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Design Method of FRP Pipe for Oil Well Frontier

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Abstract: New technologies such as the centrifugal winding method and improved GPI screw joints have expanded the application performance and research results of fiberglass reinforced plastic pipes over their long-term development. This study describes a strength design method for new oil well pipes, which are required for untapping deep oil wells as existing oil and gas fields become depleted. The durability of these pipes must exceed 30 years. Here, we quantified the withstanding pressure (100 MPa), depth (7000 m), heat resistance (250°C) and the pH of the corrosion resistance (pH = 2). We also propose a strength design method that specifies new OCTGs for a global standard; namely, the Global Oil & Gas Pipe Institute (GPI) standard.

Keywords: OCTG, EOR, Oilfield, FRP Pipe Design Method, Joint Coupling, Corrosion Resistance

1. Introduction

This design method of the Global Oil & Gas Pipe Institute (GPI) is related to the design of strengthened oil wells containing corrosion-resistant fiberglass reinforced plastic (FRP) pipes of GPI standard[1]. The pipe construction is shown in Fig. 1. The design method encompasses the tubing of the oil well, casing, and line pipes. With reference to ASME and ASTM-related standards and based on many years of research, we have developed a new method for designing oil well pipe applications. Material manufacturing is inspected by the GPI traceability or in accordance with the ASME Code Case N-155. Test procedures for quality assurance are subjected to the E oil majors of specification. Test methods for determining the acceptable levels of stress and strain must conform to GPI or ASTM. The technology and analysis methods for designing the GPI standard are described elsewhere [2].

2. Design Basis

2.1. Conventional Design Method

According to current design standards for FRP piping (ASTM, ASME), the material and thickness of the anticorrosion layer should be based on the deterioration and erosion properties of resin, while those of the reinforced layer should satisfy the required pipe strength. The allowable stress level of the reinforced layer should be decided from hydrostatic test results multiplied by a safety factor.

However, as has been confirmed through operational experience and design problems, such a macroscopic view of the design method cannot meet the FRP piping requirements under severe operating conditions, because the current rules do not necessarily consider the actual failure mechanism of FRP

Under internal pressure, FRP fails by the following mechanism: ① Initiation of micro-cracks with sound and no growth; ② Cracking of the anti-corrosion layer and subsequent penetration of water (weeping); and ③ Fast crack growth and bursting. Because the weeping pressure is controlled by cracking of the anticorrosion layer, the strain of the anticorrosion is critical in the piping design and must be evaluated. [2)–7)]

Moreover, the average failure shear stress of the secondary bonding joint is known to reduce with increasing adhesive length of the thread cone and GPI joint.

Other phenomena requiring evaluation are the delamination by fluid flow and the material deterioration during long-term operation, which significantly reduce the pipe strength. However, these phenomena are largely overlooked in current design standards. Our new FRP piping design method includes regulations for evaluating the strength and delamination of the anticorrosion layer and secondary adhesive joint. The details are given below. [8), 9)]

The design method is based on 45 years' worth of research and experience by Dr. Yoshinori Nishino and colleagues. The corrosion-resistant layer strength and the strength of the secondary adhesive joints were evaluated by measuring the amount of distortion under the allowable stress and stress of the loaded material (the *allowable distortion*). This approach is based on the design method[10–15] of OCTG constructed from FRP.

The design method is detailed below.

2.2. Strength Design Method of the FRP Pipe Developed by NBL

2.2.1. Design Basis of Anticorrosion Layer

Corrosion resistance and strength are the significant parameters in anticorrosion layer design. To ensure corrosion resistance, the constitution of the laminate materials must be appropriately selected and the layer constructed with sufficient thickness to last the designated lifetime.

Cracks in the anticorrosion layer are directly connected with pipe failure. Consequently, the strength of the anticorrosion layer depends on the allowable elongation of the laminate constitution, itself dependent on the design life of the FRP pipe. The above design basis is summarized in Table 1.

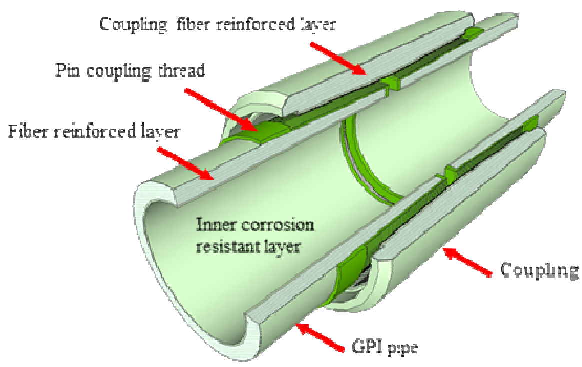

Fig. 1. *Design of GRP OCTG.*

Table 1. *Design Basis of Anticorrosion layer.*

Required Performance	Condition	Design Item
Corrosion Resistance	Environment, Fluid Condition Design Life	Selection of Laminate Constitution Material Thickness of Anticorrosion layer
Strength	Maximum Elongation of Anticorrosion layer Operation Load and Design Life	Allowable Elongation of Liner Safety Factor of Elongation

The maximum elongation of the resin layer varies not only with the kind of resin but also with its composition (that is, whether a corrosion resistant liner is included), as indicated in Table 2. The effect of fatigue and creep on the allowable elongation is also considered.

Table 2. *Maximum Elongation of Anticorrosion layer.*

Laminate Components	Resin	Maximum Elongation (%)
Resin only	Urethane-modified epoxy High-temperature imide-modified epoxy	6-18 2-8
PS-15-69 Anticorrosion layer	Urethane-modified epoxy High-temperature imide-modified epoxy	1-2 0.4-0.9

The maximum elongation of the anticorrosion layer is easily and accurately determined by the testing method indicated in Table 2. This method imposes a punch load on a circular test piece of the anticorrosion layer material and the reinforced structural core. The strain on the anticorrosion layer is measured by a strain gauge attached to the surface.

By this method, the maximum strain is imposed at the center of the anticorrosion surface. Because the crack will not initiate from the circumferential edge, the maximum elongation of the anticorrosion layer can be accurately measured by the strain gauge output. This method may also confirm the integrity of the interface between the anticorrosion layer and the reinforced structural core under shear stress.

2.2.2. Design Basis of Reinforced Structural Core

The required properties of the reinforced structural core are stiffness and strength. The stiffness must maintain the strain of the anticorrosion layer below the allowable limit, while being sufficiently durable to withstand constant, cyclic, and transient loads during operation within its designed life. The stiffness and strength of FRP pipes depends on both the pipe thickness and the laminate material constitution (denoting the content ratio and orientation of the fibers). In the structural design, the fatigue of FRP during operation depends on creep and long-term deterioration. The design items of the reinforced structural core are listed in Table 3.

Table 3. *Design Basis of Reinforced Structural Core.*

Required Performance	Condition	Design Item
Stiffness	Allowable Elongation of Anticorrosion layer Allowable Elongation of Reinforced Structural Core	Selection of Laminate Constitution Material Pipe Thickness Choice of Material
Strength	Allowable Stress Operating Load and Strain and Design Life.	Pipe Thickness

2.2.3. Design Basis of Joint

The pipe joint requires careful attention in the FRP piping design. In most current FRP piping designs, the strength of the FRP pipe joint is assumed to equal the adhesive strength of two plates, based on the mean shear stress.

However, experiments and analyses carried out by NBL Technovator Co., Ltd. have shown that the failure strength of the joints largely depends on the shear stress concentration in the adhesive layer. Therefore, multiplying the shear stress by a safety factor, as implemented in current design methods, may not be sufficiently conservative. As an example, the failure pressure (or weeping pressure) of pipe joints measured in hydrostatic tests is mainly controlled by the interfacial strength between the roving cloth layer and the chopped strand mat. In these tests, the mean shear stress reduces with increasing adhesive length. This trend occurs because the shear stress is concentrated around the edges of the adhesive layer, and the stress concentration factor is a function of the adhesive length and the stiffness of both layers.

The NBL design method allows either simplified analyses by algebraic expressions or detailed analyses based on finite element methods (FEMs). Simplified and detailed design methods require different safety factors. The orthotropic elastic properties of FRP are considered in the design analysis, and the allowable stress and strain is decided for each material. The optimal pipe thickness, geometry and dimensions are determined by trial and error.

2.2.4. Calculation Basis

In NBL design, the elastic constants of the laminate constituting materials are calculated by the linear law of mixtures or some other well-known equation (the common equations are listed in Appendix 2.) If necessary, equivalent elastic constants of the laminated wall can be calculated by the linear summation law.

In the simplified design method, the elastic constants obtained by one of the above equations are substituted into the algebraic expression shown in Section 3.

The detailed design method analyzes the stress by FEM. To this end, NBL has developed the FRP-X software, which performs two-dimensional plate, axisymmetric solid, and three dimensional shell analyses of anisotropic materials on a PC. FRP-X calculates the fiber direction and elastic modulus element by element and outputs the stress and strain components parallel and normal to the fiber. An auxiliary program, FRP-MESH, automatically generates a proper mesh from limited input data on the dimensions and material composition of the joint. It also computes the elastic constants of each material, the nodal coordinates, the node numbers composing each element, and the fiber direction of each element. Given the geometry and dimensions of the joint and the laminate constitution, the optimized joint that satisfies the stress and strain criteria at minimal cost is designed by trial and error. For example, the most-recently submitted design of the pipe joints is based on approximately 50 calculations, varying the geometry and material in each case. Incidentally, the complete set of analyses was completed in 10 hours, including preparation of the input data.

NBL is currently focused on investigating the fatigue strength and long-term deterioration of FRP materials and structures and will propose a life prediction method within a few years. Next, NBL plans to develop a CAD system for FRP structural design. Combining FRP-X, FRP-MESH, and a post processor, the CAD system will evaluate the FRP-X result with reference to the design criteria. The system will also include drawing software for displaying figures, tables, and documents. Moreover, NBL has established a failure simulation analysis method for the joint portion based on a nonlinear spring model. This simplified nonlinear technique simulates the entire failure process within a calculation time only 20–30% higher than required for linear analysis.

2.3. Design Basis

2.3.1. Basic Pipe Specifications

The pipe is constructed from the following materials:

Inner surface: The anticorrosive specifications are standardized in PS-15-69 (NBS).

Reinforced structure: Uses filament fiber reinforced core plastic.

Outer surface: Stacked anticorrosion layers.

The basic pipe dimensions are listed in Table 4. The nominal diameter is based on the inner diameter. The fitting dimensions will be shown later.

Table 4. *Basic Pipe Dimensions.*

Tubing Pipe			Casing & Line Pipe		
D inch	**Pipe Length L (mm)**	**Thread**	**D inch**	**Pipe Length L (mm)**	**Thread**
2-3/8			5		
2-7/8			5-1/2		
3-1/2			7		
4-1/2			8-3/8		
	9500 mm	GPI thread structure 8 round	9-5/8	9500 mm	GPI thread structure 8 round
			13-3/8		
			20		
			23-3/8		
			30		

The proper crest radius, total length of the thread root, and the taper angle of the thread, determined by detailed stress and strain analyses, may differ from the API standard.

2.3.2. Materials

・Raw materials

The raw materials are reinforced fiber: E glass fiber (0. 45 N/tex or higher); filament 23 μ; ε_{max} 2%; laminated density 50 vol% or higher; circumferential direction: axial direction ratio 2:1, 1000–2000 g/m^2; uniform filament length ± 0.1%; combination of non-woven fabric and CSM 100200 g/m^2; mat irrigation surface of 13μ; 200 filament; 50 mm cut.

The resin is epoxy-modified; pH 2 or higher; ε_{max} 4%–18%.

The usable temperature of resin (7 classes) ranges from its thermal deformation temperature (60 °C) to 250°C.

・Quality control

Application: The material supplier is traceable by GPI[16] or by a guarantee program constructed for the QC system and materials in accordance with ASME NCA-3800 and NCA-4135.

GPI traceability standard: the pipe manufacturer should enter the QC information of the material suppliers individual product number, manufacturing information, and performance test information, for traceability of the individual product.

The user constructs and installs the product and its matching products, based on the traceability number and conditions of use, enters the applicable construction information, and applies the quality assurance traceability by GPI signatories via the internet.

2.3.3. Design Scope

New oil well pipe design specifications (GPI load and durability performance)

The new oil well pipe specifications in the GPI standard stipulate a load of Grade 4 withstanding pressure and a Grade 6 heat resistance, as shown in the table below. The required corrosion resistance is pH 2, and (omitting the details) the short- and long-term endurance performance is 10 years and 50 years, respectively.

The standard length is 9.5 m, and the GPI standard connection fittings are pin coupling screws. The oil well pipes consist of tubing, casing and line pipe (see GPI standard.)

A GPI application product is named by its diameter, withstanding pressure grade, and heat tolerance. For example, Product 3-1/2M150 has a 3½-inch nominal diameter, a Grade M withstanding pressure, and a heat design grade of 150 °C.

Table 5. *GPI standard coupling (performance).*

Withstanding Pressure Grade	Tubing & Casing		Line Pipe		Designed Pressure	Short-term Load	10 years Durability	50 years Durability
E10	Tap water well, 100 m		For water		10 MPa	5 MPa	3 MPa	2 MPa
E20	Tap water well, 200 m below		For water		20 MPa	10 MPa	6 MPa	4 MPa
E40	Hot spring wells, 1,500-4,000 m		Shale gas, CNG		40 MPa	20 MPa	12 MPa	8 MPa
G	2,000-6,000 m for oil field		CNG gas tank		60 MPa	30 MPa	20 MPa	12 MPa
M	3,000-9,000 m for oil field		Special purpose 1		80 MPa	40 MPa	26 MPa	16 MPa
H	4,000-12,000 m for oil field		Special purpose 2		100 MPa	50 MPa	33 MPa	20 MPa
Withstanding Temperature (deg. C.)	-20 - 60	-10-80	0-110	25-250	25-200		Maximum 250	
Temp. Grade	60	80	110	150	200		250	
Product Marking	Examples of products 2-7/8G-80: one coupling, in GPI tube with the other pin screw, outer diameter 2-7/8 inches, G grade withstanding pressure, 100 degrees C. heat. Examples of products 5(W)E20-80: in GPI tube with both ends pin screw, outer diameter 5 inches (casing inner tube), E20 grade withstanding pressure, 80 degrees C. heat. Examples of products 3-1/2M-100: 3-1/2 inches at GPI coupling, pressure-resistant M grade, 100 degrees C. heat.							

Reference: API standard pipe design specifications

Long-term load: Internal pressures up to 3000 psi (21 MPa) are imposed by the buried soil pressure, and self-restraint loads are imposed by heavy thermal expansion and the piping reaction force.

Short-term load (for buried piping only): This constitutes the load associated with the track. The short-term maximum load is 4000 psi (28 MPa).

Transient vacuum load: -1.0 kgf/cm^2.

Other loads: These include the wind load, the vibration load during an earthquake, and the restraint load due to anchoring.

Heat resistance: thermal stress and buckling; no special provisions are made for these.

Corrosion resistance: acid degradation; no special provisions are made for this.

Useful life: up to 30 years (medium-term 10 years). Under varying load, the estimated number of repetitions should be biased toward safety. If many repetitions are expected but their number is difficult to estimate, the repetition number should be set to 10^7.

・Evaluation

To confirm acceptable stress and strain under long-term loading, the fatigue, creep, and aging properties are evaluated.

All combinations of short-term loads, which may act as long-term loads, are evaluated in the same manner.

・Other checks

GPI standard compliant.

3. Design

3.1. Design of Corrosion-Resistant Layer

The material composition of the FRP pipe is shown in Fig. 2. The corrosion resistant resin and the isopthalic epoxy-modified resin system (urethane, novolac, polyimide) both satisfy the required acid resistance of pH = 2.

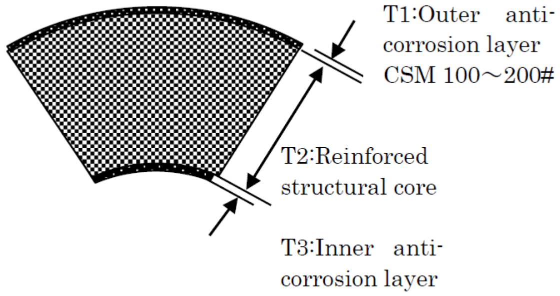

Fig. 2. *Construction of FRP Pipe.*

3.1.1. Corrosion-Resistant Layer Configuration Resin Material

T_1 layer: The resin content of the outer anti-corrosion layer is approximately 80 wt%.

T_2 layer: The reinforced structure core comprises about 30 wt% (50% vol) resin.

T_3 layer: The inner anti-corrosion layer is almost completely made of resin (~100 wt%).

3.1.2. Thickness of Anti-Corrosion Layer

The thickness of the T1 and T3 layers is finally decided from the inner diameter of the FRP pipe, the corrosive fluids, and the required abrasion resistance.

In the oil well pipe specifications of the GPI OCTG standard, the corrosive fluids are oil and gas in water, corrosive H_2S (1 bar), carbon dioxide (1 bar) saturated brine; other specifications are a maximum flow rate of 2 m/s and an ambient temperature up to 250 °C. If the fluid contains fine particles such as sand, corrosive wear must be considered even at low speed. To satisfy these requirements, the thicknesses of the layers are given as:

・ Outer anticorrosion layer (T_1 layer):0.1-0.2 mm, CSM100-200#1Ply laminated

・Inner anticorrosion layer (T_3 layer): 0.5–1.2 mm (average 1 mm).

At normal corrosive levels (below pH 2), corrosive wear is negligible. Lamination is needed only if corrosive fluid directly contacts the resin.

3.1.3. Maximum Elongation of Anticorrosion Layer

The test piece is circularly configured when the circumferential and axial strains on the inner surfaces of the FRP pipe are of similar magnitude. As the ratio of the circumferential to axial strain increases, the configuration becomes more elliptical.

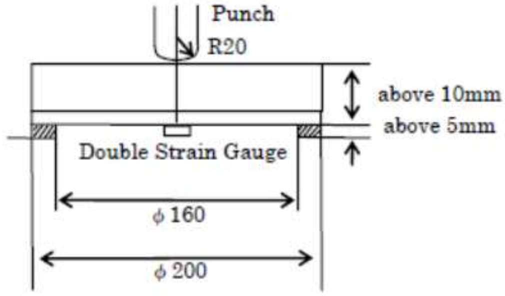

Fig. 3. *Test method for determining the maximum elongation of anticorrosion layer.*

As the anticorrosion layer cracks at the center of the circular test piece, where maximum strain is imposed, the bi-axial strain gauge should be attached there. Crack initiation is visually checked and is also detected by a discontinuity in the strain output. The allowable elongation is the strain immediately before crack initiation. The maximum elongation at high temperature is measured by placing the test piece in a constant-temperature oven.

3.1.4. Test Method for Corrosion Deterioration

Fig. 4 schematizes the test method for corrosion deterioration designed by NBL Co., Ltd. The FRP pipe is laterally compressed by a vice. A carbon steel plate is inserted between the vice and the outer pipe wall. The internal strain is measured by a compass and/or a strain gauge. Corrosive fluid is poured into the test pipe compressed at a constant rate until crack initiation. The change in the strain level and the elapsed time to crack initiation are measured as the parameters of compressive load.

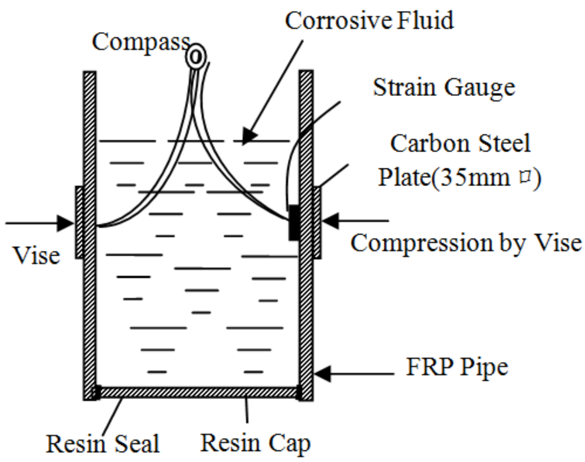

Fig. 4. *Test method for corrosion Deterioration.*

The chemical solution is identically placed (either vertically or horizontally) in all test samples. Tests in heated chemical solution, and under high-temperature high-pressure corrosion conditions, are also conducted in a pressure vessel.

The test time is 10–50 years (4×10^5 hours). Durability evaluation, usually measured at four points, must be conducted at 0, 10^1, 10^2, 10^3, and 10^4 hours, at a minimum. To determine the accuracy, we require the allowable load at 10^4

hours (the maximum elongation). On the other hand, a short-term deterioration test on a single resin test piece is effective if the allowable elongation is proportional to the weight change. This test evaluates whether high concentrations of the corrosive accelerate corrosion degradation. In the GPI standard, the test piece is immersed in acetic acid stock solution (pH 0.2) and heated to 95 °C. The pH 2 oxidation performance is then compared before and after a weight change (at 10 hours).

3.1.5. Determination of Allowable Elongation

To determine the deterioration factor C_D over the designed life, the relation between the initial strain of the anticorrosion layer and the crack initiation time obtained by the corrosion deterioration test is extrapolated to long-term behavior. The allowable elongation limit e_a is calculated by

$$e_a = C_S \cdot C_D e$$

where the variables are defined as follows:

C_s: Safety factor

C_D: Deterioration factor

e : Maximum elongation of the anticorrosive layer

3.1.6. Calculation of Strain on the Anticorrosion Layer

The strain on the anticorrosion layer is calculated by a simplified equation or by detailed FEM analysis. This specification will be applied to crude oil piping; therefore the important load is the internal load. The strain on the inner anticorrosion layer under internal pressure can be simply calculated as follows:

$$\varepsilon_\theta = \frac{P}{E}\frac{(1+\nu)d_0^2 + (1-2\nu)d_i^2}{2t(d_0+d_i)} \tag{1}$$

$$\varepsilon_\ell = \frac{P}{E}\frac{(1-2\nu)d_i^2}{2t(d_0+d_i)} \tag{2}$$

ε_θ: Circumferential strain

ε_ℓ: Axial strain

P : Internal pressure

d_0: Outer pipe diameter

d_i: Inner pipe diameter

t : Pipe thickness

E : Elastic modulus of pipe

ν: Poisson's ratio

If the axial and circumferential elastic moduli are significantly different, the smaller modulus is assumed.

3.2. Design of Reinforced Structural Core

3.2.1. Material

The reinforcing fibers' response to the direction of the force acting on the pipe should not exceed 30 inch and the pressure should remain below 100 MPa. These conditions are satisfied by E-Glass 23μ (direct-roving 0.45N/tex; circumferential axis 2:1; glass oriented without distortion in bamboo; blind knitting of fiber). In addition to the high-strength tube, S-Glass reinforcing fibers (0.55N/tex or higher) should be used. The reinforcing fibers are laminated such that all continuous fibers (content 70–73 wt%) are of uniform tension. The maximum elongation at break of the reinforcing fibers is decided as 2%.

The matrix resin defines the coverage at the heat distortion temperature. The material is tested in six temperature categories; 60 °C or less, 80 C°, 110 C°, 150 C°, 200 °C, and 250 °C. The tolerance of acid resistance durability is at least pH 2. In the allowed elongation test, a polymer blend of resin was composited to obtain the required stretch. The minimum elongation of some resins, before the test sample burst without weeping under the internal pressure, was 8–12%.

3.2.2. Minimum wall thickness (t_{mc} , $t_{m\ell}$)

・Under circumferential stressors, the minimal wall thickness is given by

$$t_{mc} = \frac{PD_0}{2S_c} + B \tag{3}$$

B : Additional thickness to allow for the extra stress imposed by grooving, damage caused by installation, operation, maintenance and inspection, and erosion (which will reduce the wall thickness), and by the additional bending moment

S_ℓ : Allowable stress under longitudinal tension

S_c : Allowable stress under circumferential tension

・Under longitudinal stressors, the minimal wall thickness is given by

$$t_{m\ell} = \frac{PD_0}{2S_\ell} + B \tag{4}$$

・The selected minimum wall thickness is the larger of (4) or (5).

$$t_m = Max(t_{mc}, t_{m\ell}) \tag{5}$$

3.2.3. Design for Buckling

・The moment of inertia under lateral load bending is given by

$$\mathrm{I} = \frac{\pi}{64}\left(d_0^4 - d_i^4\right) \tag{6}$$

where d_0 and d_i denote the outer and inner diameters, respectively.

If the pipe is thin, we have

$$\mathrm{I} = \frac{\pi}{8} d^3 t$$

$$d = \frac{1}{2}(d_0 + d_i)$$

Under cross-sectional bending, the moment of inertia is

$$\mathrm{I} = \frac{bt^3}{12\left(1-\nu^2\right)} \tag{7}$$

where t is the pipe thickness, and b is the length of the cylinder

・Moment of inertia of a stiffened cylinder

Assuming that the circumferential and axial stiffness sufficiently guard against external pressure buckling and axial buckling respectively, we have

$$\mathrm{I}^* = \mathrm{I}_0 + \frac{\mathrm{I}_s}{L_e} \tag{8}$$

I^* : Equivalent moment of inertia of cylinder reinforced with stiffener

I_s : Moment of inertia of stiffener

I_0 : Moment of inertia of cylinder alone

L_e : = I(axial buckling) = $Min\left\{\frac{\sqrt{2d_0 t}}{\left[3\left(1-\nu^2\right)\right]^{\frac{1}{4}}}, L\right\}$ (circumferential buckling)

L : Interval of the stiffener

・The limiting pressure for axial buckling is given by

$$P_{cr} = \left(\frac{m^2\pi^2 E_\ell t^2}{12\left(1-\nu^2\right)\ell^2} + \frac{4E_\theta \ell^2}{m^2\pi^2 d^2}\right)\frac{1}{S_F} \tag{9}$$

E_ℓ : Axial elastic modulus

E_θ : Circumferential elastic modulus

ν : Poisson's ratio

ℓ : Length of cylinder (interval of stiffener)

t : Pipe wall thickness

d : Diameter of cylinder

S_F : Safety factor(＝3.0)

m : Integer

・The limiting external pressure for buckling (excluding the burial pressure) is given by

$L_c = kd\sqrt{\frac{d}{t}} > L$:

k = 1.11 for ν = 0.3

$$\lambda = \sqrt[4]{\left(\frac{L}{d}\right)^2 / \left(\frac{t}{d}\right)^3}\sqrt[3]{\frac{\sigma_y}{E_\theta}} \tag{10}$$

If $\lambda \geq 0.9$, unstable buckling (shell plate buckling or general buckling) must be considered.

If $\lambda < 0.9$, the axisymmetric collapse is calculated.

$$\varphi = \frac{PD}{2\sigma_y t} \tag{11}$$

Unstable buckling may occur if φ < 0.8, and axisymmetrical collapse is possible if φ >1; both scenarios need to be checked.

1) The shell-plate buckling pressure is computed as follows:

(a) $\frac{4.72}{(L/D)^2} < \frac{D}{t}$

$$P_{cr} = \frac{2.6E}{(L/D) - 0.45\sqrt{t/D}}\left(\frac{t}{D}\right)^{2.5} \tag{12}$$

(b) $3.28\left(\frac{L}{D}\right)^2 < \frac{D}{t}$ & $\frac{2.1}{(L/D)^2} < \frac{D}{t} < \frac{4.72}{(L/D)^2}$

$$P_{cr} = \frac{2.6E}{fL/D - 0.9(f-0.5)\sqrt{t/D}}\left(\frac{t}{D}\right)^{2.5} \tag{13}$$

f: Coefficient depending on the constraint imposed by the boundary

$$N_\theta = f\frac{1}{2}PD$$

(c) $0.524\left(\frac{L}{D}\right)^2 < \frac{D}{t} < 3.28\left(\frac{L}{D}\right)^2$

General buckling needs to be considered when

$$P_{cr} = \frac{3.615E}{2.432 + (D/L)^2}\left(\frac{t}{D}\right)\left[\left(\frac{t}{D}\right)^2\left(1.216 + \frac{D^2}{L^2}\right)^2 + \frac{0.4484(D/L)^4}{\left(1.621 + D^2/L^2\right)^2}\right] \tag{14}$$

$$\text{(d)}\quad \frac{D}{t} < 0.524\left(\frac{L}{D}\right)^2 \quad P_{cr} = 2.2E\left(\frac{t}{D}\right)^3 \tag{15}$$

2) Elastic general buckling pressure

$$P_{cr} = \frac{8\left(n^2-1\right)E\left[\mathrm{I}_0 L + \mathrm{I}_s\right]}{D^3 2L_e} + 2E\left(\frac{t}{D}\right)\frac{\lambda_b^{\,4}}{\left[f'\left(n^2-1\right) + 0.5\lambda_b^{\,2}\right]\left(n^2 + \lambda_b^{\,2}\right)^2} \tag{16}$$

$\lambda_b = \dfrac{\pi D}{2L_0}$ L_0 : Total length of cylinder

$f' = \dfrac{1}{1+\dfrac{A_f}{tL}}$ A_f : Cross-section area of stiffener

where shell plate buckling may be critical, the stiffener will be sufficiently rigid to provide a >10% safety margin against buckling.

3) Axisymmetric collapse is given by

$$P_{cr} = \frac{2t\sigma_y}{d} \tag{17}$$

① Safety factor

The buckling pressure limit of the buried pipe is

$$P_{cr} = \frac{1}{S_F}\sqrt{32R_w B' E' \frac{EI^*}{d^3}} \tag{18}$$

$R_w = 1 - 0.33\dfrac{h_w}{h}$: Coefficient of water buoyancy

h_w : Water height from the top of the pipe

h : Ground height from the top of the pipe

B' : Coefficient of elastic support ($= \dfrac{1}{1+4e^{-0.065H}}$)

H : Burial depth above the top of the pipe (ft)

E' : Elastic modulus of soil

EI^* : Equivalent bending rigidity of the pipe

d : Pipe diameter

S_F : Safety factor (=3.0)

3.2.4. Design for Long-Term Load

Long-term load includes the internal pressure, the pressure due to soil weight (which acts on buried pipes only), and the reaction and constrained forces on the pipe caused by thermal expansion.

$$\frac{PD_0}{4t_m} + 0.75\frac{iM_A}{Z} + \frac{iM_C}{Z} \le S_\ell \tag{19}$$

P : Internal pressure - soil pressure

D_0 : Outer pipe diameter

t_m : Thickness of reinforced structural core

Z : Section modulus of pipe, ($= \dfrac{\pi D^2 t_m}{4}$, D: Mean dia.)

i : Stress intensification factor (0.75i ≧ 1.0)

M_A : Bending moment due to the weight load and other sustained loads

M_C : Bending moment imposed on the piping system by thermal expansion, internal pressure deformation and anchor displacement

3.2.5. Design for (Short-Term Load) + (Long-Term Load)

Short-term load includes transient over-pressure, truck load (on buried pipes), and other loads such as seismic, wind, and impact loads. As long-term and short-term loading can simultaneously occur, both load classes are combined in the design.

$$\frac{P_{max} D_0}{4t_m} + 0.75i\frac{(M_A + M_B)}{Z} + \frac{iM_C}{Z} \le 1.2S_\ell \tag{20}$$

P_{max} : Peak pressure

M_B : Bending moment imposed by transient over-pressure, earthquakes, strong wind, impact and trucks passing (above buried pipes only)

3.2.6. Detailed Analysis of Piping

If criteria (4) and (5) are not satisfied, a detailed stress analysis of the entire piping system is recommended. The design should consider the rationalized allowable stress obtained in the detailed analysis.

3.3 Design of Joint

Provided that the reinforced structural core is designed according to the criteria described in Section 3.2, the joint portion will not fail under normal stress. However, failure of the joint portion can initiate from the adhered layer; specifically, the interface between the mat and roving layers. Therefore, the adhered layer should be designed such that the actual shear stress is below the allowable level.

The shear stress of the adhesive layer is highest at the edge of the secondary portion, as indicated in Fig. 6.

$$\tau_1 = \frac{FC(E_1t_1 + E_2t_2\cosh C\ell)}{\pi d(E_1t_1 + E_2t_2)\sinh C\ell} \tag{21}$$

$$\tau_2 = \frac{FC(E_1t_1\cosh C\ell + E_2t_2)}{\pi d(E_1t_1 + E_2t_2)\sinh C\ell} \tag{22}$$

$$\tau_{max} = Max(\tau_1, \tau_2) \tag{23}$$

F : Axial load on the joint portion

$$C = \sqrt{\frac{G_0}{H}\left(\frac{1}{E_1t_1} + \frac{1}{E_2t_2}\right)} \tag{24}$$

G_0 : Shear modulus of the adhesive layer

H : Thickness of adhesive layer

E_1, E_2 : Elastic modulus of material 1.2

t_1, t_2 : Pipe thickness of range 1.2

ℓ : Length of adhesive layer

d : Diameter of adhesive layer

・ For long-term load

$$\tau_{max} \le S_{\ell c}$$

・ For (short-term load) +(long-term load)

$$\tau_{\max} \leq 1.2S_{\ell c}$$

$S_{\ell c}$: Allowable shear stress

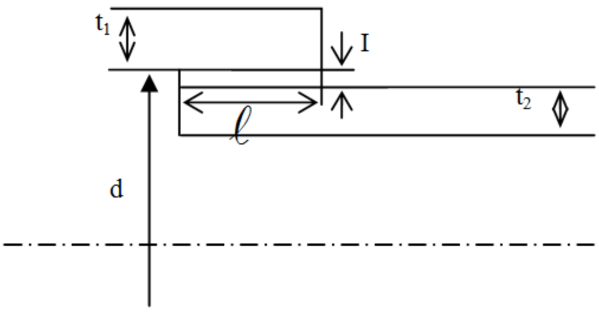

Fig. 5. Joint model.

・ As stated above, for (short-term load) + (long-term load) we have

$$\tau_{\max} \leq 1.2S_{\ell c}$$

When conducting a detailed stress analysis of the joints, the results should determine the allowable stress in the design.

In determining the smallest allowable shear stress, the joint surface is assumed to taper at 1/16. Other parameters are ℓ/t_2 = 8–10 and I = 2–4 mm. The optimal screw on the joint surface is an 8-round screw.

3.4. Design of Pin Coupling

Figure 6 shows the load–stress coupling imposed by the screw joint. The sealing pressure P2 should be 1.5 times higher than the pressure load P1. The figure shows the required distribution of the shear stress imposed by the axial force acting on the threaded portion.

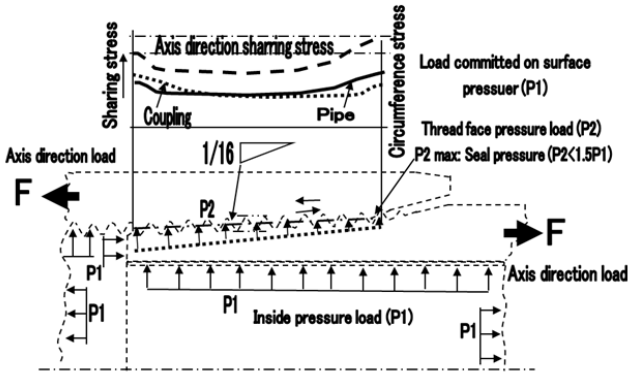

Fig. 6. Load and stress of the pin coupling screw joint.

The basic joint structures that ensure relaxation and distribution of the seal surface pressure imposed by the shear stress are illustrated in Fig. 7. This structure also ensures sufficient axial force to withstand the internal pressure.

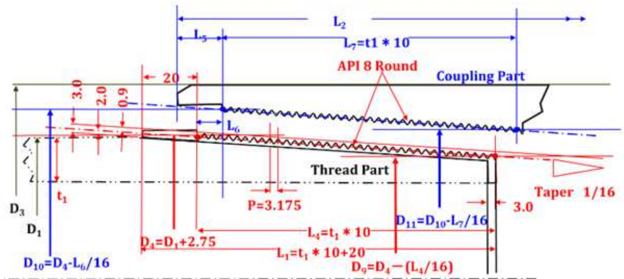

Fig. 7a. Basic structure of the pin coupling screw.

Base line and list of GPI design	Proportion	Outline of criteria	Construction standard
t1=1/3 to 1/5 of allowable stress	1	necessary thickness design for allowable load should be under the condition of less than 10 years life, 1/3 of burst stress, and 1/5 of performance in 40 years.	Durability choice
D1=API steel pipe std. OD + 3 to 4mm	2	GPI std. OD have 3 to 4 mm plus to API std. OD for having anti-corrosive layer	Casing applies the same
L3=20mm	3	To have 20mm entrance to relief stress from grinding and notch	10mm for low pressure application
L1= t1 ＊ about 10	1	max. fabrication condition of effective length should be 10 times of thickness	
t4=(1/3 to 1/4)＊t1	2	thickness for allowable buckling to make sealing pressure (same as WP) by tightening	
t5=2 to 3mm	3	thickness for allowable stress on edge and corrosion resistance	
L5=0.5 to 1.5 ＊ t1	3	length for making enough sealing pressure	
t2=0.03＊D1 or more	1	thickness against vacuum buckling	
t3=1.5＊t2	1	stractural wall condition for sealing pressure	
applied API 1/16 taper 8 round thread	1	suitable angle for stress relief, related to L1	
Thread: API 8 round (Fig12)	2	RTC by resin only for stress dispersion, different from API OCTG thread	
QC: sf 1.5 times of WP	2	QC test applies 10MPa to hotspring grade, 20MPa to E, 30 to G, 40 to M, 50 to H. (test load is 1.5 times of WP)	2 mins
need to have surface compress on thread	2	tightening torque for surface pressure same to WP. Sealing materials will be chosen due to each purpose	torque control

Fig. 7b. Basic structure of pin coupling screw.

The basic structure of the joints using an 8-round screw exploits the characteristics of an FRP-specific ratio rigid pipe by providing a corrosion-resistant layer resin layer on the internal surface that contacts the fluid. Stress relaxation is necessary such as to transmit the pressure load on the sealing surface.

3.5. Allowable Stress

The allowable stress is decided by the following tests:

① Time-to-Failure of Plastic Pipe Under Constant Internal Pressure (ASTM D1598)

② Cyclic Pressure Strength of Reinforced, Thermosetting Plastic Pipe (ASTM D2143)

③ Longitudinal Tensile Properties of Reinforced Thermosetting Plastic Pipe and Tube (ASTM D2105)

④ Fatigue Test of Reinforced Thermosetting Plastic Pipe with a Joint at the Central Region Under Cyclic Axial Tension Load

The strengths evaluated by each of these tests are listed in Table 6.

Table 6. *Strength of FRP Pipe under Various Tests.*

Test Classification	Short-Time Strength			Long-Time Strength		
	Axial	Circumferential	Shear	Axial	Circumferential	Shear
Hydrostatic Test		① S_{c1} ②	① $S'_{\ell c_1}$ ②		① $S_{\ell 2}$ ②	① $S_{\ell c2}$ ②
Tension Test	S_{ℓ_1} ③	-	$S'_{\ell c_1}$ ③	S_{ℓ_2} ④	-	$S'_{\ell c_2}$ ④

Defining the internal bursting pressure by P,

$$S_c = \frac{P(D-t)}{2t} \tag{25}$$

where t is the pipe thickness, and D is the outer pipe diameter. We also define

$$F = \frac{P(D-2t)^2}{4(D-t)} \tag{26}$$

$S_{\ell c}$ is obtained by substituting F into the equation of shear stress in the adhesive layer, introduced in Section 3.3.

The allowable short- and long-term stresses are calculated as follows:

The allowable stress for short-term stress is

$$S_\ell = \frac{1}{S_{F_1}} S_{\ell_1} \quad S_c = \frac{1}{S_{F_1}} S_{c_1}$$

$$S_{\ell c} = \frac{1}{S_{F_1}} Min\left(S_{\ell c_1} \cdot S'_{\ell c_1}\right) \tag{27}$$

The allowable stress for long-term stress is

$$S_\ell = \frac{1}{S_{F_2}} S_{\ell_2} \quad S_c = \frac{1}{S_{F_2}} S_{c_2}$$

$$S_{\ell c} = \frac{1}{S_{F_2}} Min\left(S_{\ell c_2} \cdot S'_{\ell c_2}\right) \tag{28}$$

Safely factor:

The simplified analysis based on the algebraic expression provides the following safety factor specification

$$S_{F_1} = S_{F_2} = 3.0$$

while the detailed stress analysis gives

$$S_{F_1} = S_{F_2} = 2.5$$

3.6. Allowable Stress and Temperature Dependence

The allowable stress is affected by the thermal deformation temperature (Tg) of the resin. When the temperature approaches the Tg of the resin, the pressure tensile stress tolerance exceeds the resin degradation by approximately 25%, and the buckling under compressive strength exceeds the resin degradation by about 60%.

The GPI pipe design is based on the concept of priority-thermal destruction; the priorities are destroying the internal pressure caused by oil–gas extraction (measured by the tensile strength and rigidity of the matrix material to cracking), and reducing the axial thermal stress imposed by the temperature difference generated during mining (achieved by lowering the coefficient of expansion).

In this design philosophy, the reinforcing fiber is strengthened against circumferential cracking by adopting a soft (high elongation) resin matrix. Next, the coefficient of thermal expansion is reduced to lessen the thermal stress generated by the temperature difference. We measure the stiffness reduction that allows the orientation and thermal deformation of the anisotropic reinforcing fibers in the laminated flexible resin. That is, rather than increase the allowable stress in the axial direction, we reduce the thermal expansion coefficient by lowering the material rigidity. In this design, the pipe can withstand the thermal stress generated within the allowable heat resistance of the resin.

Accordingly, the withstanding pressure of the acceptable crushing–buckling strength of the laminated pipe is lowered, while the withstanding pressure and heat resistance of the pipe is increased. Together, these measures improve the pipe performance is improved.

By this approach, the lowest acceptable compressive strength is about 40% of the axial tensile strength determined from the design and test results (100 MPa). The heat degradation is reduced by 10% at the maximum allowable temperature, and finally contributes around 30% of the allowable stress (75 MPa). Thus we have designed an oil well pipe that can withstand the target internal pressure of 100 MPa, a maximum temperature difference of 250°C, and a corrosion resistance of pH 2. The expected durability of the oil well pipe is 50 years.

4. Quality Assurance

The quality assurance program of the OCTG interpolates the IC chip along with the visible character information and the bar code information display, which are visible from outside of the pipe surface with the internal pipe surface.

The design information from which the final material load test was devised and the specified durability period is maintained, is provided in the database. The information can be confirmed via the Internet, according to the GPI traceability[16)] provided by a third party or by the API standard quality assurance testing program. Detailed information is omitted.

In the GPI quality assurance program, the product traceability may be subjected to a preferred insurance system, such as PL liability insurance guarantees.

5. Conclusion

This work has described the basic design theory by which we produce strong, durable (expected lifetime = 50 y) oil well pipes. The pipes can withstand a pressure of 100 MPa and a depth of 7000 m. In addition, they are heat-resistant to 250°C and anti-corrosive to a pH of 2. The material constants derived by the applied stress analysis are presented in the Appendix (the theoretical details of the analysis are omitted).

In designing the pipe deployment, we drew on long-term research by the authors, some of which is provided in the reference list.

Fig. 8. *Examples of products manufactured under the proposed design theory.*

The present strength design method for FRP pipes in new oil wells is based on the design logic of OCTG in the GPI technology standard. Examples of pipes satisfying the GPI standards are photographed in Fig. 8. These pipes have been commercially available since 2009 and have made a significant contribution to the market.

PS: For OCTG applications, please refer to the GPI standard. (http://gpi-pipe.org)

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GPI homepage (URL: http://www.gpi-pipe.org/)

Appendix: Material Constants Formulae

A.1: Glass content

$$V_f = \frac{W_f \rho_m}{W_f \left(\rho_m - \rho_f\right) + \rho_f} \tag{29}$$

V_f : Volume of the glass fiber
W_f : Weight of glass fiber
ρ_m : Specific gravity of resin
ρ_f : Specific gravity of glass fiber

A.2: Elastic constants of the unidirectional reinforcement

$$E_L = E_f \nu_f + E_m \left(1 - V_f\right) \tag{30}$$

$$\frac{1}{E_T} = \frac{1.36\left(K_f - K_m\right)}{\left(K_f - K_m\right)^2 - \left(\nu_f K_f - \nu_m K_m\right)^2} + \frac{1 - 1.05\sqrt{\nu_f}}{E_m} \tag{31}$$

$$\nu_L = \frac{1.05\sqrt{\nu_f}\left(\nu_f - \nu_m\right) K_f}{K_f - K_m} + \nu_m \tag{32}$$

$$\nu_T = \frac{\nu_L E_T}{E_L} \tag{33}$$

$$\frac{1}{G_{LT}} = \frac{1.36}{G_f - G_m} + \frac{1 - 1.05\sqrt{V_f}}{G_m} \tag{34}$$

$$K_f = \frac{E_f}{1 - \nu_f^{\ 2}} \quad K_m = \frac{E_m}{1 - \nu_m^{\ 2}}$$

$$G_f = \frac{E_f}{2\left(1 + \nu_f\right)} \quad G_m = \frac{E_m}{2\left(1 + \nu_m\right)}$$

E_m : Modulus of elasticity of resin
E_f : Modulus of elasticity of glass
ν_m : Poisson's ratio of resin
ν_f : Poisson's ratio of glass

A.3: Modulus of elasticity of the mat (chopped strand mat)

$$E = \frac{\left[E_L + E_T - 2E_L\nu_T + 4G_{LT}\left(1-\nu_L\nu_T\right)\right]\left(E_L + E_T + 2E_L\nu_T\right)}{3\left(E_L + E_T\right) + 2E_L\nu_T + 4G_{LT}\left(1-\nu_L\nu_T\right)} \quad (35)$$

$$G = \frac{E_L + E_T - 2E_L\nu_T + 4G_{LT}\left(1-\nu_L\nu_T\right)}{8\left(1-\nu_L\nu_T\right)} \quad (36)$$

$$\nu = \frac{E_L + E_T + 6E_L\nu_T - 4G_{LT}\left(1-\nu_L\nu_T\right)}{3\left(E_L + E_T\right) + 2E_L\nu_T + 4G_{LT}\left(1-\nu_L\nu_T\right)} \quad (37)$$

A.4: Modulus of elasticity of the helical winding FW material

$$1/E_x = \left(1/E_{xo}\right) - x^2 G_{xyo} \quad (38)$$

$$1/E_y = \left(1/E_{yo}\right) - \varphi^2 G_{xyo} \quad (39)$$

$$\nu_x / E_x = \nu_y / E_y = \left(\nu_{xo}/E_{xo}\right) + x\varphi G_{xyo} \quad (40)$$

$$\frac{1}{G_{xy}} = \frac{1}{G_{xyo}} - \frac{\chi\left(\chi+\varphi\nu_{yo}\right)}{1-\nu_{xo}\nu_{yo}}E_{xo} - \frac{\varphi\left(\varphi+\chi\nu_{xo}\right)}{1-\nu_{xo}\nu_{yo}}E_{yo} \quad (41)$$

$$\frac{1}{E_{xo}} = \frac{\cos^4\alpha}{G_{xyo}} - \frac{\chi\left(\chi+\varphi\nu_{yo}\right)}{1-\nu_{xo}\nu_{yo}}E_{xo} - \frac{\varphi\left(\varphi+\chi\nu_{xo}\right)}{1-\nu_{xo}\nu_{yo}}E_{yo} \quad (42)$$

$$\frac{1}{E_{yo}} = \frac{\sin^4\alpha}{E_L} + \frac{\cos^4\alpha}{E_T} + \left(\frac{1}{G_{LT}} - \frac{2\nu_L}{E_L}\right)\sin^2\alpha \bullet \cos^2\alpha \quad (43)$$

$$\frac{1}{G_{xyo}} = \left(\frac{1+\nu_L}{E_L} + \frac{1+\nu_T}{E_T}\right)\sin^2 2\alpha + \frac{1}{G_{LT}}\cos^2 2\alpha \quad (44)$$

$$\frac{\nu_{xo}}{E_{xo}} = \frac{\nu_{yo}}{E_{yo}} = \frac{\nu_L}{E_L}\left(\cos^4\alpha + \sin^4\alpha\right) + \left(\frac{1}{G_{LT}} - \frac{1}{E_L} - \frac{1}{E_T}\right)\frac{\sin^2 2\alpha}{4} \quad (45)$$

$$\chi = \left[\frac{\sin^2\alpha}{E_T} - \frac{\cos^2\alpha}{E_L} + \frac{1}{2}\left(\frac{1}{G_{LT}} - 2\frac{\nu_L}{E_L}\right)\cos 2\alpha\right]\sin 2\alpha \quad (46)$$

$$\varphi = \left[\frac{\cos^2\alpha}{E_T} - \frac{\sin^2\alpha}{E_L} - \frac{1}{2}\left(\frac{1}{G_{LT}} - 2\frac{\nu_L}{E_L}\right)\cos 2\alpha\right]\sin 2\alpha \quad (47)$$

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