Design technique

Design Method of FRP Pipe of GPI Standard

Takashi SHIMOSAKON[1,2], Shinichi TAMURA[2,3], Yoshinori NISHINO[1,2]
[1]NBL International Co., Ltd. [2]NBL Technovator Co., Ltd. [3]Graduate School of Medicine, Osaka University

Abstract: Recently, the spread of new technology development, such as centrifugal winding (CW) method and GPI (Global Oil & Gas Pipe Institute) screw joint advances, application performance and research results of the FRP pipe over the long term has been accumulated. This paper described that the strength design method of new oil well pipes, required to untapped deep oil wells derived from depletion of the existing oil and gas fields, depletion oil field of play EOR mining, more than 30 year of durability of new specifications, such as the withstanding pressure 100MPa, depth 7000m, heat-resistant 250 ℃, pH2 level of corrosion resistant, was clarified.

Keywords: OCTG, EOR, oilfield, FRP pipe design method, joint coupling, corrosion resistance.

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1. Introduction

This design of GPI standard method is related strength design of oil well for corrosion-resistant FRP pipe of GPI standard[1)] that is shown in Fig. 1.

The scope of application of this design method is tubing for oil well, casing, and line pipe. Design method described herein, while the reference to ASME or ASTM-related standards, is obtained by create our own design method required for oil well pipes of new applications based on the many years of research by the authors. Material, manufacturing, for inspection, apply the GPI treceability or in accordance with the ASME Code Case N-155. Test procedures for quality assurance is subjected to the E oil majors of specification. Test methods for determining an acceptable level of stress and strain is according to GPI or ASTM. More information about the technology and analysis method used to design standard described here are shown in the reference [2)].

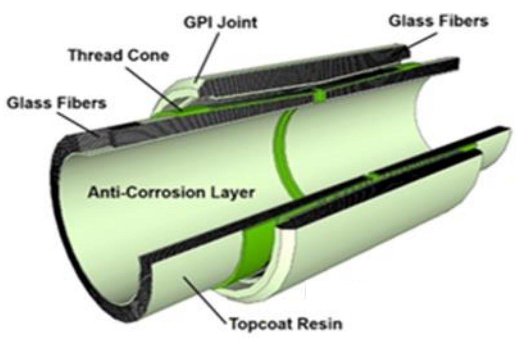

Fig. 1. Design of GRP OCTG

2. Design Basis

2.1 Subject of Conventional Design Method

Currently used design Standards for FRP piping (ASTM, ASME) require that material and thickness of anticorrosion layer should be determined considering deterioration and erosion of resin and those of reinforced layer should be designed based on required pipe strength. Allowable stress level of reinforced layer should be settled using hydrostatic test results multiplied by safety factor.

However, it has been clarified that the design method from such macroscopic view point is insufficient to meet the FRP piping design applied to a severe operating condition through experiences of operation and some troubles.

The reason is that the current rule might not reflect the actual failure mechanism of FRP. The failure mechanism of FRP under internal pressure is as follows; ①Initiation of micro-cracks with sound and no growth, ②Cracking of anti-corrosion layer which leads to penetration of water(weeping), ③Fast growth of crack and burst. This shows that weeping pressure is controlled by cracking of anticorrosion layer, and therefore, the evaluation of strain of anticorrosion layer is indispensable in piping design.[2)～7)]

Moreover, it has known that averaged failure shear stress of secondary bonding joint comes smaller with adhesive length of thread cone and GPI joint.

There are some other difficult subjects to be evaluated, such as delamination by fluid flow, material deterioration during long-term-operation which have significant influence on pipe strength. But the current design standards have few regulations regarding these subjects. New FRP piping design method including evaluation of strength and delamination for

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anticorrosion layer and secondary adhesive joint. The detail is given in the below. [8)～9)]

Here revealed design method is based on the research results and experience over 45 years by Dr. Yoshinori Nishino et al., corrosion-resistant layer strength and the strength of the secondary adhesive joints (evaluation) were evaluated based on the evaluation of the comprehensive amount of distortion the allowable stress and stress of the material due to the load (basic the allowable distortion) is a design method which is based on the design method[10)～15)] of OCTG made of FRP.

Detail explanation is shown in the below.

2.2 Strength design method of the FRP pipe developed by NBL

(1) Design basis of anticorrosion layer

Corrosion resistance and its strength are significant items in anticorrosion layer design. The assurance of corrosion resistance requires the appropriate selection and constitution of laminate materials and sufficient thickness of anticorrosion layer depending on design life.

Strength of anticorrosion layer is consequently depending on allowable elongation of laminate constitution material, because crack on anticorrosion layer is directly connected with pipe failure. Allowable elongation is depending on design life of the FRP pipe. Design basis as above mentioned is listed on Table 1.

Table 1. Design Basis of Anticorrosion layer

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

Maximum elongation of resin layer varies not only with the kinds of resin but with the composition, that is, with or without corrosion resistant liner as indicated in Table 2. In addition, the effect of fatigue and creep on allowable elongation shall be taken into consideration.

Maximum elongation of anticorrosion layer can be obtained easily and accurately using testing method indicated in Table 2.

Table 2. Max. Elongation of Anticorrosion layer

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

This testing method is to impose load by punch on a circular test piece composed of anticorrosion layer and reinforced structural core, and to measure strain on anticorrosion layer using strain gauge attached on the surface.

Using this method, the maximum strain occurs at the center of the anticorrosion surface, and the crack will not initiate from circumferential edge, so that the maximum elongation of the anticorrosion layer can be measured accurately by an output from strain gauge. And, this method may also confirm the integrity of the interface between anticorrosion layer and reinforced structural core under shear stress.

(2) Design basis of reinforced structural core

Required properties for reinforced structural core are stiffness and strength. Reinforced structural core must have sufficient stiffness to keep strain of anticorrosion layer below allowable limit, and also have durable strength for itself not to cause failure under constant, cyclic and transient loads during operation within designed life. Stiffness and strength of FRP pipe depend on not only pipe thickness but laminate material constitution, in other word, fiber content ratio and fiber orientation.

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

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In structural design fatigue of FRP during operation should be considered creep and long-term deterioration. Design items of reinforced structural core are listed in Table 3.

(3) Design basis of joint

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

However, the experiments and the analyses carried out by NBL technovator Co., LTD have shown that shear stress concentration in adhesive layer has outstanding influence upon failure strength of joints, and the current design method based on the mean shear stress multiplied by safety factor may not be conservative. As an example, failure pressure, in other word, weeping pressure, of pipe joints in hydrostatic tests is mainly controlled by interfacial strength between roving cloth layer and chopped strand mat, and mean shear stress becomes lower as adhesive length longer. This is because shear stress concentration arises nearby edge portion of adhesive layer, and stress concentration factor is a function of adhesive length and stiffness of both layers.

NBL design method allows using either simplified method by algebraically expressions or detailed method using FEM analyses. Different safety factors shall be applied to the simplified and detailed design methods. Orthotropic elastic properties of FRP are considered in design analysis, and allowable stress and strain are settled for each material. Optimized pipe thickness, geometry and dimension shall be determined by trial and error.

(4) Calculation basis

In NBL design, elastic constants of laminate constituting materials are calculated using linear law of mixture or other well-known equations (which are shown in Appendix 2.) If necessary, equivalent elastic constants of laminated wall may be calculated using linear summation law.

In the simplified design method, the elastic constants as obtained above should be substituted into the algebraically expression shown in Section 3.

Detailed design method uses stress analysis by FEM. NBL has developed the software FRP-X to perform two dimensional plate, axisymmetric solid and three dimensional shell analysis considering material anisotropy, and it has been installed in PC. FRP-X can calculate the fiber direction and elastic modulus element by element, and output stress and strain components parallel and normal to fiber. As an auxiliary program, FRP-MESH is equipped which performs proper mesh generation automatically using limited input data on dimension and material composition of a joint, and prepares data of elastic constants of each material, nodal coordinates, node numbers composing each element, fiber direction of each element. The optimized joint, which satisfies the criteria on stress and strain and is cost-minimized, can be designed by trial and error analyses using, as parameters, geometry and dimension of a joint and laminate constitution. For example, design of pipe joints submitted this time is based on about 50 cases calculations varying on geometry and material. Incidentally, total time to be consumed by those analyses was only 10 hours including preparation of input data.

NBL is devoting itself to study fatigue strength and long-term deterioration of FRP material and structure, and will propose the life prediction method within a few years. Then, NBL has the plan to accomplish CAD system for FRP structural design which composed of FRP-X, FRP-MESH, post processor to evaluate analysed result of FRP-X making reference to design criteria, and drawing software of various Fig.s, tables, and documents. Moreover, NBL has established the failure simulation analysis method for joint portion using non-linear spring model. This is a simplified non-linear analysis method which can simulate whole failure process by calculation time exceeding that of linear analysis only by 20-30%.

2.3 Design Basis

（1）Basic specification of pipe

Material constitution of pipe is as follows.

Inner surface: Possess an anticorrosive specification standardized on PS-15-69 (NBS).

Reinforced structure: Use filament fiber reinforced core plastic.

Outer surface: Lay up anticorrosion layer

Basic dimensions of pipe are listed in Table 4. Nominal diameter is based on inner diameter. Dimensions of fittings will be shown later.

Proper values of radius of crest and root total length of thread, and taper angle of thread may be settled, differed from API standard, according to the result of detailed analysis of stress and strain.

Table 4 Basic Pipe Dimension

<table>
<tr><th colspan="3">Tubing Pipe</th><th colspan="3">Casing ＆ Line Pipe</th></tr>
<tr><th>D inch</th><th>Pipe Length L (mm)</th><th>Thread</th><th>D inch</th><th>Pipe Length L (mm)</th><th>Thread</th></tr>
<tr><td>2-3/8</td><td rowspan="9">9500 mm</td><td rowspan="9">GPI thread structure 8 round</td><td>5</td><td rowspan="9">9500 mm</td><td rowspan="9">GPI thread structure 8 round</td></tr>
<tr><td>2-7/8</td><td>5-1/2</td></tr>
<tr><td>3-1/2</td><td>7</td></tr>
<tr><td>4-1/2</td><td>8-3/8</td></tr>
<tr><td></td><td>9-5/8</td></tr>
<tr><td></td><td>13-3/8</td></tr>
<tr><td></td><td>20</td></tr>
<tr><td></td><td>23-3/8</td></tr>
<tr><td></td><td>30</td></tr>
</table>

(2) Material

・**Raw materials**

Reinforced fiber：E glass Fiber（0.45N/tex or more），

Filament 23 μ, εmax 2%, laminated density 50vol% or more, circumferential direction: axial direction ratio 2:1, 1000~2000g/㎡ filament uniform length±0.1%, combination

QC information of material suppliers to the individual product number, manufacturing information, and performance test information, to the individual product of traceability.

Product construction and installation (user), as well as by matching products apply information from traceability No. and conditions of use, enter the applicable construction information, to apply the quality assurance traceability by GPI signatories via the internet.

(3) Design Scope

・**New oil well pipe design specification** (GPI load and durability performance)

Load of GPI standard required by the new oil well pipe specification consisting of four withstanding pressure grade and six heat-resistant grade shown in the table below. Required corrosion resistance is pH2, endurance performance omitted details, short-term 10 years, and long-term 50 years.

<table>
<tr><th>Withstanding Pressure Grade</th><th colspan="2">Tubing</th><th colspan="2">Casing & Line Pipes</th><th>Designed Pressure</th><th>Short-term load</th><th>10 years Durability</th><th>50 years Durability</th></tr>
<tr><td>E10</td><td colspan="2">Tap water well, 100m</td><td colspan="2">For water</td><td>10MPa</td><td>5MPa</td><td>3MPa</td><td>2MPa</td></tr>
<tr><td>E20</td><td colspan="2">Tap water well, 200m below</td><td colspan="2">For water</td><td>20MPa</td><td>10MPa</td><td>6MPa</td><td>4MPa</td></tr>
<tr><td>E40</td><td colspan="2">Hot spring wells, 1500m or less well</td><td colspan="2">Shale gas, CNG</td><td>40MPa</td><td>20MPa</td><td>12MPa</td><td>8MPa</td></tr>
<tr><td>G</td><td colspan="2">2000m or less for oil field</td><td colspan="2">3000m or less CNG gas tank-</td><td>60Mpa</td><td>30MPa</td><td>20MPa</td><td>12MPa</td></tr>
<tr><td>M</td><td colspan="2">3000m or less for oil field</td><td colspan="2">4000 m or less</td><td>80MPa</td><td>40MPa</td><td>26MPa</td><td>16MPa</td></tr>
<tr><td>H</td><td colspan="2">4000m or less for oil field</td><td colspan="2">Special purpose</td><td>100MPa</td><td>50MPa</td><td>33MPa</td><td>20MPa</td></tr>
<tr><td>Withstanding Temperature</td><td>－２０～６０℃</td><td>－１０～８０℃</td><td>０～１１０℃</td><td>２５～１５０℃</td><td colspan="2">２５～２００℃</td><td colspan="2">～２５０℃</td></tr>
<tr><td>Grade</td><td>60</td><td>80</td><td>110</td><td>150</td><td colspan="2">200</td><td colspan="2">250</td></tr>
<tr><td rowspan="3">Product marking</td><td colspan="8">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, 110 ℃ heat.</td></tr>
<tr><td colspan="8">Examples of products 5 (W) PE20-80: in GPI tube with both ends pin screw, outer diameter 5 inches (casing inner tube), E20 grade withstanding pressure, 80℃ heat.</td></tr>
<tr><td colspan="8">Examples of products 3-1 / 2JM-100: 3-1 / 2 inches at GPI coupling, pressure-resistant M grade, 100 ℃ heat.</td></tr>
</table>

Table 5 GPI standard coupling (performance)

of non-woven fabric and CSM 100 ~ 200g / m² mat irrigation surface of 13μ 200 filament 50mm cut.

Resin：Epoxy-modified, pH2 or more, εmax 4～18%

It is possible to use resin from thermal deformation temperature 60 ℃ up to max 250 ℃ with 7 classes.

・**Quality control**

Application: GPI traceability is applied to the material supplier.[16)] Or QC system and material guarantee program is made in accordance with ASME NCA-3800 and NCA-4135.

GPI traceability standard：Pipe manufacturer should enter

Standard length is 9.5m with GPI standard connection fittings pin coupling screws. Consists of three kinds of Tubing · Casing · Line Pipe. (See GPI standard)

GPI application product name is displayed as an example 3-1/2M150, the first 3-1/2 shows the inch diameter nominal dimension, M shows the withstanding pressure grade, 150 shows a heat ℃ design grade.

Reference：API standard pipe design specification

Long-term load: internal pressure up to 3000psi (21MPa) buried soil pressure itself restraint load due to heavy thermal expansion and the piping reaction force.

Short-term load (including only buried piping) load associated with the track passing short-term maximum 4000psi (28MPa)

Transient vacuum: -1.0kgf / cm^2

Other: wind load, vibration load at the time of the earthquake, restraint load due to anchor, etc.

Heat resistance: thermal stress, buckling, no special provisions.

Corrosion resistance: acid degradation, no special provisions.

Useful life: up to 30 years, and medium-term 10 years. When varying load, number of repetitions should be estimated appropriately on the safe side. Number of times a lot, and if the accurate estimation is difficult, the number of repetition should be 10^7.

・Evaluation

To confirm the stress and strain due to long-term load is acceptable levels considering the fatigue, creep, and aging.

To confirm all combinations of short-term loads which may act long load and at the same time that stress and strain is the below acceptable levels.

・Other

GPI standard compliant.

3. Design

3.1 Design of corrosion-resistant layer

Material composition of the FRP pipe is shown in Fig. 2. The corrosion resistance resin, epoxy-modified resin system (urethane, novolac, polyimide), and such as isophthalic system, both will be applicable and with the acid resistance of pH2.

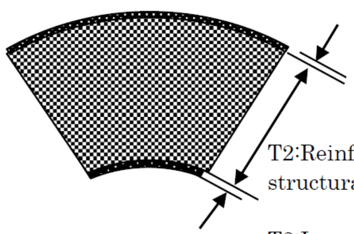

Fig. 2. Construction of FRP Pipe

(1) Corrosion-resistant layer configuration resin material

T_1 layer：Outer anti-corrosion layer resin content of about 80wt%

T_2 layer：Reinforced structure core resin content of about 30wt%（about 50%vol）

T_3 layer：Inner anti-corrosion layer resin content of about 100wt%

(2) Thickness of anti-corrosion layer

The thickness of T1 and T3 layer is finally decided in consideration of the inner diameter of the FRP pipe, corrosive fluids, and abrasion resistance.

Standard GPI OCTG of oil well pipe specifications in addition to water of oil and gas as corrosive fluid, corrosive H_2S (1 bar), carbon dioxide (1 bar) saturated brine, maximum flow rate 2m/sec and the ambient temperature to 250 ℃. However, if the fluid is pretty containing fine particles such as sand, consider the corrosive wear even at low speed.

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

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

At normal (pH2 below) corrosive level, corrosive wear is negligible.

Lamination is needed only the case of corrosive fluid directly to resin.

(3) Maximum elongation of anticorrosion layer

Test method developed by NBL is applied shown in Fig. 3.

Configuration of test piece is circular when circumferential and axial strains on inner surface of FRP pipe are of similar magnitude, and it is elliptical in accordance with the ratio of circumferential strain to axial.

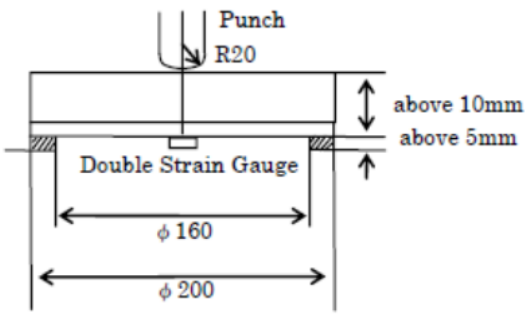

Fig. 3. Testing method for determination of maximum elongation of anticorrosion layer

As cracks on anticorrosion layer causes at the center of the circular test piece where maximum strain occurs, bi-axial strain gauge should be attached there. Initiation of a crack shall be checked visually and detected by discontinuous change of strain output. Allowable elongation is the strain just before crack initiation. Maximum elongation at high temperature shall be measured by putting test piece into constant-temperature oven.

(4) Testing method for corrosion deterioration

Fig. 4 indicates the testing method for corrosion deterioration designed by NBL Co., Ltd. FRP pipe is compressed laterally using vice through carbon steel plate. Inside strain is measured by compass and/or strain gauge. Corrosive fluid is poured into the test pipe compressed by constant until crack initiation. Change in strain level and elapsed time till crack initiations are measured as parameters of compressive load.

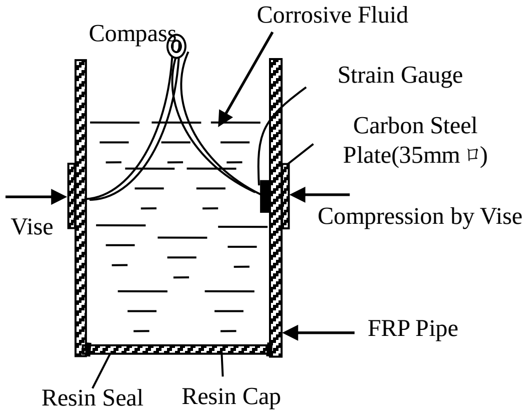

Fig. 4. Testing method for corrosion Deterioration

Test piece with such vertical or horizontal placement of the chemical solution are all the same. Heating of chemical solution, high temperature high pressure corrosion test in addition pressure vessel takes place.

Test time is 10 years to 50 years (4 × 10^5 hours). For durability evaluation, usually 4 point of measurement, at least 0, 10^1, 10^2, 10^3, and 10^4 hours is needed. To determine the accuracy, measurement of the allowable load at 10^4 hours (maximum elongation) is necessary. On the other hand, short time deterioration test by the resin single test piece is effective if applied similarity rule (allowable elongation and weight change). It is an evaluation test method of high concentration accelerated corrosion degradation. In the GPI standard, test piece is immersed to acetic acid stock solution (pH0.2) heated on 95 ℃, and the relative merits comparative evaluation of pH2 oxidation performance is taken place in the weight change of 10 hours.

(5) Determination of allowable elongation

Relation between initial strain of anticorrosion layer and crack initiation time obtained by corrosion deterioration test shall be extrapolated to long-term side in order to determine deterioration factor C_D for design life. Allowable limit of elongation e_a is calculated as follows;

$$e_a = C_S \cdot C_D e$$

Where

C_s: Safety factor

C_D: Deterioration factor

e : Maximum elongation of anticorrosive layer

(6) Calculation method of strain on anticorrosion layer

Strain on anticorrosion layer shall be calculated by either simplified equation or detailed FEM analysis. In case of crude oil piping to which this specification shall be applied, most careful load is internal load. Strain on inner anticorrosion layer under internal pressure can be calculated simply by the following equation.

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

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

Where

ε_θ: Circumferencial strain

ε_ℓ: Axial strain

P : Internal pressure

d_0: Outer diameter of pipe

d_i: Inner diameter of pipe

t : Pipe thickness

E : Elastic modulus of pipe

ν : Poisson's ratio

Select the smaller value if axial elastic modulus differs from circumferencial one significantly.

3.2 Design of Reinforced Structural Core

(1) Material

Reinforcing fibers in response to the direction of the force acting on the pipe, not exceed 30 inch and pipe design pressure below 100MPa, E-Glass 23μ direct roving 0.45N/tex circumferential axis 2:1 glass undistorted oriented in bamboo blind knitting of fiber should be used. In addition to the high-strength tube 0.55N/tex or more of the reinforcing fibers of S-Glass fiber should be used. In common reinforcing fibers laminated to use all continuous fibers in the range of content 70 ~ 73wt% of a uniform tension. The maximum elongation at break of the reinforcing fibers to adopt 2%.

Matrix resin defines the coverage by the heat distortion temperature. Divided into 6 species; 60 ℃ or less, 80, 110, 150, 200, 250 ℃. Tolerance of acid resistance durability will be at least pH2 and allowed elongation performs a polymer blend of resin to be applied composite law in order to obtain the required stretch. Using a minimum of 8 to 12 percent elongation of some resin required for burst without weeping by the internal pressure.

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

・Circumferential direction

$$t_{mc} = \frac{PD_0}{2S_c} + B \quad \cdots\cdots (3)$$

B : Additional thickness considering excessive stress resulted from reduction of thickness by grooving, damage on installation, operation, maintenance and inspection, and errosion, and from additional bending moment

S_ℓ : Allowable stress for longitudinal tension

S_c : Allowable stress for circumferential tension

・Longitudinal direction

$$t_{m\ell} = \frac{PD_0}{2S_\ell} + B \quad \cdots\cdots (4)$$

・Minimum wall thickness

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

(3) Design for buckling

・Moment of inertia : Bending by lateral load

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

d_0 : Outer diameter d_i : Inner diameter

If a pipe is thin.

$$I = \frac{\pi}{8} d^3 t \qquad d = \frac{1}{2}\left(d_0 + d_i\right)$$

Bending in cross sectional place,

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

t: Pipe thickness, b: Length of cylinder

・Moment of inertia of cylinder with stiffener

It is assumed that circumferential stiffness are effective for buckling by external pressure, and axial stiffness are for axial buckling.

$$I^* = I_0 + \frac{I_s}{L_e} \quad \cdots\cdots (8)$$

I^* : Equivalent moment of inertia of cylinder with stiffner

I_s : Moment of inertia of stiffner

I_0 : Moment of inertia of cylinder only

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 stiffner

・Limit of pressure for axial bucking

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

E_ℓ : Axial elastic modulus

E_θ : Circumferencial elastic modulus

ν : Poisson's ratio

ℓ : Length of cylinder(interval of stiffner)

t : Pipe wall thickness

d : Diameter of cylinder

S_F : Safety factor（＝3.0）

m : Integer for the minimum

・Limit of pressure for buckling by external pressure (except for burial pressure)

① $L_c = kd\sqrt{\frac{d}{t}} > L$:

General buckling shall be considered where

k =1.11 for ν =0.3

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

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

If $\lambda < 0.9$, axisymmetric collapse shall be calculated.

③ $$\varphi = \frac{PD}{2\sigma_y t} \quad \cdots\cdots (11)$$

Possibility of instable buckling where $\varphi < 0.8$ and axisymmetrical collapse where $\varphi > 1$ shall be checked.

④ Shell-plate buckling pressure

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

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

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

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

f : Coefficient depending on constraint by boundary

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

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

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

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

⑤ Elastic general buckling pressure

$$P_{cr} = \frac{8(n^2-1)E[I_0L+I_s]}{D^3 2L_e} + 2E\left(\frac{t}{D}\right)\frac{\lambda_b{}^4}{\left[f'(n^2-1)+0.5\lambda_b{}^2\right](n^2+\lambda_b{}^2)^2} \cdot\cdot\cdot\cdot\cdot\cdot (16)$$

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

$f' = \frac{1}{1+\frac{A_f}{tL}}$ $\quad A_f$: Section area of stiffner

Where shell plate buckling may be critical, the rigidity of the stiffner shall have safety margin exceeding ten for buckling.

⑥ Axisymmetrical collapse

$$P_{cr} = \frac{2t\sigma_y}{d} \cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot (17)$$

⑦ Safety factor

- Buckling pressure limit for burial pipe

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

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

h_w : Water height from the top of pipe

h : Ground height from the top of pipe

B' : coefficient of elastic support $\left(= \frac{1}{1+4e^{-0.065H}}\right)$

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

E' : Elastic modulus of soil

EI^* : Equivalent bending rigidity of pipe

d : Pipe diameter

S_F : Safety factor (=3.0)

(4) Design for long-term load

Long-term load includes internal pressure, weight load soil pressure (only buried pipe), and pipe reaction and constrained force caused by thermal expansion.

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

P : (Internal pressure)-(Soil pressure)

D_0 : Outer diameter of pipe

t_m : Thickness of reinforced structural core

Z : Section modulus of pipe,

$\left(= \frac{\pi D^2 t_m}{4}\right.$, D: Mean dia. $\left.\right)$

i : Stress intensification factor (0.75i≧1.0)

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

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

(5) Design for (Short-term load) + (Long-term load)

Short-term load includes transient over-pressure, truck load (buried pipe), seismic load, wind load, and impact load, etc. Combinations of the long-term and short-term loads which is possible to act simultaneously shall be evaluated.

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

P_{max} : Peak pressure

M_B : Bending moment imposed by transient over-pressure, earthquake, strong wind, impact and truck passing (only buried pipe)

(6) Detailed analysis of piping

When the criteria of (4) and (5) might not be satisfied it is recommended to perform detailed stress analysis of entire piping system and design using rationalized allowable stress based on the detailed analysis.

3.3 Design of pin coupling

Coupling screw joint by screwing shown in Fig. 5. P2 effect sealing pressure should be secured 1.5 times higher than the P1 pressure load, and required distribution structures shear stress due to the axial force acting on the threaded portion.

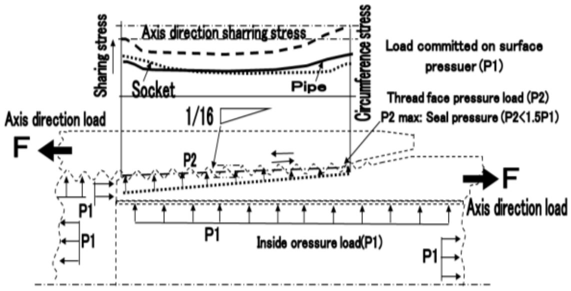

Fig. 5. Load and stress of pin coupling screw joint

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Joint basic structure to ensure the relaxation and the seal surface pressure of the shear stress, and to obtain the axial force required to withstand internal pressure is Fig. 6 and 7.

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

② Cyclic Pressure Strength of Reinforced,

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. 6. Basic structure of pin coupling screw

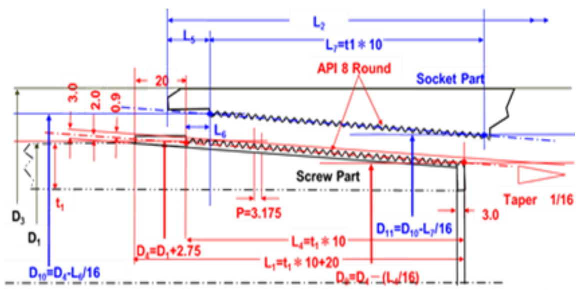

Fig. 7. Basic structure of pin coupling screw

The basic structure of the joints using an 8 round screw was taking advantage of the characteristics of FRP-specific ratio rigid pipe by providing a corrosion-resistant layer resin layer on a surface that inside the pipe fluid is in contact. Joint structure of stress relaxation is necessary such as to transmit the pressure load on the sealing surface.

3.4 Allowable stress

Allowable stress shall be decided by the following tests;

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

By these tests, strength listed in Table 6 shall be evaluated.

Test Classification	Short-Time Strength			Long-Time Strength		
	Axial	Circum-ferencial	Shear	Axial	Circum-ferencial	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

Table 6 Strength of FRP Pipe

Where bursting internal pressure is P,

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

t: Pipe Thickness, D: Outer Diameter

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

$S_{\ell c}$ shall be obtained by substituting the F value into the equation for shear stress in adhesive layer, indicated in Section 3.3.

Allowable stress shall be calculated using the following equation.

Allowable stress for short-time

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

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

Allowable stress for long-time

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

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

Safely factor:

Using the simplified analysis in other word algebraically expression indicated in this specification

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

Using the detailed stress analysis

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

3.6 Allowable stress and temperature dependence

Allowable stress is affected by the thermal deformation temperature (Tg) of the resin. Pressure tensile stress tolerance exceeds degradation of resin up to about 25% by increasing temperature within the range of resin's Tg. Buckling of compressive strength exceeds degradation of resin to about 60%.

Here, the basic theory of GPI pipe is the design concept of priority-thermal destruction; internal pressure destruction priority to oil - gas extraction (tensile strength and rigidity matrix material crack measures priority design) and the axis direction thermal stress due to temperature difference generated during mining to a minimum of the low coefficient of expansion.

In this design philosophy, it is being selected that a first improvement of the effective reinforcing fiber due to the circumferential crack prevention by the use of soft (high elongation) resin matrix, then smaller coefficient of thermal expansion that reduces the thermal stress generated by the temperature difference, measure stiffness reduction that allows the orientation and thermal deformation of direct anisotropic reinforcing fibers that laminated design of flexible resin used. That is, the axial direction rather than seek larger allowable stress, it is possible to reduce that the rigidity to reduce the thermal expansion coefficient, to adopt a method of designing a pipe to withstand the thermal stress generated in the allowable heat resistance of the resin.

Accordingly, an object withstanding pressure of the crushing-buckling acceptable strength of the laminated pipe becomes lower, on the other hand, withstanding pressure and heat resistance of pipe becomes higher, and pipe performance is improved.

In other words, the lowest acceptable compressive strength is about 40% of the axial tensile strength from the design and test results (100MPa), and heat degradation is further reduced by 10% at the maximum allowable temperature, finally become about 30% of the allowable stress (75MPa), then target internal pressure 100MPa, the maximum temperature difference 250 ℃, corrosion resistance pH2, is accomplished to design of oil well pipe to withstand the 50 years durability.

4. Quality assurance

Quality assurance program of OCTG interpolates IC chip in addition to the visible character information and the bar code information display visible from outside of the pipe surface with the internal pipe surface.

The design information leading to the final load test from the material and the application of the durability period is maintained in the database and is confirmed via the Internet, according to GPI traceability[16)] provided by third party store or API standard quality assurance testing program. Detail information is omitted.

In the GPI quality assurance program for applying the product traceability, it is possible to subject to preferential insurance system, for example, PL liability insurance guarantees.

5. Conclusion

In this work described the basic design theory of strength design of oil well pipes to allow endurance performance in 50 years, withstanding pressure 100MPa, depth 7000m, heat-resistant 250 ℃, and anti-corrosion pH2 specification.

Here the applied stress analysis logic expression employs a significant expression. The detail theoretical formula is omitted and for obtaining a material constant written in next paper[17].

Quoted research that was used to design the logical deployment, using a long-term research by the authors that shown in the following. Some of the literature was described in reference list.

PS: For application to OCTG, please refer to the GPI standards. (http://www. gpi-pipe.org)

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

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