24-016

Challenges of Design and Fabrication of Fiber Reinforced Polymer (FRP) Flanges—A Review

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ABSTRACT

Fiber Reinforced Polymer (FRP) is an excellent material choice for a broad spectrum of corrosive fluids and, in many cases, offers the best value per dollar. FRP Flanges present the greatest design challenge of all standard piping components. The theory underlying the design of flanges is very complex. In addition, due to the nature of FRP material, proper fabrication of the flanges is as critical as the design. In this review, the challenges of making FRP flanges along with the design techniques and best practices of fabrication that will lead to a high-quality flange will be discussed.

RPS COMPOSITES

With over 45 years of experience, RPS Composites is a leading provider of composite pipe and vessel solutions for a wide range of industries, including mineral processing, chemical processing, power generation, and marine applications. Their expertise is underpinned by three flagship FRP manufacturing plants, strategically located to optimize production and delivery schedules. Committed to safety and service excellence, they deploy Field Service teams across the US, serving Fortune 100 industrial manufacturers and processors. RPS also plays a significant role in the energy transition, supporting projects related to hydrogen production, EV battery recycling, and carbon capture and storage, aligning with the growing demand for critical minerals. With a strong presence in North and South America, they have earned a reputation for the superior performance of their FRP piping, tanks, and vessels, securing major projects and offering both supply and installation services to their clients.

FIBER-REINFORCED MATERIAL VS. STEEL

In the dynamic worlds of mining and chemical industries, the choice of materials for pipes and tanks plays a key role in the success of operations. Traditionally, steel has been the go-to material for these critical components. However, in recent years, FRP has emerged as a formidable alternative. This section explores the advantages of using FRP pipes and tanks compared to steel counterparts:

1. Corrosion Resistance

One of the most significant advantages of FRP pipes and tanks in mining and chemical industries is their excellent resistance to corrosion. Chemical processes, aggressive chemicals, and high humidity levels in mines can rapidly degrade steel, leading to maintenance headaches and safety concerns. FRP, on the other hand, is resistant to corrosion, offering a longer service life.[1,2]

2. Lightweight

FRP pipes and tanks are notably lighter than their steel counterparts. This weight advantage could be beneficial, particularly in the mining industry, where the ease of transportation, installation, and reconfiguration is vital. Lighter FRP components could simplify logistics, and make handling in remote or challenging locations more manageable.[3]

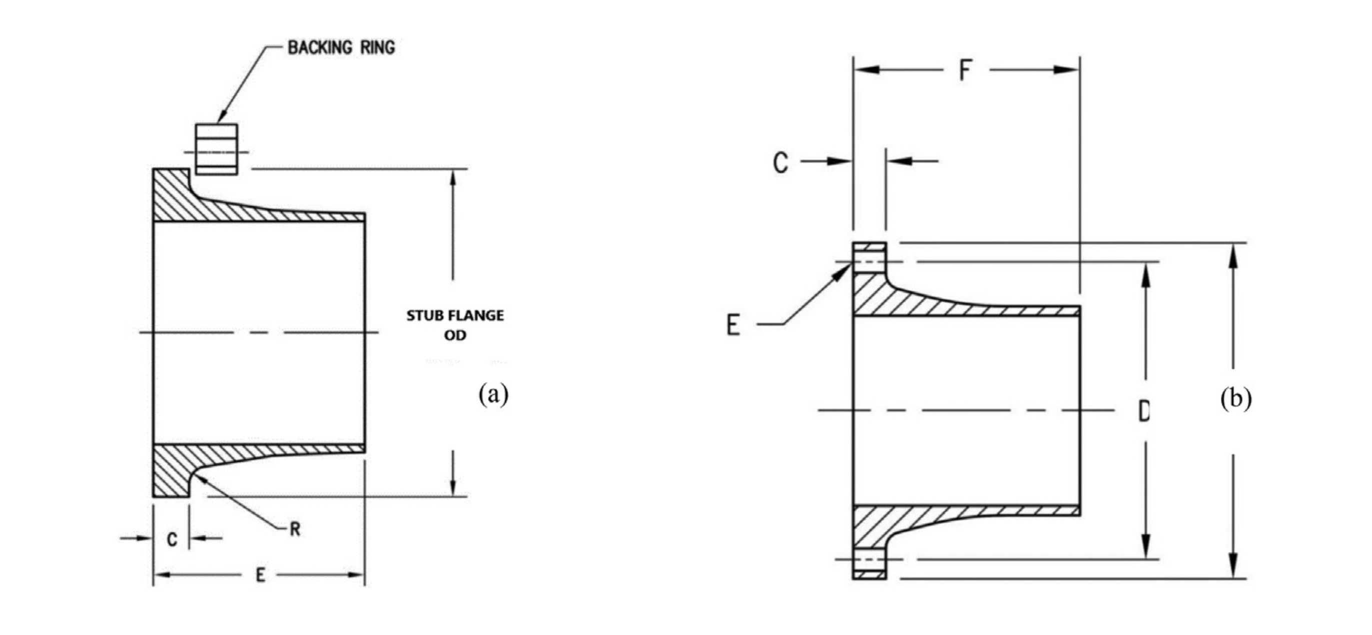

Figure 1. (a) LJ and (b) FF flange

4. Chemical Compatibility

s and solvents. FRP has a broader range of chemical compatibility compared to steel. It can resist the effects of a wide array of chemicals without suffering degradation, which steel might not withstand.[4,5]

5. Customization

FRP components offer extensive customization options, allowing for the creation of intricate shapes in a single piece without the requirement for additional welding or joints. Furthermore, the layered composition of FRP enables the design to be tailored for maximum strength in the desired direction, thereby optimizing both the cost and weight of the components.[6]

6. Insulating Electrical Properties

FRP is a non-conductive material. This property is valuable in environments where electrical conduction is hazardous. It should be noted that the corrosion barrier of the FRP pipes and tanks can be made conductive when grounding is a requirement

7. Insulating Thermal Properties

FRP offers good thermal insulation properties which is beneficial where there is a need to design for thermally insulated components.[7] Similar to the electrical conductivity, the thermal properties of the corrosion barrier can be increased if proper heat distribution properties are beneficial.

8. Reduced Maintenance Cost and Longevity

Steel pipes and tanks demand an integrity and rehabilitation plan that can include blast cleaning, re- painting, geometry inspections, ultrasound assessment, and more. The non-corrosive nature of FRP reduces the need for regular upkeep, saving both time and money. In mining and chemical industries where assets are expected to endure harsh conditions, the durability of FRP can be a significant cost-saving factor over time.

9. Environmental Impact

FRP materials have a smaller carbon footprint compared to the production of steel. Using FRP aligns with sustainability goals and regulatory requirements[8].

As technology and manufacturing techniques continue to advance, FRP will likely play an increasingly vital role in ensuring the efficiency, safety, and sustainability of mining and chemical operations. These industries are adapting to harness the benefits of FRP, recognizing it as a worthy alternative to steel for several applications.

FULL FACE (FF) AND LAP JOINT (LJ) FLANGES

A flange is a mechanical component that serves as a connection point in a system of machinery or piping. Flanges are used to facilitate the assembly and disassembly, alignment, and secure attachment of various components, such as pipes, valves, or other mechanical elements. They have

Table 1. LJ flanges vs FF flanges

Performance Aspect	FF	LJ	Comments
Design Pressure	✓	✓	For the common pressure ratings for FRP flanges, there is no difference between FF and LJ and both can be designed to take the pressure
Design Temperature	✓	✓	There is no difference between FF and LJ regarding the design temperature
Installation		✓	With a loose backing ring, it is easier to align and install LJ flanges
Backing ring		✓	Since the backing ring is separate from the flange, a different material can be selected for the backing ring to take advantage of higher strength material when there is no contact with service fluid
Sealing		✓	Since the contact area for LJ flanges is smaller than FF flanges, a certain amount of torque will lead to higher seating stress in the gasket providing an easier seal.

bolt holes that allow for the connection of multiple parts, forming a sealed mechanical connection. There are two main types of FRP flanges commonly used in the industry, Full Face (FF) and Lap Joint (LJ) (see Figure 1)

A full-face flange is a type of pipe flange that is characterized by its solid, circular design, which covers the entire face of the pipe end.

A LJ flange is a type of flange used to connect two piping components and allows for easy alignment, disassembly, and maintenance. The LJ flange contact face only covers the area inside the bolts and not the entire face of the flange like FF flanges. It consists of two main components: (i) Stub End: This is a short, cylindrical pipe section with a larger OD than the pipe at the end. It is typically attached to one of the pipes being joined. (ii) Backing Flange: The backing flange is a separate, flat plate with bolt holes. It is usually made of a material such as carbon steel, stainless steel, or FRP. The backing flange is not laminated to the pipe and is free to rotate and move.Table 1 summarizes the difference between FF flanges and LJ flanges.

GASKETS

When using FRP flanges, it's crucial to select an appropriate gasket to ensure a reliable and leak-free connection. The choice of gasket material should consider the specific application, the chemicals or fluids being transported, temperature, and pressure.

One of the important factors to consider when selecting a gasket for FRP flanges is seating stress. This is the stress required for the gasket to conform to the flanges and provide a seal at the operating pressure. The most common type of gaskets being used with FRP flanges are soft gaskets (60–70 durometer) such as EPDM (Ethylene Propylene Diene Monomer), Viton, and neoprene. These rubber gaskets have the lowest seating stress of all types hence less demanding to achieve a seal.

For more chemically aggressive services, expanded PTFE (Polytetrafluoroethylene) can be used for its exceptional chemical resistance. However, virgin expanded PTFE typically has a high seating stress which makes it unsuitable for FRP flanges. As a workaround, the gasket manufacturers have created different low seating stress expanded PTFE gaskets using a variety of techniques such as re-structuring the gasket or reducing the area. This low seating stress makes them suitable for FRP flanges.

FRP FLANGE DESIGN

Designing flanges poses a significant challenge among standard piping components due to the intricate nature of flange design theory and the reliance on trial-and-error methods. The process typically involves assuming a flange configuration, assessing its stress levels, and if deemed unacceptable, iteratively adjusting the configuration and reevaluating the stresses. Flange design is inherently complex for several reasons:

- Flanges consist of multiple components that act together, such as the flange ring, flange hub, bolts, and gasket.
- The individual components of the flange are typically composed of materials with significantly different properties. For Instance, the bolts are metallic and hence very stiff; the gasket is typically elastomeric and hence very flexible.

As a result, most flange design approaches are either "simplified" elastic analyses or empirical in nature. The primary design methods used for contact molded, full-face FRP pipe flanges, closely align with standards like ASME NM.2[9], ASME RTP-1[10], and ASME BPV Code Section X[11].

These methods are adapted from metallic flange design principles outlined in ASME BPV Code Section VIII[12] for metallic pressure vessels. Notably, Section VIII assumes a raised-face configuration where there is no contact between flanges beyond the bolt circle, leading to high longitudinal hub stresses. Such stress levels are challenging for materials like FRP to handle, which is why FRP flanges are frequently designed with full flange face contact to reduce these stresses. This configuration, however, necessitates higher initial bolt loads to effectively seat gaskets, limiting its use to relatively low pressures, such as 150 psi.

The ASME standards mentioned here, do not yet offer a design method for FRP lap joint flanges. RPS Composites has an internal design method developed for the lap joint flanges that closely follows the approach used for full-face flanges but with contact confined within the bolt circle, making the ASME Section VIII design method more applicable. We have qualified our design method for lap joint flanges by meeting the performance requirements specified in ASTM D5421[13]. These requirements include a sealing test, bolt torque test, and burst test, ensuring that the flange can withstand pressure, torque, and burst conditions without failure.

While the discussed design methods are suitable for contact-molded flanges, it's worth noting that some FRP flanges are manufactured through methods other than contact molding, such as filament winding. In this manufacturing method, the flange mold is rotated about the flange axis, and continuous strands of glass are applied in the hoop direction. These flanges exhibit superior hoop strength and stiffness, enabling them to withstand higher bolt-tightening and operational loads. Due to their non-standard geometry and orthotropic material properties, standardized design methods have yet to be established. Therefore, filament wound flanges are typically designed empirically, with proven configurations modified as needed to meet specific design conditions. Verification of filament wound flange performance can be conducted using the criteria outlined in ASTM D4024[14] which includes a sealing test, bolt torque test, and burst test.

The main challenge inherent in the design of a flange stems from the limited space available for the flange hub. Typical applications necessitate compliance with standardized bolting patterns as per ASME B16.5[15] and ASME B16.47[16]. These standards specify the dimensions of the flanges including the Bolt Circle Diameter (BCD) and the flange Outside Diameter (OD). On the other hand, the inner pipe diameter (ID) imposes limitations on the inside dimension. These two constraints invariably restrict the thickness of the flange hub, regardless of the necessary thickness to withstand applied mechanical stresses. This issue is further exacerbated when designing LJ flanges or machine-backed FF flanges, where all hub material on the back of the flange up to the ID of the backing ring must be removed to accommodate the backing ring. In the case of spot-faced FF flanges, only minimal material is machined to fit a narrow washer, retaining some material between the bolt holes that contributes to the flange's structural integrity. Having a thick sacrificial corrosion barrier (CB) or dual laminate products (an FRP pipe lined with thermoplastic corrosion liner) will further limit the available space for structural layers of the hub compounding the issue.

Unfortunately, there is no one-size-fits-all solution to this problem. Multiple approaches can render a flange design viable, but each solution comes with undesirable side effects. The choice of the best solution depends on several critical factors, including customer-specific requirements and constraints, cost considerations, and prevailing design conditions. In this discussion, we elaborate on these potential solutions:

1. Increasing the Flange Thickness

The limitation imposed on hub thickness, as explained earlier, results in elevated stresses within the hub. One solution to mitigate these elevated stresses is to increase the flange thickness. Unlike the hub, there is typically no inherent limitation on increasing the flange thickness. However, this approach presents certain drawbacks:

- A substantial increase in flange thickness is often required to reduce hub stresses to acceptable levels.
- It increases the overall cost of flange, especially for larger sizes
- Longer bolts may be required to accommodate the increased flange thickness
- An increase in the weight of the flange is another consequence of this strategy.

2. Reducing the Pipe ID

As explained in the preceding section, hub thickness is determined by the dimensions of the pipe ID and BCD. One solution to create more space for the hub is to reduce the pipe ID. However, this approach has certain disadvantages:

- A reduced ID could cause flow-related issues and result in increased pressure losses.
- This may lead to higher fabrication costs, as a custom mold may be required to accommodate the altered pipe ID.

3. Changing Flange Drilling Patterns or Sizing:

Relief from the constraints on hub thickness can be achieved by expanding the BCD. This can be done by altering the drilling pattern to a higher pressure class, such as using Class 300 drilling pattern for a 150 psi flange. A similar

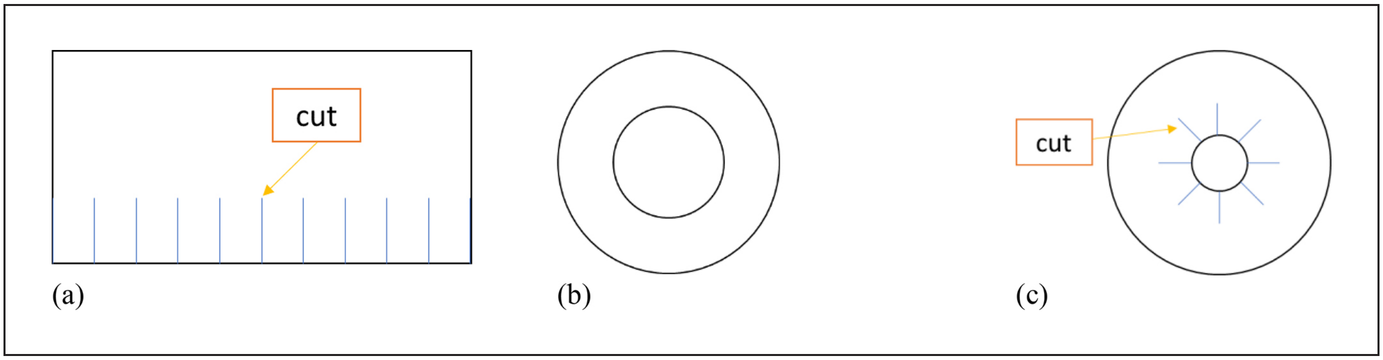

Figure 2. Typical laminate shapes used in the fabrication of FRP flange (a) skirt (b) ring (c) star

alternative is to increase the size of the flange while keeping the pipe size, for example, using a 3" flange on a 2" pipe. However, this strategy has certain disadvantages:

- Project costs increase due to the procurement of more expensive flanges and potential equipment adapted to the revised drilling pattern/size.
- The unavailability of mating equipment compatible with the new drilling pattern/size may pose additional complications

FRP FLANGE FABRICATION

Similar to the design of FRP flanges, the fabrication of the flanges is not a straightforward process. Here is a summary of some common practices in the fabrication of hand lay-up (HLU) flanges.

There are two main fabrication methods for FRP HLU flanges, integral flanges and flanges on pipe. In the flange-on-pipe method, a premade pipe will be used as a starting point and the rest of the flange will be laminated onto the pipe. In the integral method, there is no premade part and the whole flange will be made from starch.

The flange-on-pipe type is usually less expensive because long lengths of pipe can be made on a mandrel, cut into pieces, and then used for flanges, reducing the time required for flange fabrication. On the other hand, integral flanges offer superior structural integrity as all layers including pipe layers are interconnected to the flange face. It should be noted that regardless of the type of fabrication the flanges are designed adequately for the operating conditions.

FRP flanges are typically made using the reinforcement shapes shown in Figure 2.

- Skirts are rectangular fabrics with cuts on one side. This fabric is wrapped around the flange stub, with the cut pieces extending onto the flange face. The skirts increase the thickness of the stub, hub, and flange.
- Rings are circular fabrics with a hole in the middle with the size of the hub. The rings increase the flange thickness without altering the hub or stub thickness.
- Stars are similar to rings with smaller holes in the middle and some cuts. By applying stars on the flange face, the cut portion of the star extends onto the hub. Stars contribute to the flange thickness and depending on the dimensions could contribute to the hub thickness. Stars are not as common as rings in the industry.

There is no standard method of fabrication and typically each manufacturer uses a different method based on their experience, tooling availability, and comfort. The complexity of fabrication typically arises from the following factors:

- Different ways to achieve the specified thicknesses do not necessarily lead to the same flange quality.
  - The interdependency of thicknesses of different sections.
- Strict tolerances, especially in the case of LJ flanges and FF flanges with backing rings.
- The geometry makes it more challenging to apply and roll the reinforcement.

Due to these challenges, proper fabrication planning is as important as proper design in achieving a high-quality FRP flange.

Another major contributing factor in the fabrication of high-quality flanges is the number and distribution of the layers that connect the flange face to the hub, i.e., skirts and stars (with proper dimensions). Since the flange thickness is usually larger than the hub thickness some ring layers are required to build up the flange. However, stacking large numbers of rings without having some interspersed skirts could lead to flange with lower structural integrity. There is no hard-and-fast rule for the number of rings allowed between skirts. However, skirts or contributing stars should be distributed between the rings as evenly as practical.

DESIGN FOR FABRICATION

In the last two Sections, the challenges of the design and fabrication were discussed. The most common practice in the industry is designing the flange first and then developing a plan to fabricate it. Since the fabrication plan is typically not straightforward, the final achieved thicknesses are often different from the designed ones. In addition, there is always a risk of making a low-quality flange due to improper lamination planning.

Ideally, the fabrication plan should be made concurrently with the design of the flange. That is, creating detailed specifications for numbers, types, shapes, dimensions, and layer sequences during the design. This approach allows us to have a detailed fabrication plan and a compliant design simultaneously. Additionally, other considerations, such as pipe thickness for integral flanges and the butt joint length for flange-on-pipe, need to be properly incorporated into the design. To achieve this, numerous interconnected variables and trial-and-error practices come into play, which makes it impractical for the designer to manually keep track of all changes.

RPS has developed an internal tool (see Figure 3) that makes the design for fabrication possible. This tool is developed by VBA programming. After establishing the inputs of the design, including size, pressure, design factors, type of flange, etc., the designer can start by applying different types of layers. By adding each layer, the tool updates the achieved safety factors, dimensions, geometry, etc. It also keeps track of potential interferences between the hub and backing ring or spot face depth and warns the designer of any potential issues while providing visual aids of the achieved profile of the flange.

This tool makes the design and fabrication planning process very quick while reducing the chance of making mistakes. Once the design is completed, a detailed fabrication specification is also prepared.

FRP FLANGE INSTALLATION

Proper installation of flanges is the last step of using FRP flanges. In this Section, some of the most important factors that play a role in the successful installation of flanges are discussed.

Ensure that the gasket used for installation is the same gasket used in the flange's design. This information should be provided to the designer as an input.

- Using sealing rings on the flange face makes sealing easier when the gasket is flat. Use flat-faced flanges when the gasket has sealing ribs.
- Ensure that the gaskets used in abrasion systems have an inside diameter of at least ¼" larger than the pipe's inside diameter. This prevents the gasket from protruding into the flow and causing turbulence, which could result in an abnormally high rate of pipe erosion.

Alignment

Ensuring that mating flanges align well is critical, as misaligned flanges may be damaged during the bolting process.

Torquing the bolts is typically the step where installers deviate from the instructions provided by the FRP flange fabricator. This mainly occurs because they exceed the bolt torque values recommended by the vendor

- The maximum bolt torque should be provided by the fabricator/designer of the flange
- A torque wrench should be used. The use of air- powered or electric wrenches is not recommended unless they have an in situ torque control feature.
- Use either Teflon-coated or well-lubricated bolts, unless otherwise specified by the fabricator/vendor
- Start with 30% of the max torque value in a crisscross sequence.
- Repeat the previous step with 60% of the maximum torque.
- Repeat the previous step with 100% of the maximum torque.
- Torque all bolts to 100% one more time with a simple circular pattern (not crisscross)

It is not recommended to mate an FF FRP flange with an LJ flange or valve with lining. In situations where it is inevitable, using a spacer ring or an FRP Lap Joint flange is advisable, as it provides a solution that minimizes stress levels. The spacer ring should have higher stiffness than the gasket.

CONCLUSION

The challenges surrounding the design and fabrication of Fiber Reinforced Polymer (FRP) flanges are complex and multifaceted. FRP materials offer numerous advantages over traditional steel counterparts, such as corrosion resistance, lightweight properties, chemical compatibility, customization options, and reduced maintenance costs. These benefits make FRP an attractive choice for various industries, including mining and chemical processing, where the reliability and longevity of components are crucial.

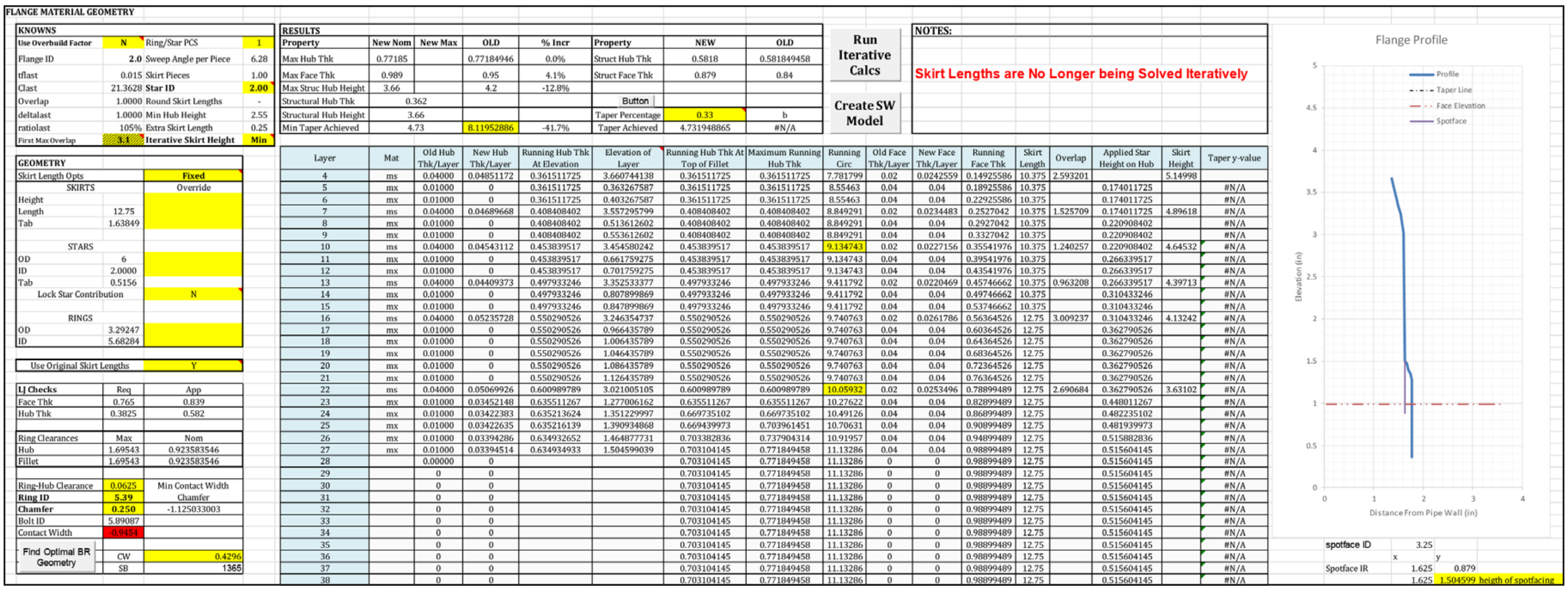

Figure 3. Screenshot of the RPS internal tool for designing flanges

The design of FRP flanges is a complex endeavor due to the unique properties and requirements of these materials. Different manufacturing methods and material combinations necessitate careful consideration and planning during the design phase to achieve the desired results. Proper planning for fabrication is essential to ensuring high-quality flanges that meet safety and performance standards. RPS Composites has developed a valuable tool that enables concurrent design and fabrication planning, streamlining the process and reducing the risk of errors. This innovation enhances the efficiency of designing FRP flanges while improving the accuracy of the fabrication process.

Proper installation of FRP flanges is equally crucial, involving considerations such as gasket choice, alignment, and torque application. The importance of adhering to recommended installation procedures to ensure the integrity and longevity of the flange connections was discussed.

In summary, the challenges associated with the design and fabrication of FRP flanges are intricate and diverse, but they are essential to harness the benefits of FRP materials in various industries. By addressing these challenges with sound design principles, innovative tools, and meticulous fabrication practices, it becomes possible to fully realize the advantages of FRP flanges while ensuring the efficiency, safety, and sustainability of operations in the mining and chemical processing sectors.

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24-017

Characterizing Fire in Large Underground Ventilation Networks Using Machine Learning

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ABSTRACT

Underground mine accidents, such as mine fires, remain a health and safety risk to mine workers. Researchers at the National Institute for Occupational Safety and Health (NIOSH) are developing a data-driven, predictive model for characterizing the location and size of unknown underground fires. This study examines applying a machine learning-based model to predict fire size and location in a large underground metal mine based on hypothetical scenarios on the model performance. The results show that the size and location of an unknown fire can be determined with over 80% and 90% accuracy, respectively, and potentially help to reduce the risk of hazardous conditions for emergency response.

INTRODUCTION

Mine fires continue to occur, although at a very low occurrence rate; however, they remain a health and safety risk to both surface and underground mining operations. Smoke and toxic gas are hazardous results of an underground mine fire, which flows to other areas of the mine via the ventilation network [1] posing a higher health and safety risk compared to the surface mine fires. Equipment fires have been recognized as being responsible for most mining injuries during 2000–2013 [2]. To reduce fire-caused injuries in underground mines, it is important to ensure the safety of the underground mine environment during a fire emergency.

In underground mines, an Atmospheric Monitoring System (AMS) is employed to monitor air quality parameters such as air velocity and other gasses concentrations such as methane, CO, and CO2. The use of an AMS for early warning and fire detection has a significant potential to enhance the safety and well-being of underground miners [1]. The AMS has been used to develop methodologies to characterize an unknown fire in the Safety Research Coal Mine (SRCM) at the Pittsburgh Mining Research Division site and to determine fire location using carbon monoxide (CO) arrival time and concentration [3-5].

An underground mine fire could cause changes in the mine ventilation system by increasing airway resistance by 10%–20% [6], which could lead to changes in airflow quantities and airflow directions. Such changes could unexpectedly contaminate fresh air escape routes. Large-scale test results in the literature show that a typical burning of a wheel loader can generate a peak heat release rate of approximately 20 MW, a CO concentration of 900 ppm, and a smoke rollback of over 50 m in the mine entry that could pose a severe risk to underground mine workers [7].

The ventilation network in metal/nonmetal mines tends to have many airways and is complex with many branching-off zones. This complexity is compounded by using ventilation controls such as doors, regulators, booster fans, and auxiliary fans to deliver fresh air to the working faces. Therefore, there is a need to predict fire size and location within a mine to determine the potential impact of a fire emergency. Such a tool may provide mine operators the ability to evaluate and improve mine ventilation networks to mitigate risk of hazardous exposures to miners, and, to develop improved mine rescue plans for emergency responders.

Successful forward modeling of an underground mine fire scenario using mine fire simulation software requires