
RPS A-150 and P-150 FRP Piping - Design Basis

References:

1. RPS Doc. No. E-433
2. ASME B31.1 and B31.3
3. ASME RTP-1

1. General

This report describes the design basis used by RPS in designing A-150 and P-150 piping. The report includes discussions on justification for the design basis, design of FRP piping components, and determination of allowable stresses suitable for use in a pipe stress analysis in accordance with ASME B31.1 or B31.3. (This report is not applicable to absorber internal spray pipes. Refer to E-437 for design information on RPS “AA” Series absorber spray piping).

2. Safety Factor

RPS uses a minimum safety factor of 6 in the design of piping components. This has been adopted in several Industry codes and standards as described below:

- ASTM D6041 requires contact-molded FRP pipe and fittings to be designed with an allowable stress not in excess of 1/6 of the laminate strength.
- German standards DIN 16965 and DIN 16966 require the failure pressure of FRP pipe and fittings to be not less than 6 times the pressure rating.
- British standard BS 6464 requires that no FRP pipe or fitting be designed with a design factor less than 6.
- ASME B31.1 and B31.3 require a design factor of not less than 2 be applied to the Hydrostatic Design Basis (HDB) when designing filament wound FRP pipe. The HDB is the long term hydrostatic hoop strength of the pipe. Long term testing has shown that the strength of the pipe reduces by a factor of 2.5 – 3 over the life of the pipe. Multiplying the design factor of 2 by the long term strength reduction factor of 3, results in a short term safety factor of 6.

3. Piping Component Design

3.1 Pipe

RPS has determined the strength of filament wound pipe to be at least 40,000 psi in the hoop direction, and 20,000 psi in the axial direction. These strengths have been determined by many hydrostatic burst tests over many years. RPS uses an allowable hoop stress of not more than 4000 psi when determining the required structural wall thickness of pipe for a given pressure rating. This provides a safety factor of 10 in both the hoop and axial directions based on pressure alone. The safety factor of 6 applies when other axial loads are taken into consideration (Refer to Section 4.2).

3.2 Elbows

Elbows, like other fittings, are manufactured by contact molding. This means that reinforcements are applied to an open mold, either by hand (hand lay-up) or by using a chopper gun (spray-up). RPS has conducted many laminate tests over the years to determine and verify the strengths of different types of reinforcements. The two most widely used types of reinforcement are chopped strand glass and woven roving. The strength of chopped strand glass has been determined to be 600 lb/in. for 1 layer of 1.5 oz/ft², and the strength of woven roving has been determined to be 1250 lb/in for 1 layer of 24 oz/yd². RPS then designs the elbow by determining how many layers of each type of reinforcement are required to provide the necessary strength.

For example, a 12" diameter, 150 psi elbow has a design hoop load of $(P \times D \times FOS) / 2 = (150 \times 12 \times 6) / 2 = 5400$ lb/in. A suitable laminate for this elbow would include 5 layers of 1.5 oz chopped strand glass and 2 layers of 24 oz. woven roving. The strength of this laminate would be $5 \times 600 + 2 \times 1250 = 5500$ lb/in. This example used a safety factor of 6. In fact, RPS uses a design factor of 8 for pressure piping elbows to provide capacity for loads other than pressure.

3.3 Other Fittings

Other fittings are designed in much the same way as for elbows. Other types of reinforcements may be utilized to efficiently resist the higher stresses inherent in fittings due to their geometric discontinuities. For example, the discontinuities associated with tees require the tees to be much thicker than the adjoining pipe. In fact, RPS uses a pressure stress multiplier of 2.6 when designing tees. This means a tee must possess 2.6 times the strength of a contact molded pipe.

4. Allowable Stresses

4.1 General

In determining allowable stresses which would be suitable for a pipe stress analysis in accordance with ASME B31.1 or B31.3, it is necessary to consider not only the characteristics of the FRP material, but also the forms of the equations for stress as specified in B31.1 and B31.3.

With respect to the first point, FRP does not yield in the same manner as a ductile material. There is, therefore, very little justification for allowing higher stresses for displacement-induced stresses as compared to primary load stresses. All operating stresses, including displacement-induced stresses, should be compared to the specified allowable stress.

With regard to the second point, the equations for stress as specified in B31.1 or B31.3 are primarily intended to calculate axial stresses, and strictly speaking, are only applicable to isotropic materials. As FRP components typically have different axial and hoop strengths, it is necessary to ensure that the code equations provide an adequate assessment of stress.

4.2 Pipe

RPS filament wound pipe has different strengths in the hoop and axial directions, i.e. it is orthotropic. The hoop strength of 40,000 psi is primarily used only for determining the thickness of the structural wall. For pipe stress analysis, it is the axial strength we are interested in. When the pipe is exposed to only biaxial pressure (i.e. pressure load in hoop and axial directions), the axial strength is 20,000 psi. When the pipe is exposed to axial stress alone, as in the case of bending, the axial strength is only 12,000 psi. Most often the pipe is exposed to biaxial stress arising from both pressure and from other loads acting in the axial direction. In order to maintain a consistent safety factor, determination of allowable stresses must account for the different strengths. This has been done by using the Quadratic Interaction Criterion (Ref.: ASME RTP-1, Mandatory Appendix M-3). The Quadratic Interaction Criterion provides a rigorous means of assessing the effects of the bi-axial loading and the different laminate strengths. By using the Quadratic Interaction Criterion, the strain limits defined in RTP-1 (Mandatory Appendix M-3), and a minimum strength ratio of 1.6 for unidirectional layers (Ref.: RTP-1, Paragraph 3B-500), RPS has determined appropriate allowable stresses for the pipe.

4.2 (cont'd)

The specific steps involved in doing so were:

- i) Model the filament wound pipe in TRILAM II (a laminate analysis software package).
- ii) Apply a biaxial pressure of 150 psi.
- iii) Determine how much additional axial load can be applied to the pipe while maintaining a strength ratio of at least 1.6.
- iv) Calculate the allowable stress as the axial pressure load plus the additional axial load, all divided by the pipe cross-sectional area.

An example of this approach follows:

12" diameter A-150 pipe has a structural wall thickness of 0.26", and a cross-sectional area of 10.19 in². When this pipe is modeled in TRILAM with a biaxial pressure of 150 psi applied, the minimum strength ratio in the laminate is 2.60. When an additional axial load of 9500 lb. is applied, the minimum strength ratio reduces to 1.60. The allowable stress is then:

$$(\pi / 4 * 12^2 * 150 + 9500) / 10.19 = 2597 \text{ psi.}$$

The same approach could be used for determining the allowable stress at other pressures such as 100 psi, 50 psi, and 0 psi, for instance, but a simpler approach is to use 12,000 / 6 = 2,000 psi at 0 pressure, and interpolate for intermediate pressures. This is somewhat conservative.

Notes:

1. An alternative approach would be to use a "combined factor of safety", calculated as follows:

$$FOS_C = (\sigma_p / 20000 + \sigma_B / 12000)^{-1}$$

where: σ_p = Axial stress due to pressure

σ_B = Axial stress due to bending

For the 12" diameter A-150 pipe:

$$\sigma_p = 1665 \text{ psi,}$$

so, for a $FOS_C = 6.0$, $\sigma_B \leq 1001 \text{ psi.}$

Therefore, Allowable stress = 1665 + 1001 = 2665 psi.

This is somewhat less conservative than the previous approach.

2. The maximum principal strain using the above approach will not exceed 0.0015 at any pressure.

4.3 Elbows

Determining appropriate allowable stresses for elbows required not only the use of the Quadratic Interaction Criterion, but also Finite Element Analysis. FEA was required due to the complex stress response of the elbows to moment loading, and due to the form of the B31 equations for stress. A detailed explanation follows:

As the structural layers of the elbow are primarily quasi-isotropic, the appropriate minimum strength ratio becomes the same as the safety factor, i.e. 6. This would make the determination of the allowable stress easy (i.e. strength / 6) if not for the next issue.

When an in-plane moment is applied to the elbow, the maximum stress is a hoop stress, not an axial stress. Note: the elbow SIF's have been determined based upon these hoop stresses. But the B31 equations for stress include an axial stress term for pressure stress ($PD / (4T)$). Therefore, application of the B31 equations for stress will result in an axial pressure stress being added to a hoop bending stress. The resulting stress has no direct physical significance. As it is not possible to change the B31 equations (at least not in the short term), it was necessary to specify appropriate allowable stresses to which the B31 stresses could be compared. This was done as follows:

- i) An allowable stress was chosen for the elbow at a pressure of 150 psi.
- ii) The maximum allowable moment was calculated from this allowable stress by deducting out the pressure stress, dividing by the elbow SIF, and multiplying by the elbow section modulus, i.e.

$$M_{\text{allow}} = Z / \text{SIF} \times (\text{SIG}_{\text{allow}} - \text{SIG}_P)$$

where: Z = Section modulus of elbow

$\text{SIG}_{\text{allow}}$ = Allowable stress

SIG_P = Pressure stress ($P \times D / (4 \times T)$)

- iii) The elbow was modeled in FEA and loaded with 150 psi of pressure and the moment calculated in (ii).
- iv) The resulting hoop and axial stresses were input to TRILAM to ensure the minimum strength ratio of 6 was achieved. If not, the allowable stress was reduced and the process repeated until successful.

For the case of 0 psi pressure, the situation is much simpler. The B31 equations provide accurate prediction of the hoop stresses due to bending. Nevertheless, the procedure detailed above was repeated using the specified allowable stresses at 0 psi to again ensure the minimum strength ratio of 6 was achieved.

4.4 Other Fittings

Due to the complex geometry of most fittings other than elbows, it is not practical to undertake the the same level of analysis as for elbows. Even though these fittings are manufactured primarily by contact molding, as a conservative approach, the same allowable stresses as for the pipe have been specified.