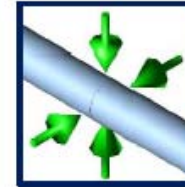- Equipment Connections
- In-line Components
- Flexibility

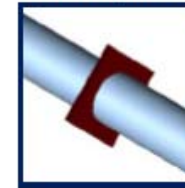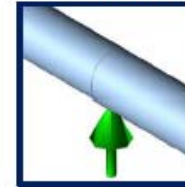# FRP Piping Arrangement- Fully Restrained System

Guide

Anchor/Fixed

Slide or Hanger

FRP Piping Arrangement-
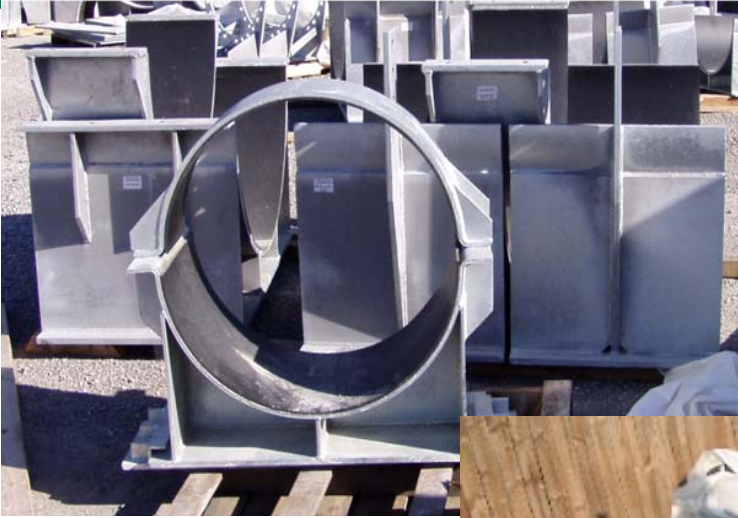Flexible System

Deficient Engineering

Examples of Deficient Pipe Supports

Pipe Supports for FRP Pipe

Lessons Learned

- Qualify Vendors

- Specifications should be Current

- Pipe Stress Analysis is usually needed

- Check Vendors Calculations

- Get Supports for FRP Pipe

Lessons Learned

- Set Expectations Early
- Require Certified Laminators
- Shop Inspections are Beneficial
- Field Inspection Improves Execution
- Flange Torqueing is Critical

Conclusions

Gateway to
the Future

- Understand the Fundamentals of the Material
- Analysis prevents Failures
- Pipe Supports are Important to Performance
- Certified Laminators and Inspection are needed to ensure of a Successful Installation

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