Public Quarterly Report

Date of Report: *7th Quarterly Report – June 30, 2023*

Contract Number: *693JK3211RA0001*
Prepared for: *DOT PHMSA*
Project Title: ***Using Alternative-Steel and Composite Material in Gas and Hazardous Liquid Pipeline Systems***

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For quarterly period ending: June *30, 2023*

1: Work Performed During this Quarterly Period

Figure 1 presents the related deliverable milestones. The circled items are the completed ones this quarter.

Task 2 – Evaluate Material Properties and Testing Procedures:

This task is complete. Work included the identification of required material properties, setting testing procedures, and performing tests:

- Performed evaluation of denting and pressure tests on the composite samples.
- A report on material properties and testing was submitted last quarter (6th Quarter).

Task 3: Design for Maximum Allowable Operating Pressure:

This task is completed this quarter. Work in this task included:

- Performed stepped loading tests to determine long-term performance of the composite.
- Task 3 Interim Report (*Item 10 of the Deliverables Table in Figure 1*) is in Attachment A of this report (a late submission).
- The 15th Quarterly Report (*Item 15 of the Deliverables Table in Figure 1*) is this report (on time).

2: Items Not Completed During this Quarterly Period:

Work in Task 4 is in progress and a submission of its interim report is planned in the following quarter.

Further tests for the evaluation of other composites, including the Safe-Guard material, are planned in a separate new Task 11 in the Project Delivery Milestones.

OVERVIEW

1.1 Background

Composite pipe materials are gaining attention in the oil and gas industry where they are either inserted in a steel host pipe or directly buried for transmission and high-pressure distribution systems. A critical assessment of their performance, particularly in directly buried applications where they are exposed to higher stresses and harsher environments, is needed to ensure they are operated safely and reliably. To support this research initiative, Gas Technology Institute (GTI) contracted C-FER Technologies (1999) Inc. ("C-FER") to conduct a review of modern composite pipe material properties and to assess the suitability of their qualification procedures. The composite pipes that are commonly used for the transmission and distribution of oil and natural gas were identified in Task 2 (1). This Task 3 report summarizes the key findings from literature and testing on aspects related to estimating design pressure and lifespan of composite pipes.

This portion of the overall project is described under Task 3 of the Agreement for Services no. S1111 dated January 12, 2022.

1.2 Objective

The current investigation aims to identify important considerations, limitations, and/or knowledge gaps that exist within the current body of publicly available standards and recommended practices for determining the maximum allowable operating pressure (MAOP) and lifespan for composite pipes used in transmission and high-pressure distribution of oil and gas. The key objective is to investigate testing methods used to determine the hydrostatic design basis (HDB) and their applicability to modern composite pipes.

1.3 Approach

The approach for Task 3 consisted of three main components:

1. a literature review,
2. development of a preliminary, complementary testing methodology; and
3. demonstration of the testing methodology via empirical methods.

2. LITERATURE REVIEW

2.1 Current Qualification Procedure for Composite Pipes

As part of the qualification procedure of composite pipes, hydrostatic tests are conducted under specified loading conditions and temperature to determine the pipes' performance. This qualification step allows composite pipe manufacturers to establish appropriate safety factors, while complying with relevant national and international regulatory codes. Section 192.619 of 49 CFR 192 recommends the use of the HDB to determine the MAOP of plastic pipes (2). Similarly, API 15S (3) proposes the use of either ASTM D1599 (4) (for steel reinforcement) or ASTM D2992 (5) (for non-metallic reinforcement) to determine the HDB and lifespan for composite pipes. However, API 15S specifies that the occurrence of strength regression over time is not significant in steel-reinforced composite pipes compared to fiber-reinforced as visco-elastic/plastic properties of polymer reinforcements (e.g., in fiberglass) can cause loss of strength and stiffness over time (3). Therefore, the pressure rating for such pipes is generally determined through a long-term hydrostatic test according to ASTM D2992. Also, the required number of burst tests varies depending on whether the strength of the reinforcement material regresses or not. A minimum of five burst tests are recommended, in ASTM D1599, for reinforcing material with non-significant strength regression (e.g., steel-reinforced composite pipes), whereas eighteen burst tests are needed for reinforcing material presenting significant strength regression (e.g., non-metallic-reinforced pipes) (5). In the latter scenario, the 18 burst test results are used to establish a log-log linear relationship between the time-to-failure and the hoop stress. The obtained equation is then used to estimate the long-term hydrostatic strength of composite pipes by extrapolating to the design life of the pipe, which is often 20 years. To account for product variability and experimental errors, a 97.5% lower confidence limit (LCL) is calculated for all the results.

Typically, pipelines experience significant hoop and axial strain throughout their life span. The related mechanical properties are difficult to accurately measure on composite pipes based on existing qualification guidelines. Also, the pressure rating obtained from hydrostatic testing is often influenced by test conditions, material composition, and/or the manufacturing process. A recent study (6) highlighted other complexities that may affect the qualification of multi-layered composite pipe materials. It identified the following ways through which composite pipes made of various constituents can fail under hydrostatic pressure:

- Thermoplastic layer(s) reinforced with metal in the middle: The outer and middle layer will typically burst under high internal pressure. Also, both outer layers will buckle/debond from the internal liner under high temperature and/or external forces.

- Fibre-reinforced layer on thermoplastic liner: The outermost layer will burst under high pressure, buckle/debond from the internal liner under high temperature, and debond from the internal liner when subjected to external forces.
- Multiple layers of fibre-reinforced plastic: This will burst with high internal pressure and buckle or crush/collapse under high external forces.
- Internally lined existing pipe: The outer pipe will burst with high internal pressure and buckle/debond under high temperature and external forces.

Choosing the appropriate procedure for determining HDB in a particular composite pipe depends on the qualitative differences in strength regression behavior. Currently, there is no systematic approach for estimating the extent to which composite pipes will lose their strength over time. The general belief is that fiberglass-reinforced composites are prone to strength regression and should be subjected to long-term tests based on ASTM D2992. However, this phenomenon may become more complicated for different product types. Therefore, it is important to develop a procedure that helps manufacturers determine if their product is either susceptible to strength regression, and therefore, should be evaluated using a long-term test according to ASTM D2992; or if the material is not susceptible to strength regression, and therefore, can be evaluated using a short-term test according to ASTM D1599. Also, understanding the strength regression behavior in composite pipes will be helpful in re-validating products after changes are made to materials and/or manufacturing process.

2.2 Determination of the Hydrostatic Design Basis

The HDB for composite pipes and adjoining fittings is complex to determine due to varying product characteristics across manufacturers. To properly evaluate the long-term hydrostatic strength of composite pipes, it is important to understand the mechanical properties of their constituents (7).

The conventional long-term hydrostatic test is largely performed according to guidelines specified in ASTM D2992. It involves subjecting composite pipes to an internal hydrostatic creep rupture test, linearizing the relationship between the time-to-failure and the hoop stress, and extrapolating the results to up to 50 years. The pressurized pipe is allowed to sit for up to 10,000 h at the prescribed pressure until creep rupture occurs. Throughout the test, the pipe specimens are immersed in a temperature-controlled water bath to account for potential sensitivity to operational temperature conditions.

Two separate hydrostatic test methods have been used to obtain the HDB of various fiber-reinforced composite pipes (6,8,9): 1) Procedure A, which requires cyclic loading; and 2) Procedure B, which requires continuous (static) loading. Irrespective of the test procedure adopted, the appropriate service (design) factor must be used to determine the allowable stresses and design limits for composite pipe. For example, ASME NM.2 (10) recommends a design factor of not more than 1 when Procedure A is used, while a design factor not exceeding 0.5 is specified for Procedure B. Note that both standards (i.e. ASTM D2992 and ASME NM.2) refer to composite pipes that are made of glass-fiber-reinforced thermosetting resin. Such pipes are mostly rigid (i.e. non-spoolable); thus, they are not considered for the transmission and distribution of oil and gas. The composite pipe products that are the focus of this project are mostly reinforced thermoplastic composite as established in Task 2 of this project (1). Therefore, proper consideration should be given to the use of these test procedures for establishing HDB for reinforced thermoplastic resin pipes.

API 15S (3) offers guidance for qualifying spoolable, reinforced plastic pipe and specifically recommends the use of Procedure B for non-metal-reinforced products in Section 5.3.1. It is assumed that these types of composite pipes are qualified at the temperature selected by their manufacturers (less than or equal to the design temperature), while using water as the pressurizing fluid. Any alternate fluid used should be declared and further guidance be sought from API 15S Annex F. The loading condition must be static for Procedure B to be applied on these types of pipes. If cyclic loading is a concern, API 15S Annex G clearly describes the qualification requirements for evaluating pressure fluctuations based on Procedure A. Note that typical pipeline operations involve some degree of pressure cycling (e.g. pressure pulsations, pump on/off cycles, pump jack strokes), and therefore, are believed to operate outside the baseline conditions identified in API 15S.

When manufacturers change material, manufacturing processes, construction, and liner thickness or fitting design, it is recommended that the reconfirmation of the product using the product representative regression line built follows ASTM D2992 (5). During the reconfirmation, the new product is subjected to 1000 h of hydrostatic pressure, and the pressures are selected in the lower prediction level established following ASTM D2992. Only weepage is considered a failure, and after 1000 h, the product is estimated safe for the same design lifetime of 20 or 50 years.

It appears that new pipe products should undergo a 1000-h test that results in a “pass” or “fail” decision. The binary output and the long time required for the reconfirmation of new variants of a composite family is a limitation for manufacturers to develop or enhance more products. Moreover, at least six specimens are required for the requalification procedure.

2.3 Alternative Short-term Hydrostatic Test

Given the limitations noted above and the rather onerous nature of the requalification procedure, consideration has been given to the possibility of an alternative short-term test capable of making similar predictions about the HBD of new products in a family, but with far fewer tests (one to two specimens) and significantly shorter hold times. Such a test could also be used to determine whether a particular composite pipe material would be subject to strength regression and determine its HDB.

Much research has been undertaken to find a possible correlation between short- and long-term hydrostatic burst tests for composite pipes. Finite element analysis was used to determine the residual strength of composite pipes based on creep phenomena, stress analysis, and failure behavior (11,12). These studies show some similarities between the short-term pressure tests with long-term performance of fiber-reinforced composite pipes. Also, they observed reasonable correlation between the results of finite element analysis and experimental data.

Among several techniques that have been explored to provide alternative solutions for predicting long-term hydrostatic pressure, one option seems particularly promising. It involves analyzing the stress-strain pattern with the intention of identifying the onset of non-linearities in the elastic behavior of pressurized composite pipe through a combination of strain-to-failure and ultimate elastic wall stress (UEWS). The UEWS is defined as the pressure at which non-linear stress-strain response begins to manifest. This behavior has been observed on a short-term cyclic pressure test where the intent was to identify the hoop stress (i.e., pressure)-strain value above which the rate of damage progression becomes a concern for long-term failure. The technique was applied for different pipe materials, including fiberglass-reinforced thermosets (12,13) and glass/epoxy composite pipes (14,15). So far, no significant attention has been paid to applying this method during quasi-static burst test. Also, most of the studies reported in the literature were conducted on thermoset-based fiberglass composite pipes. It is important to evaluate this technique on thermoplastic-based fiberglass composite pipes.

Figure 2.1 presents an illustration of the long-term strength regression phenomenon compared to the short-term UEWS method. Notice that the experimental results in Figure 2.1a are regressed to a design life of 20 years, where the HDB is determined as the corresponding hoop stress at that point. Alternatively, Figure 2.1b shows the overall linearity of strain prior to the UEWS and a sharp progression into non-linearity afterwards. In an earlier study by Frost and Cervenka (13), it was found that glass-fibre-reinforced composite pipes displayed significant changes in the linear progression of axial and hoop strain responses at pressures of 160 bar (16MPa) and 120 bar (12MPa), respectively. The results indicate excellent correlation between the UEWS and the long-term LCL value used to determine HDB. However, note that these results were obtained from fibre-reinforced composite pipes under cyclic loading conditions.

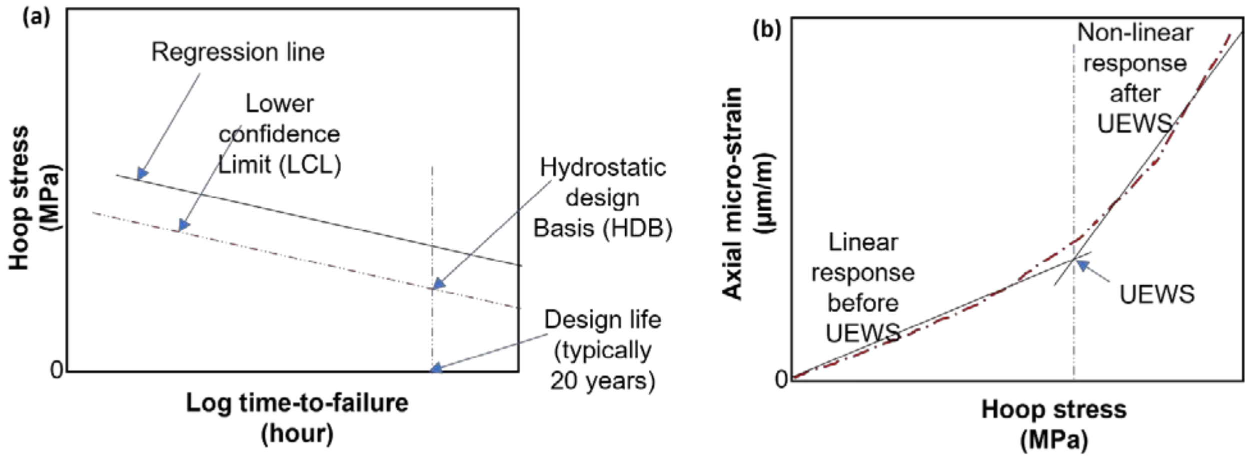

Figure 2.1 (a) Strength Regression Over Time based on Long-term Hydrostatic Test and (b) Axial vs. Hoop Strain Responses Before and After UEWS is Attained (adapted from Hoppel et al. and Frost and Cervenka)

The major advantage of the regression-based approach is the use of statistical techniques to capture the strength deterioration trend of the composite material and predict its future value (i.e. at 20 or 50 years). While this approach is acceptable for the qualification of a new product, it is cumbersome for requalification of a product variant. A summary of the unique distinctions and similarities between the UEWS approach is presented in Table 2.1.

Metric	Regression Method (as per ASTM D2992)	UEWS Method
Effort/convenience (i.e. time + cost)	The requalification test method is time consuming with a testing requirement exceeding 1,000 h and results in “Yes” or “No” (according to ASTM D2992) for each of the six required specimens, which may be unacceptable for such an expensive program. The test set-up is fixed in place for a long time.	This test method is less time consuming, and the results (a numerical value representing the UEWS) can be obtained within a day of testing.
Sensitivity to changes in material composition	This test method is sensitive to changes in material properties and pipe manufacturing techniques.	This test method is also sensitive to changes in the material properties and pipe manufacturing methods.
Chemical compatibility	Both test methods are not useful for assessing long-term degradation of composite pipes exposed to different environmental conditions.	

Table 2.1 Summary of Differences Between the Conventional Regression-based Approach and the UEWS Test Technique for Qualifying Composite Pipes