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PROJECT REPORT

REPORT NUMBER: TAP-101122-1

DATE: November 30, 2022

CLIENT INFORMATION
Taproot Energy Partners
555 17th Street, Suite 800
Denver, CO 80202
Attn: Dale Hunt

SAMPLE DESCRIPTION
Three (3) samples of 4" Shawcor Flexpipe (FP301W) were received from the client on 10/11/2022. These three (3) samples were reportedly removed from the "Big Mountain Viper" pipeline and consisted of a ruptured section approximately 10 feet long with the rupture at the approximate center of the sample, as well as two undamaged sections approximately 8 feet long which were removed from locations near the failure. The samples contained the following printline:

"|XXXXm (XXX.XX ft) 94004-1-1543 SHAWCOR 4"FP301W 03-14-2020 MADE IN CANADA |XXXXm [BARCODE]"

The ruptured section footage markings consisted of 0112m (367.45 ft) to 0114m (374.02 ft). The undamaged sections footage markings consisted of 0176m to 0178m and 0182m to 0184m.

The ruptured sample can be seen below in Figure 1. A closer image of the failure location can be seen in Figure 2.

Report Written by:

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Report Reviewed by:

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Figure 1. Ruptured sample as-received. Note failure location at approximate mid-length of the sample indicated by red arrow.

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Figure 2. Close-up image of the failure location on the ruptured sample shown in Figure 1. Note pipe axis deviation centered on the failure locus.

TEST PERFORMED

The client requested that a dissection and failure analysis be performed on the ruptured section of pipe in order to ascertain the cause of the failure. This dissection was performed in accordance with Shawcor's Flexpipe Linepipe Dissection SWP (Document Number 10-2522, Revision Number 10, Issued October 28, 2021). In general, this procedure consists of three (3) steps:

1. Removal of the outer high-density polyethylene (HDPE) jacket.
2. Removal and unwrapping of the fiberglass reinforcement layers (outer and inner)
3. Examining the inner high-density polyethylene (HDPE) liner

These three (3) components (jacket, reinforcement, and liner) corresponding to the steps listed above can be seen below in Figure 3.

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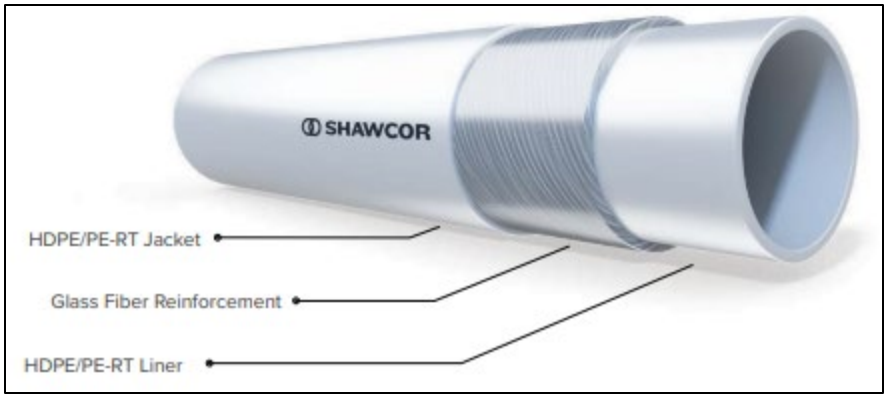

Figure 3. Schematic of the three (3) layers used in the production of the Shawcor Flexpipe (taken from the Shawcor Flexpipe Data Sheet).

ASTM D2122 Dimensions:
The sample was tested in accordance with ASTM D2122-22, *Standard Test Method for Determining Dimensions of Thermoplastic Pipe and Fittings*. Specifically, the sample was tested for average outside diameter. Locations tested were at the ends of the as-received rupture sample.

RESULTS
In order to ease sample handling, the ruptured sample was sectioned. A 3-foot-long section of the sample was removed with the center of this section corresponding to the failure locus.

Figure 4. The 3-foot-long section of the rupture sample marked prior to cutting.

Following sectioning of the rupture sample using a reciprocating saw, the section was marked using masking tape. Two (2) lines running down the axis of the pipe were marked allowing cutting of the outer jacket outside of the rupture location (see Figure 5).

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Figure 5. The 3-foot-long section following marking with masking tape. Note that another line is marked approximately 180° opposite the one shown.

Using a utility knife with the blade depth set to the thickness of the jacket, incisions were made along the pipe axis, leaving approximately one inch on either end of the section in-tact. This was done in order to keep the reinforcing fiberglass layers held in place (see Figure 6, 7, and 8).

Figure 6. The rupture section following removal of the outer jacket.

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Figure 7. Close-up image of the rupture location with the outer jacket removed. Note separation of the outer fiberglass reinforcement surrounding the leakage locations.

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Figure 8. Fiberglass reinforcement at one end of the rupture section following removal of the outer jacket. Note uniformity of the reinforcement layer just outside of the rupture location.

The approximately one-inch-wide jacket sections (see red arrow in Figure 8) were then removed from the specimen. The outer and inner fiberglass reinforcement layers were then unwound from the section, allowing for observation (see Figures 9 and 10).

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Figure 9. Inner view of the outer fiberglass reinforcement layer following removal from the liner. Note main rupture location at red arrow and broken inner fiberglass reinforcement layer pieces at red circle. Also note uniformity of fiberglass reinforcement just outside of the rupture location.

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Figure 10. Inner view of the inner fiberglass reinforcement layer following removal from the liner. Note random, i.e., not straight or aligned, breaks of the fiberglass reinforcement layer at red arrows.

After removal of the fiberglass reinforcement layers, the HDPE liner was then exposed. The liner showed the failure mode to be torsional in nature (see Figures 11, 12, and 13).

Figure 11. HDPE liner following removal of the fiberglass reinforcement layers. Note rupture and discoloration at the center of the liner section.

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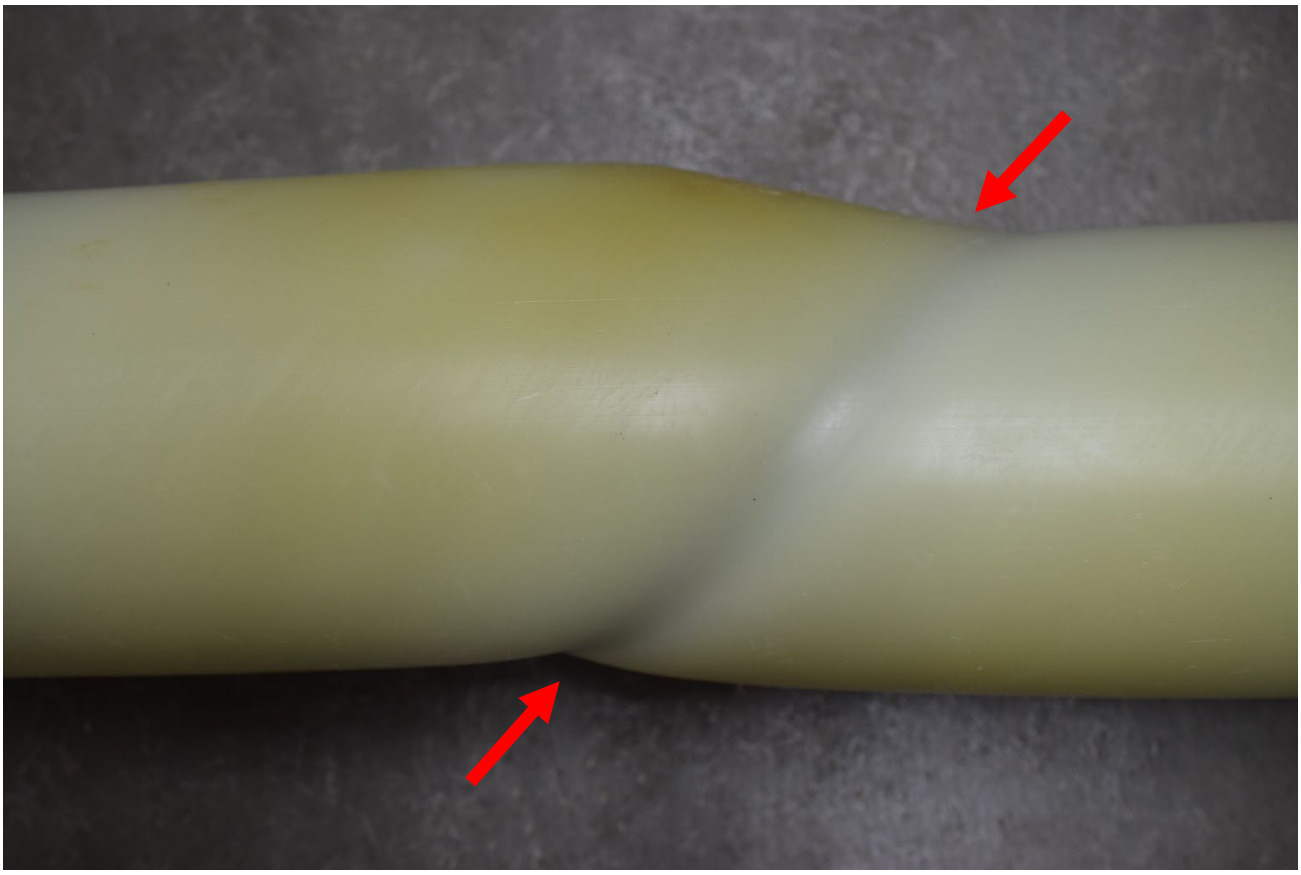

Figure 12. Close-up image of the HDPE liner opposite the rupture location. Note ductile deformation on the pipe between red arrows corresponding to torsional yield of the liner.

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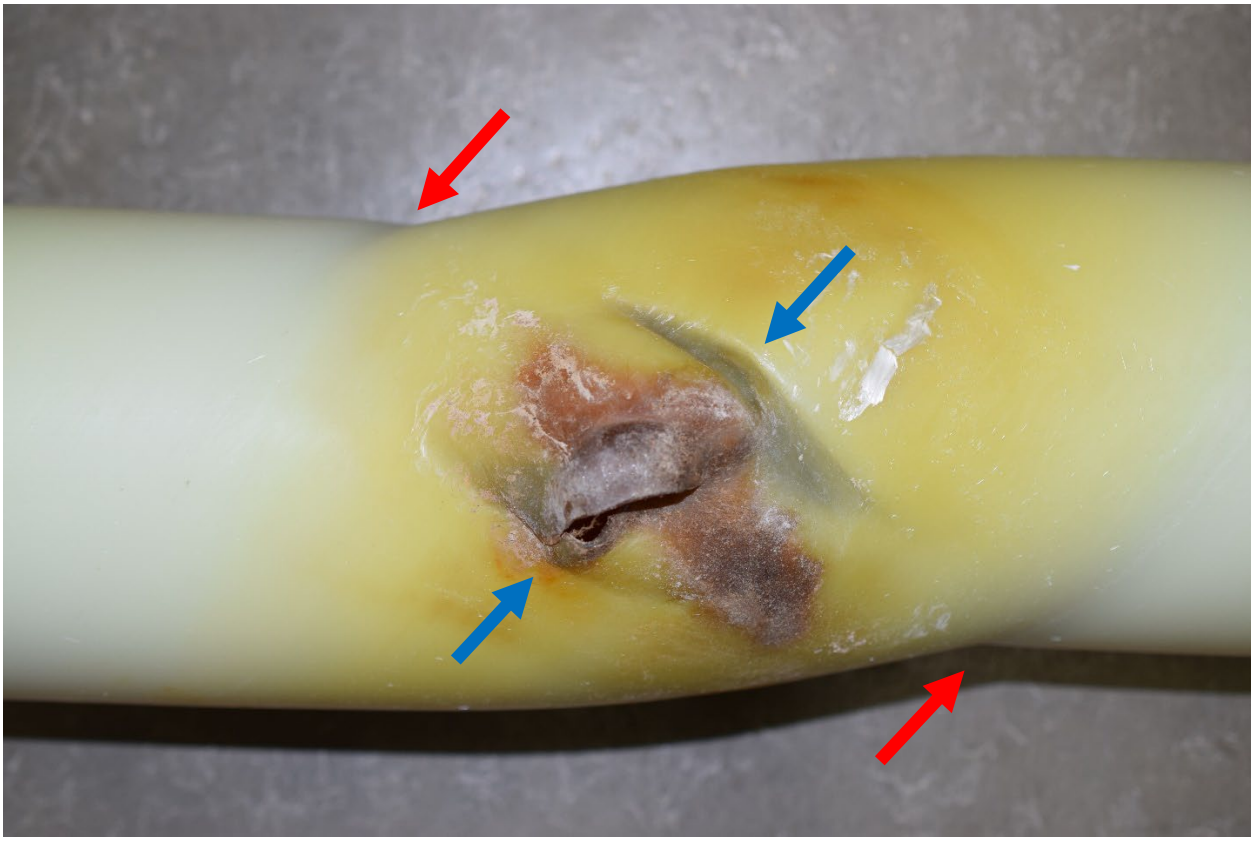

Figure 13. Close-up image of the rupture location seen in Figure 11. Note ends of the torsional yield shown in Figure 12 at red arrows. Also note edges of the ductile rupture location at blue arrows.

ASTM D2122 Dimensions:

Location	"A" End	"B" End
Ave. OD (in.)	4.911	4.911

Table 1. ASTM D2122-16 average outside diameter measurements. Note uniformity of dimensions on either side of the failure location.

DISCUSSION

The failure observed on the Shawcor Flexpipe rupture sample is consistent with a torsional failure mode. More specifically, the failure very closely resembles what is referred to as “birdcaging”. In this failure mode, torsional forces cause the inner reinforcement layer to be put in tension, while the outer reinforcement layer is put in compression. This in turn reduces the contact pressure between the two layers and allows displacement of the outer reinforcement layer. This description of the failure is consistent with the observations made, i.e., the inner fiberglass reinforcement layer was in the same direction as the applied torque and would be expected to be put in tension. Similarly, the outer fiberglass layer was in the opposite direction of the applied torque and expected to be put in compression; the 90 degree crossed helixes shown in Figure 13 are the expected result of these stress orientations.

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Displacement of the outer reinforcement layer then left areas of pipe with reduced reinforcement capacity, allowing creep and subsequent ductile rupture of the liner as seen in Figure 13. “Unwinding” of the outer reinforcement layer effectively reduced the reinforcement by half at the failure locus. Note that during this process, i.e., elimination of half of the outer reinforcement and increase of stress on the inner reinforcement, the inner reinforcement layer would experience significantly greater tensile stresses, resulting in the breaks of the fibers seen in Figure 10. Additionally, the edges of the ductile rupture location indicated by the blue arrows in Figure 13 are running along the same direction as the outer fiberglass reinforcement layer. This provides further evidence of displacement of the outer fiberglass reinforcement layer, i.e., the failure location was well reinforced just outside of the ductile rupture location. A schematic of the “birdcaging” failure mode can be seen below in Figure 14.

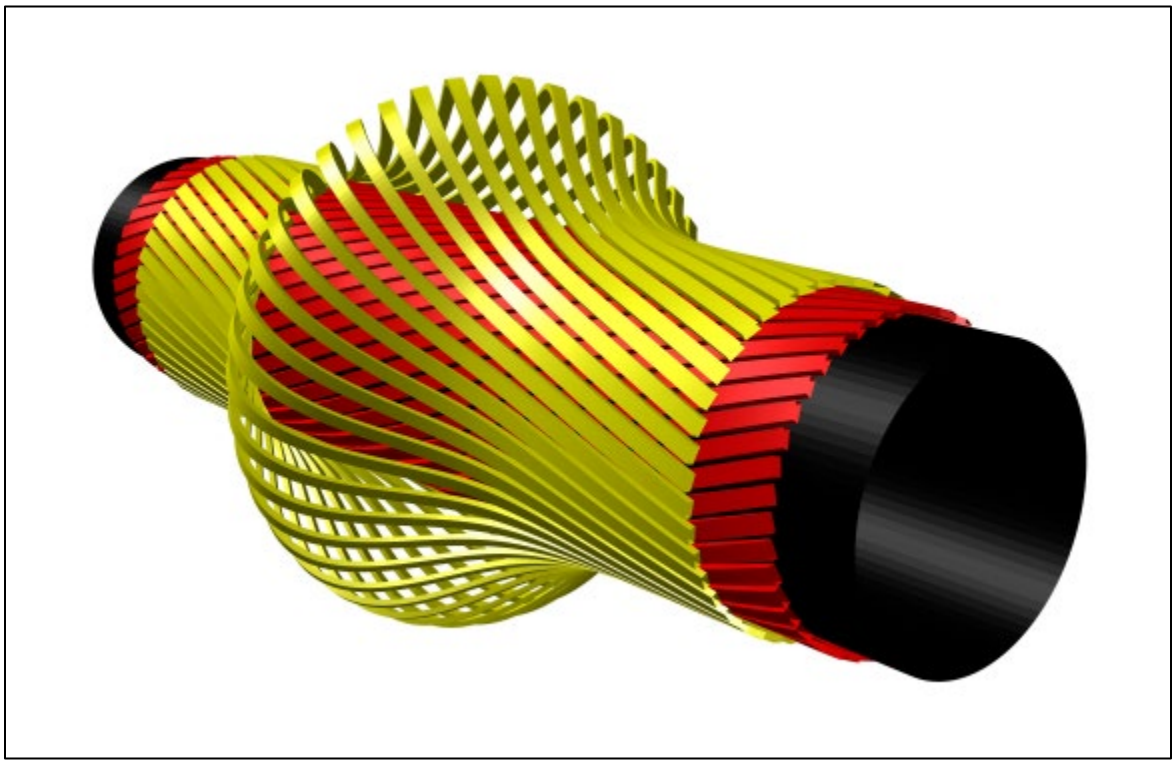

Figure 14. Schematic demonstrating the effects of “birdcaging” due to torsional forces on the flexible pipe. Note that this graphic is exaggerated due to the fiberglass reinforcement layer being bound by the outer jacket.

CONCLUSION

There are numerous operations that could have resulted in the application of torque which ultimately led to the failure of the Shawcor Flexpipe. In general, these operations would all consist of various handling and/or installation operations. Two potential sources of this applied torque were suggested by the client during discussion. The first consisted of torque inadvertently applied to the pipe during unspooling operations. The second consisted of torque inadvertently applied to the pipe during swaging operations. Note that the client indicated that the failure was located approximately 20 feet from a 90° bend in which swaging was used to create the transition.