DESIGN METHOD OF API HIGH PRESSURE FRP PIPE

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ABSTRACT

We have developed centrifugal forming (CW) API standard FRP pipe with 50 MPa use pressure tolerance which is twice stronger than conventional FW FRP pipes and also stronger than the steel pipes. In this paper, we propose the design rule of FRP pipe and how to test it for such high pressure environment.

KEYWORDS: FRP pipe, High pressure, Pipe joint, Centrifugal forming

1. CENTRUFUGAL WINDING FRP PIPE

Centrifugal winding (CW) pipe has features of light weight and high pressure tolerance [1, 2] than conventional filament winding (FW) pipes [3-5]. We have succeeded to manufacture the CW-API pipe with length of 9.6m, and outer diameter 2-7/8 inches (6cm). The nominal use pressure tolerance is e.g., 500 atoms (50 Mpa), and practically it can tolerate 1000 atm. In this paper, we present design method for such high pressure FRP pipe including joint.

2. PIPE STRENGTH

Destruction strength

Determining fiber diameter and tex (weight [g] per 1000 [m]), destruction strength is obtained by the following equation:

$$\alpha = \alpha i \times R \qquad (1)$$

where α =destruction strength [N/tex]

αi = ideal destruction strength [N/tex] such that, e.g., 0.45 [N/tex] in case of 26μm

R = degraded coefficient such as 0.8.

Next, we define a glass content rate of the pipe in the below. Though in the CW method, glass content rate of the pipe is maximum about 65 wt%, it is possible to obtain enough strength even with 50 wt%. Content rate of the sample one is also 50 wt%. From the predetermined 50 wt% of content rate, total weight of the glass cloth is given as follows:

$$Wg = Vp \times C \times \rho \qquad (2)$$

Where Wg = total weight of glass cloth in pipe [kg]

Vp = total volume of pipe [ℓ]

C = content rate of pipe

ρ= specific gravity 2.6 of glass

Yearn count of glass cloth

Number of layers (plys) is determined from diameter of FRP pipe. In relatively small pipes with less than 100 mm of diameter, it is desired to make less than 5 layers. By this, yearn count of glass cloth (weight per m^2) is determine as follows:

$$Y = Wg / (Ng \times S) \quad (3)$$

Where Y = yearn count of glass cloth [kg/ m^2]

Ng = number of layers (plys) of glass cloth in pipe

S = wall (outer surface) area size of pipe [m^2]

Circumferential strength and axial strength of glass cloth

Circumferential strength and axial strength are given by

$$B_\theta = \alpha_\theta \times T_\theta \times Nr_\theta, \qquad \beta z = \alpha z \times Tz \times Nrz \quad (4)$$

where β_θ = circumferential strength [N/cm]

βz = axial strength [N/cm]

T = tex of glass cloth roving [tex]

Nr = number of rovings per 1 [cm] of glass cloth [pcs/cm]

Tolerable inner pressure

Then from wall thickness of pipe, number of layers, and tolerable stress, and tolerable inner pressure of FRP pipe are given by thin wall theory as

$$\sigma_\theta = \beta_\theta \times Ng / t, \quad \sigma z = \beta z \times Ng / t \quad (5)$$

where σ_θ = circumferential tolerable stress [N/cm^2]

σz = axial tolerable stress [N/cm^2]

t = wall thickness of pipe [cm]

The tolerable inner pressure is given by

$$p = \max \{ p_\theta, pz\}$$

$$p_\theta = 2t \times \sigma_\theta /d, \quad pz = 4t \times \sigma z /d \quad (6)$$

where d = diameter of pipe [cm]

Ordinary, it is designed so that $p_\theta = pz$, that is $\sigma_\theta = 2 \sigma z$.

3. STRENGTH CHARACTERISTICS OF STRAIGHT PIPE AND MATERIALS

For CW-API pipes, three grades of strength characteristics of glass fiber material can be chosen. They are 0.65 [N/tex] with high quality glass fiber of 6-9 [µm], 0.55 [N/tex] with 11-13 [µm], and 0.45[N/tex] with 14-28 [µm]. Fig.1 shows the relation between glass fiber diameter and axial tensile strength. The thinner the diameter is, the stronger the strength is. Strength characteristics of the CW-API pipe is shown in Fig.2. The upper curve shows the pipe using mat specially arranged in order containing 42 wt% of formed glass with 2:1 of circumferential and axial direction strengths, and the lower one is using conventional orthogonal roving cloth containing 34 wt%. The pipe is destroyed at the maximum stress of Fig.2. Simply speaking, the product characteristics are given by calculation with the thin wall theory. In 2-7/8 inches API pipe, assuming the thickness of reinforced layer is 6mm, destruction inner pressure is about maximum 660 [kgf/cm^2] with 0.45 [N/tex] glass fiber, about maximum 780 [kgf/cm^2] with 0.55 [N/tex] glass fiber, and about maximum 1000 [kgf/cm^2] with 0.65 [N/tex] glass fiber, and destruction axial force is 18 tons, 22 tons, and 28 tons, respectively. These are twice strength of conventional FW formed pipes. The API standard is generally about 350 [kgf/cm^2] and allowable short time pressure is about 250 [kgf/cm^2]. The CW pipes are massively produced with three kinds of use pressure (permissible use pressure) of 250 [kgf/cm^2], 375 [kgf/cm^2], and 500 [kgf/cm^2]. Since the tolerable elongation rate of the inner anti-corrosion layer is 15 % for resin only and 3 % for anti-corrosion layer as a whole, and material is chosen so as to be able to keep the water proof effect of anti-corrosion layer before the destruction of the reinforced layer, destruction of the reinforced layer becomes destruction of the pipe.

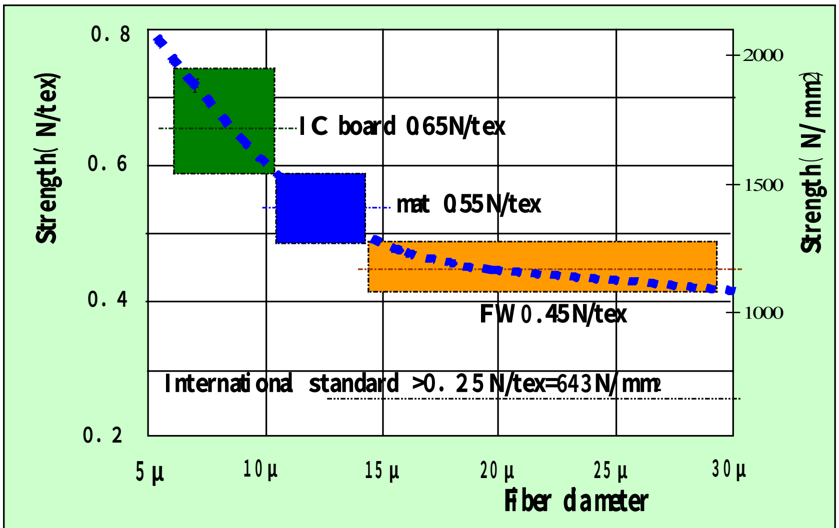

Fig 1 E-Glass tensile strength vs. fiber diameter.

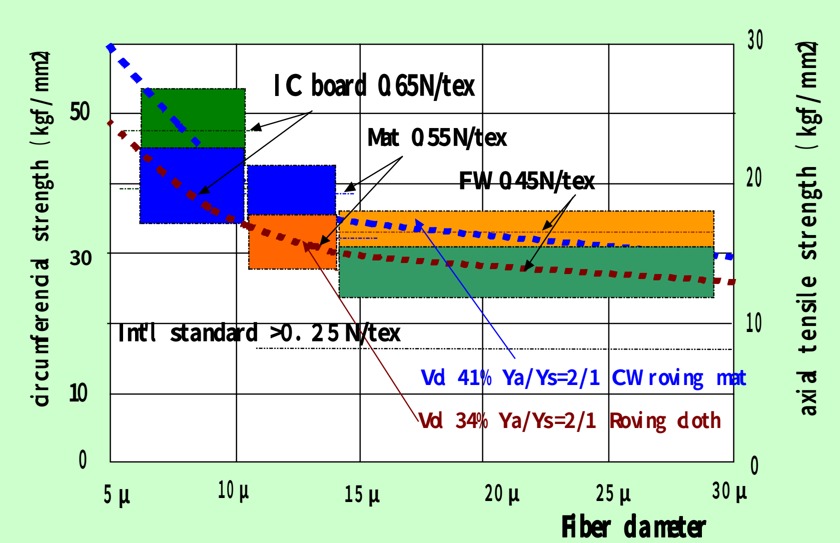

Fig 2 FRP pipe axial tensile strength vs. glass fiber filament

Let compare the strength of this pipe with that of steel pipe. General material strength of the steel is about 21 [kgf/mm^2], and therefore the destruction inner pressure is 420 [kgf/cm^2]. That is the CW high pressure pipe has twice strength of the steel pipe, and has a feature of light weight of 1/5 compared with the steel pipe since the specific gravity of the steel is about 8 and that of CW pipe is about 1.5. Further, since the CW standard pipe product is provided by the equal price with the steel pipe, is superior in anti-corrosion characteristics (not corroded), and is light and easy to handle, it has superiority than the steel pipe.

4. JOINT STRENGTH AND SOCKET STRUCTURE

General specification of FRP pipe at joint is 8 round screw of API standard. Fig.3 shows CW pipe joint structure. We can see from the figure that pitch, initial diameter, and gradient of the screw are specified in the standard. There exist the characteristic of the longer the length of

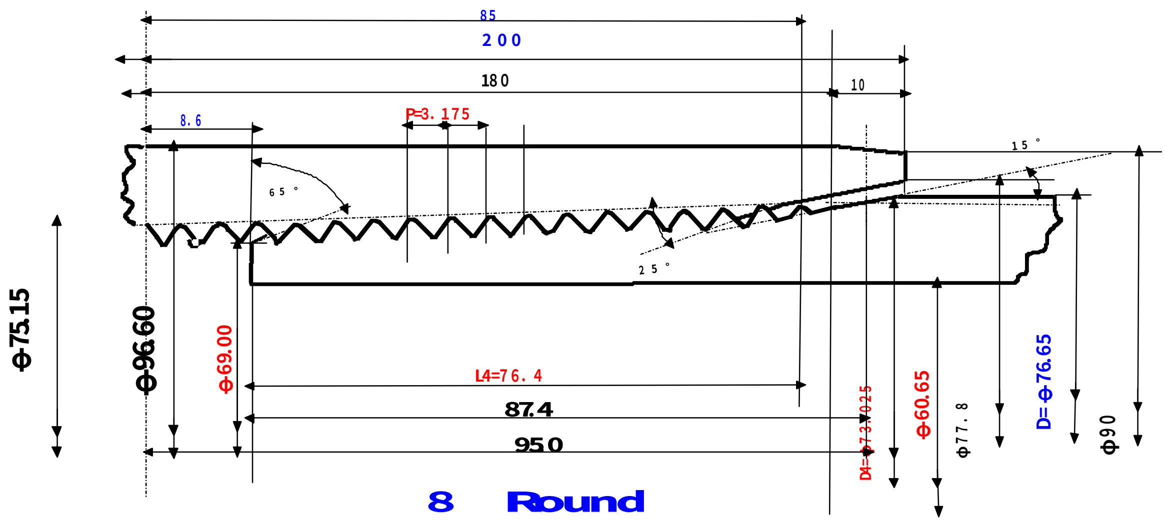

Fig.3: CW-API pipe joint structure

the screw is, the larger load can be tolerated. Then in the product shown in the figure took the maximum length of the screw allowed in the API standard.

Elongation rate giving destruction is about 1.5 % by the axial force. The most important factor to protect the destruction by stress concentration at the secondary adhered screw is to make shear force at the screw part works uniformly. In order to fulfill this requirement, adequate tolerable deformation utilizing slipping the screw is necessary for expansion by the load in radial direction and expansion by the load in axial direction. That is, with the structure of generating uniform shear force by the deformation of the screw for the elongation by axial force, material selection is necessary which does not cause stress concentration leading to destruction of screw material. Since the composition is designed considering that in the screw material and layer structure of the CW-API pipe, necessary axial force is obtained. The selected screw material using epoxy modified resin is superior in elongation deformation, and allow the destruction shear force of 2 [kgf/mm^2]. Therefore, the maximum axial force is obtained in simplified way by the product of screw area and allowable shear force from layer structure generating uniform shear stress. The surface area size of the joint is S=75×76×3.14=17,898 [mm^2], and the destruction axial force is 35,796 [kgf]. This corresponds to 1200 [kgf/cm^2] of axial force destruction. From the above, 8 round screw structure of CW-API pipe has a performance of the maximum destruction pressure 1000 [kgf/cm^2] of the pipe.

5. SEAL PERFORMANCE

Since the pipe is non-rigid body, slipping by deformation occurs at the screw part. However, from the structure of Fig.3, when the pressure works in the pipe, the thin wall part of the pipe end is expanded, and the pushing pressure is generated at the central thick wall part of the socket. If sum of the pushing pressure and pushing pressure occurred by the initial screw-in force is assumed 1.5 times of necessary seal pressure, seal by the seal theory exist. Further if the proper caulking material inserted in the gap, perfect seal is obtained. Concerning the wall thickness and length of the socket, since the structure is adopted such that able to generate enough pressing pressure for the occurred deformation at the seal part, high pressure 8 round screw could be developed which had been impossible so far. For the low pressure 8 round socket, it is possible to make the external size small, and it is superior in the cost.

Let us compare this joint with that of conventional steel joint. Since the steel joint is made of uniform material and screw is made by cutting, by the surface scratch and stress concentration, though the material itself is firm, destruction strength is low than the CW-API pipe. Further, the surface is not smooth, and seal effect shown in the above is hard to work.

6. HIGH PRESSURE PIPE TEST DEVICE

Since FRP pipes formed by the above design is very superior in pressure tolerance, it is often difficult to evaluate by conventional pressure tolerance tests. Therefore we developed a tolerance test device up to maximum about 1000 [bar] for high pressure pipe as shown in Fig.4.

The biggest critical point is seal at the cutting section in the pressure tolerance test of FRP single straight pipe. The reason is as follows: Though adhering force between layers of glass cloths is different by resin used, it is about 7 MPa. If the pressure of more than 7 MPa is

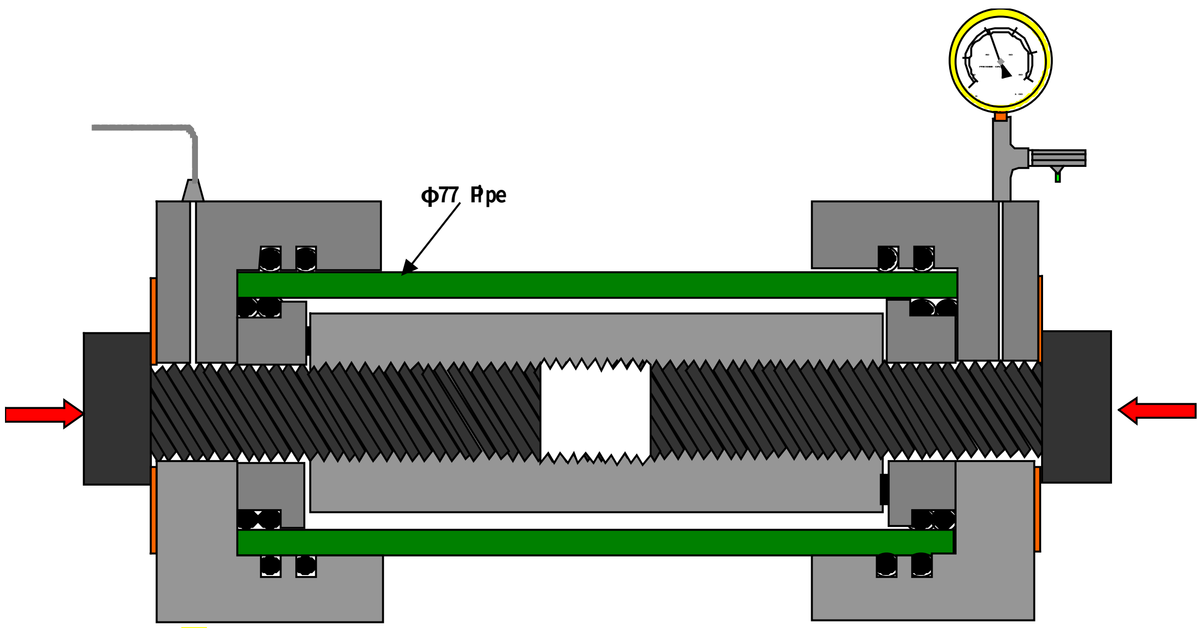

Fig.4: High pressure pipe test device

applied to the sectional plane, it breaks through between layers. By this, water or oil for inner pressure invaded from the section leaks out through the delaminated gap. This situation cannot pass the tolerable inner pressure test of the purpose. This is the reason that seal of the sectional plane is important in the pressure tolerance test. Pressure test device has a structure such that high pressure water or oil passes only inside of the device through small pipe. Seal at the sectional plane is attained with making contraction of O-ring set at the inner wall by screwing up bolts at both ends. Contraction rate of 8 % of O-ring is adequate, and we have experimental data that the seal cannot function well with even more than or less than that contraction rate.

7. CRITICAL POINTS FOR PRESSURE AT JOINT

Fig.5 shows five critical points for internal pressure of the API pipes with joint. They are: (1) Inner anti-corrosion layer; since it has large elongation capability as 15%, major cause of the destruction of this layer is from notch caused by shearing stress between this layer and the reinforced layer irrespective of thickness of the anti-corrosion layer, (2) Reinforced layer; the basis is its rigidity, and CW pipe has higher pressure tolerance than conventional FW (Filament Winding) pipe. (3) Shearing stress at each thread of the screw; screw structure can disperse the shearing stress and therefore reduce the peak stress often happens at the end of the bonded joint, (4) Elongation of the joint; it is important to adapt and to reduce the peak stress between the pipe, (5) Invasion of inner liquid from cut end of the pipe (delamination); water protection lining is required at also here. Fig.6 shows leaked oil jet through (5) at the pressure test of the pipe.

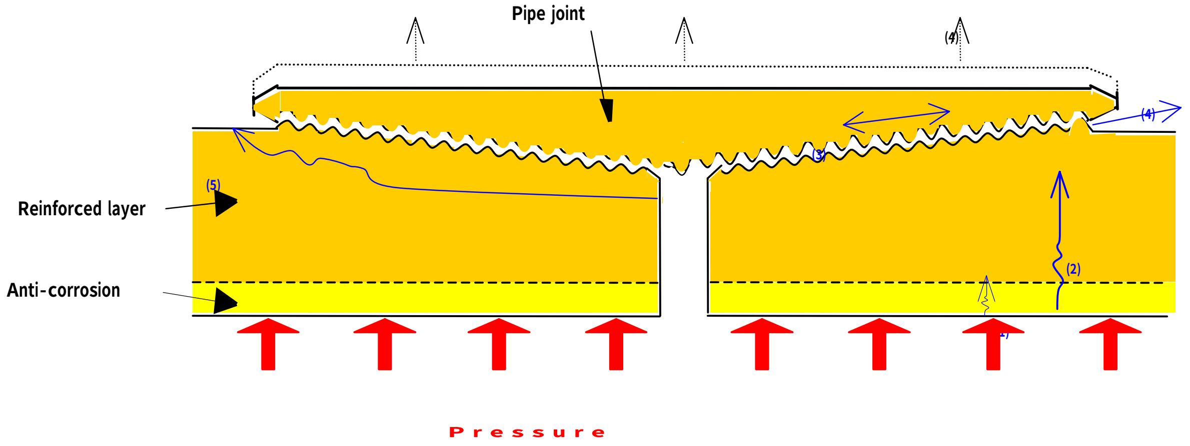

Fig.5 Critical points for internal pressure of API pipes having joint

The pipe has a structure of symmetric around the rotational axis, and critical points to the destruction are known. Though finite element analysis method is powerful for the general purpose, it is not adequate in such case, and conventional analysis method focused to such critical points may be adequate.

Previous analysis methods consider the shear stress uniform with average value regarding the material being homogeneous and multiply safety coefficients instead of analyzing precisely. The key point is to reduce the peak stress often happens at the end of joint. It is required to design with balance between these five points so as to have uniform stress as far as possible considering temperature and pressure.

Experimental results

Concerning the short length pipes cut out from CW-API pipes, we have tested about 10 samples, which showed 400-620 [kgf/cm^2] of destruction pressure, and their average was 540 [kgf/cm^2]. These values are almost the same (420 [kgf/cm^2]) or more with predicted by the thin wall theory of Eq.(5, 6).

Concerning the joint part, we have confirmed it is not destroyed by 280 [kgf/m^2] which is enough higher than 220 [kgf/m^2] of API standard. However, we could not tested with more high pressure because of leakage from the screw gap. We are going to select a proper caulking material/way to be able to realize the 1000 [kgf/m2] tolerance pressure as is the theory.

8. CONCLUSIONS

We have shown the design and testing methods for FRP high pressure pipe which were manufactured by our unique CW (centrifugal winding) method. We have developed a high pressure test device of compact size. Results showed the physical strength agrees very well with the theory.

Fig.6: Leakage of inner oil through crevice in reinforced layer.

Our CW-API pipe is only one product made by centrifugal forming method in FRP API pipes. It's feature is that it is manufactured by the outer shape ruling. Therefore, though socket can be commonized, wall thickness of the pipe can be selected freely. Since the outer size of socket is also selectable, it is possible to use the economically designed pipe for necessary pressure tolerance. Further, selection of the resin material related to temperature tolerance is also free, it is recommended to select the resin with proper characteristic. The main usages of the CW-API pipes are well pipe and down force tubing for oil production. Depth of the well is 1000-5000 m. Temperature tolerance is 80-150 C degrees.

For FW pipes, many testing methods have been reported for joint [6], transverse cracking [7], multiaxial analysis [3, 8], fatigue [9], and burst [10] etc. Also we are investigating and testing the CW high pressure pipes including these view points.

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