Design and Certification of Offshore FRP Piping Installations

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Abstract
FRP piping installations have significantly expanded their application in offshore industry in recent years. Although light weight, low cost, superior corrosion resistance, and simple maintenance have been recognized as major advantages of using FRP piping, the design and certification of FRP piping are typically not as well understood as those for metallic counterpart. Material anisotropy and long-term degradation of FRP require distinctive strength design methods, acceptance criteria and testing procedures. Regulatory safety requirements also impose design restrictions on electric conductivity and fire endurance that may not be significant for metallic pipes. This paper discusses these critical design and certification issues in a way that is consistent with the guideline recently published by American Bureau of Shipping. Three major topics are covered in this paper, including (1) the strength criteria and recommended design methods for FRP pipes, (2) the approaches for achieving electric conductivity requirements, and (3) the interpretation of the roles of various testing requirements.

Introduction
Fibre Reinforced Plastic (FRP) piping has significantly expanded their application in offshore industry in recent years [11]. Although light weight, low cost, superior corrosion resistance, and easy maintenance have been recognized as major advantages of using FRP piping, the design and certification of FRP piping are typically not as well understood in offshore industry as those of metallic counterpart. There exist several standards with various levels of details addressing design and certification of FRP piping installed on offshore platforms [1-2, 7, 10, 14, 15]. The presentation
in this paper is consistent with the performance-based guideline developed by American Bureau of Shipping (ABS) [1]. Major contents of this ABS guideline are summarized in Figure 1.

This paper is focused on the discussion of critical design issues, recommended practices, and certification requirements for the offshore FRP piping. Main topics covered in this paper include structural design methods and long-term strength criteria for FRP piping components, electrical conductivity requirements and design approaches, and interpretation of the roles of various testing requirements. Other important issues including fire endurance, visual inspection, and onboard testing are also briefly discussed.

**Structural Design**

Due to the nature of anisotropy and performance degradation of FRP materials, the structural design for FRP piping follows a unique philosophy. The structural design typically includes the design for internal pressure, external pressure, axial strength, bending strength, and buckling strength. Testing based methods are required in most cases in order to establish the long-term performance limits of FRP piping components, whilst the design strain based calculation may also be used along with short-term verification tests.

According to the ABS guideline specifically [1], the long-term (sustained) allowable internal pressure can be obtained through either short-term burst pressure test following ASTM D1599 [4] or long-term hydrostatic pressure test following ASTM D2992 Procedure B [7]. Different safety factors are defined to give the credit to the long-term pressure testing. Design strain method is also allowed as an alternative for internal pressure design.

Since FRP is a non-isotropic material, there is often more than one allowable stress. As a minimum, there are three long-term allowable stresses that need to be defined: 1) allowable axial stress, 2) allowable hoop stress, and 3) allowable bending stress. The allowable hoop stress $\sigma_h$ is determined by long-term hydrostatic pressure test and the following equations:

$$\sigma_h = \frac{\sigma_{qs}}{\eta}$$

$$\sigma_{qs} = \frac{f_1 P_{LHP}D}{2t_r}$$

where $\sigma_{qs}$ is typically called the qualified stress; $P_{LHP}$ denotes the long-term hydrostatic pressure obtained following ASTM D2992 Procedure B [7]; $f_1$ is a factor to represent the 97.5% Lower Confidence Limit (LCL) of $P_{LHP}$, based on a design life of 20 years; $t_r$ is the average reinforced thickness of the wall (i.e., excluding the thickness of linear and added thickness for fire protection); $D$ is the mean pipe structural diameter calculated by $D = D_i + 2t - t_r$ where $D_i$ and $t$ denote the inside diameter and total wall thickness, respectively:
The long-term allowable axial stress is determined by a combination of tests and calculations. Since FRP piping components are made of non-isotropic materials, the allowable axial stress is typically
different from the allowable hoop stress. For a generic 55-degree filament wound pipe, the allowable axial stress actually varies with the magnitude of hoop stress. Therefore, it is normally necessary to develop a bi-axial (hoop-axial) failure envelope, from which the short-term and long-term allowable axial stress can be derived. Figure 2 shows a flowchart, which is adapted from the ABS Guide [1], to demonstrate the overall procedure to establish a failure/design envelope. In addition to the long-term hydrostatic pressure test following ASTM D2992 Procedure B [7], two more short-term tests with target bi-axial stress ratios hoop/axial=0/1 (pure axial tension following ASTM D2105 [5]) and hoop/axial=2/1 (internal pressure with capped end effect following ASTM 1599 [4]) are required to determine the allowable axial stresses of FRP components. Design strain based calculation is also a valid tool for determining the pure axial strength, where bi-axial stress ratios hoop/axial=0/1, of a non-isotropic FRP component.

The long-term allowable axial stress with bi-axial stress ratio hoop/axial=0/1 is calculated by

\[ \sigma_a = \frac{0.5 r \sigma_{qs}}{\eta} \quad \text{and} \quad r = \frac{2 \sigma_{sa}}{\sigma_{sh}} \]

where \( \sigma_a \) is the long-term allowable axial stress with bi-axial stress ratio hoop/axial=0/1; \( \sigma_{sa} \) is ASTM D2105 [5] axial strength or design strain based axial strength (short-term) for pure axial strength; \( \sigma_{sh} \) is short-term hoop strength due to internal pressure obtained from ASTM 1599 [4] burst test; \( \eta \) is safety factor with default value of 1.5 for normal operation; \( r \) is bi-axial failure stress ratio.

The long-term allowable axial stress with bi-axial stress ratio hoop/axial=2/1 is determined by

\[ \sigma_{a1h2} = 0.5 \sigma_{qs} / \eta \quad \text{when} \quad r \leq 1.0 \]
\[ \sigma_{a1h2} = 0.5 r \sigma_{qs} / \eta \quad \text{when} \quad r > 1.0 \]

where \( \sigma_{a1h2} \) is the long-term allowable axial stress with bi-axial stress ratio hoop/axial=2/1; \( \sigma_{qs} \), \( r \) and \( \eta \) are as defined above.

With the long-term allowable axial stresses determined above, a failure envelope as shown in Figure 3, for example, can be established. A long-term allowable (design) envelope for FRP pipes is obtained after applying the safety factor \( \eta \). The sum of the axial stresses due to pressure, weight, expansion and other dynamic and sustained loads should not fall outside this allowable envelope. Similar allowable envelope can also be established for other FRP piping components such as fittings and joints. Different bi-axial failure stress ratio \( r \) should be used to define the mechanical properties of non-isotropic materials. When no reliable data are available, the biaxial stress ratio of pipes, fittings or joints may be selected from the default values given in Table I.

Determination of the long-term allowable bending stress is not as straightforward as that of hoop and axial allows. There is also no reliable testing method that can directly evaluate the long-term bending behaviour of FRP pipes. The ABS guidance provides a combination of short-term tests and design strain based calculations as follows [1]:

\[ \sigma_b = \frac{0.5 r_b \sigma_{qs}}{\eta} \quad \text{and} \quad r_b = \frac{2 \sigma_{sb}}{\sigma_{sh}} \]

where \( \sigma_b \) is the allowable bending stress; \( \sigma_{sb} \) is the short-term bending strength obtained by bending test following ASTM D2925 [6] or ASTM D790 [9] or by design strain method; \( \sigma_{sh} \) is the short-term hoop strength obtained by burst pressure test following ASTM D1599 [4]; \( r_b \) is the bi-axial bending
failure stress ratio; \( \eta \) denotes the safety factor with default value of 1.5 for normal operations; \( \sigma_{qs} \) is the qualified stress as defined above.

As noted in the definition of long-term allowable stresses, the safety factor \( \eta \) has default value of 1.5 for normal operations under sustained loads. Sustained loads generally include internal pressure, external pressure, vacuum, piping weight, insulation/fire protection weight, fluid weight, inertia loads due to motion during operation (e.g., daily wave action), and sustained environmental loads (such as ice and snow). In the case of sustained thermal expansion induced stresses, which is self-balance loading, the default safety factor can be reduced to 1.2. When considering the stresses due to occasional loads, the default safety factor is 1.12. Occasional loads include, for example, internal pressure from hydro-testing, pressure surges from water hammer, pressure surges from safety valve releases, transient equipment vibrations, impact, inertia loads from motion during transportation, occasional environmental loads (such as wind from storms), and overpressures from blasts and other occasional loads. It should be noted that certain design conditions such as severe internal or external corrosive conditions, elevated temperatures, and cyclic loading (more than 7000 cycles), may necessitate a reduction in the allowable stress values [14].

For external overpressure and buckling strength, testing methods should be adopted to determine the failure limit due to lack of reliable calculation methods for FRP pipes. A default safety factor of 3 is typically used for these two cases.

![Flow Chart of Structural Design of FRP Piping](image)

**Figure 2. Flow Chart of Structural Design of FRP Piping**
Electrical Conductivity

Uncontrollable electrostatic discharge of FPR pipes may ignite a spark and introduce explosions in a vapour rich environment. The requirement of electrical conductivity for the offshore FRP piping traditionally follows IMO Resolution A.753(18) [12], which was originally enacted for using plastic pipes in ships. Non-conductive FRP piping is therefore not allowed in hazardous areas onboard ships and offshore platforms regardless of the fluid being conveyed. The practical experience in offshore applications, as discussed in [16], however, reveals that the prescriptive guidance given by the IMO regulation appears to be overly restrictive.

The ABS Guide [1] provides a performance-based approach with consideration of potential electrostatic accumulation and discharge mechanisms. For an FRP piping conveying fluids with conductivity less than 1000 pS/m (pico-siemens per meter), the pipes and fittings must be internally conductive with resistance per unit length less than $10^5$ Ohm/m, and provide an adequate electrical path to ground. Seawater and crude oil typically have conductivities higher than 1000 pS/m (deionized water, for example, is about $10^6$ pS/m), while natural gasoline, diesels, kerosene, heating oils, lubricating oils and jet fuels typically have conductivities lower than 1000 pS/m.

For an FRP piping pass through hazardous areas, two design approaches can be used to manage the electrical conductivity requirement. The first option is to follow the current IMO regulation [12] such that the FRP pipes and fittings must be externally conductive with resistance per unit length less than $10^5$ Ohm/m, and provide an adequate electrical path to ground. As an alternative, the required level of electrical conductivity may also be determined through a performance-based approach. Table II can be used as a guideline for such performance based design approach in
association with the severity level of external charge generating mechanism. Typically tribocharging can be considered as one of the weak forms of external charge-generating mechanism, while unshielded thunderstorm strikes, tank washing, cleaning, purging, and loading operations, as well as an efflux of a two-phase fluid past the FRP pipes can lead to much stronger external charge generating. Other than the performance based criteria for various severity levels of external charging mechanisms, the recent study [12] may provide a possible risk assessment criterion that is directly associated with the potential ignition risk in specific vapour rich environments on offshore platforms.

In the case of externally conductive FRP piping coated with external insulation/fire protections, the insulation/fire coating must also be externally conductive and have an adequate electrical path to ground. Electrically conductive coatings may also be used to provide required external conductivity for non-conductive FRP pipes, provided that the integrity of insulation/fire coatings can be maintained and has an adequate electrical path to ground.

### TABLE II. Electrical Conductivity Performance Based Assessment Guidelines [1]

<table>
<thead>
<tr>
<th>Service Conditions</th>
<th>Guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal charge generating mechanisms</strong></td>
<td></td>
</tr>
<tr>
<td>Piping that contains fluids with conductivities greater than 1000 pS/m</td>
<td>No internal conductivity requirement.</td>
</tr>
<tr>
<td>Piping that may contain fluids with conductivities less than 1000 pS/m</td>
<td>Piping is to have a resistance from inside to outside the pipes of $10^5$ ohms per meter or less. Conductive piping and all isolated metal objects of significant size are to be earthed with a maximum resistance to earth of $10^6$ ohms.</td>
</tr>
<tr>
<td><strong>External charge generating mechanisms</strong></td>
<td></td>
</tr>
<tr>
<td>Piping not located in hazardous areas.</td>
<td>No external conductivity requirement.</td>
</tr>
<tr>
<td>Piping located in hazardous areas that may be exposed to weak external charge-generating mechanisms during normal operations</td>
<td>No external conductivity requirement except all isolated metal objects of significant size are to be earthed with a maximum resistance to earth of $10^8$ ohms.</td>
</tr>
<tr>
<td>Piping located in hazardous areas that may be exposed to moderate external charge-generating mechanisms</td>
<td>Piping is to have a resistance of $10^5$ ohms per meter or less. Conductive piping and all isolated metal objects of significant size are to be earthed with a maximum resistance to earth of $10^8$ ohms.</td>
</tr>
<tr>
<td>Piping located in hazardous areas that may be exposed to strong external charge-generating mechanisms</td>
<td>Piping is to have a resistance of $10^5$ ohms per meter or less. Piping and all isolated metal objects of significant size are to be earthed with a maximum resistance to earth of $10^6$ ohms.</td>
</tr>
</tbody>
</table>
Fire Endurance

Fire resistance and high-temperature composite materials, such as carbon fibre reinforced composites and metal matrix composites, are widely used in aerospace or defence industries. However, these types of materials can hardly provide a cost efficient solution for the FRP pipes used in offshore oil and gas industry. To date, the most commonly used FRP piping material in offshore platforms is Glass Fibre Reinforced Plastics (GFRP), which typically have a relatively low fire endurance limit.

The ABS Guide [1] provides detailed testing requirements for increasingly stringent Level 1, 2, and 3 fire endurance tests, mainly following the IMO regulation and the current ABS requirements on using the plastic pipes onboard ships and MODUs [12,16]. Level 3 Modified fire endurance test based on the US Coast Guard regulatory requirement is also adapted into the ABS Guide. Although Level 3 FRP pipes have become commodity nowadays, there are only limited number of suppliers of Level 2 FRP pipes, and it is believed to be very difficult to produce cost efficient Level 1 GFRP pipes with currently available technology. Future development of risk assessment based acceptance criteria may be possible.

Recently published ISO 14692 [14] adopted a quite different fire performance rating system, which is developed from the previous UKOOA requirement. The fire performance of a pipe system is rated according to a fire classification code representing the prescribed level of service function, fire type and performance. The IMO requirements [12] are incorporated into the ISO 14692 along with a few more rating options.

FRP Pipe Joints

Either bonded or mechanical joints can be used to connect FRP piping. The common types of joints include adhesive-bonded joints, laminated joints, flanged joints, and other mechanical joints. The selection of the jointing method is typically determined by the balance of performance requirement, bending resistance, and ease of fabrication, qualification, and installation.

The ABS guideline provides qualification requirements on pipe bonding procedure [1]. More design guidance on various joint types is given in a number of codes such as ISO14692 [14] and API Spec 15HR [2].

Inspection and Onboard Testing

FRP piping components are susceptible to mechanical damage due to impact or improper handling. Lower impact energy levels may cause surface cracks or deeper cracks that would not be experienced in carbon steel piping. Therefore, lifting, loading, unloading and storage must be performed in accordance with procedures agreed upon beforehand between relevant parties. All FRP piping components need to be visually inspected after receiving and before and after installation. A comprehensive list of acceptance criteria for visual inspection and corrective actions are provided in ABS Guide [1].

After installation of a piping system, a hydrostatic test needs to be performed. The test pressure should normally not less than 1.5 times the design pressure, but no more than 1.5 times the rated pressure of the lowest rated component in the system. For piping required being electrically conductive, grounding also needs to be checked and tested. Wherever the electrically conductive piping is required, the resistance to earth (ground) from any point in the piping should not exceed 1 mega-ohm following the requirement of IMO, unless the risk assessment can justify higher resistance.
Summary

Key design methods and certification requirements for offshore FRP piping are discussed on the basis of ABS guideline. The performance based approach and criteria are presented for the structural design and electrical conductivity design.

Acknowledgements

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