

Successful Development of Coiled-Tubing Connectors Using Virtual Testing

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Abstract: Since its introduction in the 1960s, coiled tubing (CT) has evolved from smaller sizes and a few cleanout jobs to larger diameters and heavier grades with higher flow rates. Some of the limiting factors, especially on offshore platforms, are limited crane-weight capability and poor weather conditions, which severely limit the size of the reel that can be lifted. With offshore crane capabilities as low as eight tons on some platforms, a CT reel is often transported in two or more sections, requiring offshore assembly. A conventional method of joining the two strings was to butt weld them, which reduces fatigue life to 35%. Most recently, spoolable connectors, also called cold connections, have gained popularity because of their easy and safe installation. A nonlinear, FEA-based, virtual-test method was developed to quickly and cost effectively design spoolable connectors. Using the virtual test extensively in the development of the spoolable CT connectors, and guided by engineering mechanics principles, we have successfully developed a CT connector tool that exceeds the fatigue life of field butt weld. This CT connector tool has an industry-leading fatigue life and requires a fraction of the developmental cost and time that the conventional procedure of using trial-and-error physical tests requires. The virtual test, selected virtual- test results, physical results from a fatigue machine test, and a full-scale yard test are discussed in this paper.

Keywords: coiled tubing, connector, fatigue, virtual testing

1. Introduction

As the offshore industry accesses deeper reserves, the CT workstrings required for intervention operations have become longer and heavier. By far, the largest and heaviest component of a CT unit is the CT itself and the reel on which it is handled. In offshore applications, weight handling limitations presents a big challenge because many platforms were not designed to lift the heavy CT reels off the workboats and onto the platform. Because of this, CT must be placed on multiple reels before being transported to a worksite. The CT workstring must be assembled before a job is initiated. Joining the CT sections together into a continuous string is a major design challenge. Until recently, the preferred method has been to connect the CT sections by butt welding the ends of the CT; however, this can be an expensive and time-consuming proposition. First, welding specialists are required to complete the operation and, in most situations, a special work permit is required and a discrete area on the rig must be used. Second, in many instances, the well(s) must be shut in for the duration of the welding job for safety reasons. Finally, the welds have to be x-rayed by other specialists with more equipment. Because of these factors, development of a spoolable, mechanical, CT connector is of great interest.

In the development of the mechanical, spoolable connector, the goal was to design a connector that can outlast fatigue life of butt-weld. This was not easy. In the early stage, several attempts based on trial-and-error using physical tests yielded no significant insight into how to achieve this goal; and it took a long time. Eventually, it was decided to explore the design through virtual testing to gain insight, while saving time and costs. Using virtual testing enable us to design and test multiple designs and end result even exceed our own expectations.

This paper discusses a nonlinear, FEA-based virtual testing method and its application in CT-connector design iterations. This work documents the development of a novel, mechanical, spoolable connector with a usable fatigue life in excess of butt weld. Since fatigue data is statistical in nature, individual test results of spoolable connector are presented against 50 % median life of pipe and butt-weld pipe.

2. Physical Tests

There are two types of tests used for the development of CT or CT connectors. One is the lab test performed with a CT-fatigue test machine (see Figure 1), which was originally developed by Tipton and co-workers (Tipton 1994). This test is used frequently in the development of new CT or CT connectors. The other one is a full-scale yard test, which is performed on an actual reel (see Figure 2).

Lab Fatigue Tests

The fatigue machine uses 48-in. and 72-in. radius bend blocks for testing. Several prototypes were tested by varying the position and orientation of the connector on the bent block until the weakest spot of the connector was confirmed. All testing included a pressure test in the maximum bent position on 48-in. and 72-in. radius bend blocks. This was to simulate trip-out conditions under well control when high pressure pumping may be required, while the connector is still bent on the spooling drum. In addition, fatigue testing was conducted at pressures ranging from 1,000 to 10,000 psi. The 10,000-psi pressure is used to simulate a worst-case scenario, even though the CT connector assembly would rarely be fatigued at such high pressures.

Full-scale testing of spoolable connectors was conducted with a yard-spooling device on a 130-in. diameter drum, injector, and tubing guide (Figure 2). Multiple samples are tested at different pressures. The core of diameter drum was approximated as the most likely bend diameter; a spoolable connector will be installed at.

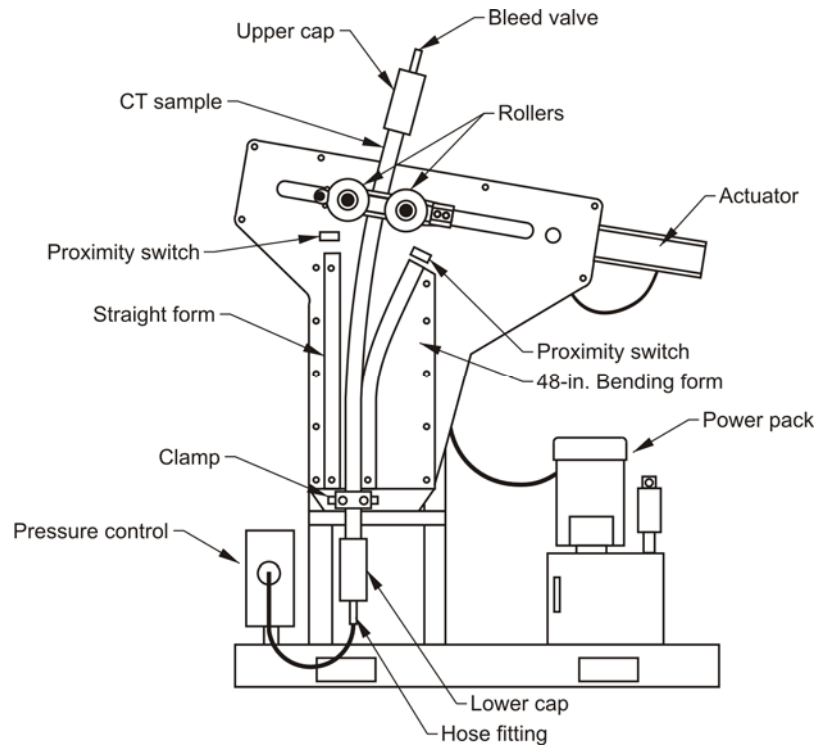


Figure 1. Sketch of the fatigue test machine.

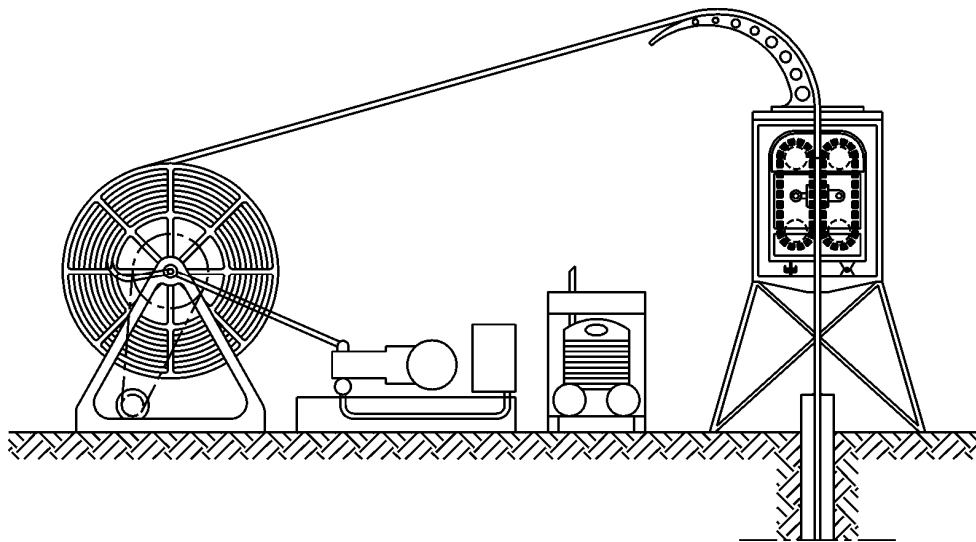


Figure 2. Sketch of the yard test.

3. Virtual Testing

A virtual test was developed for the lab bending fatigue test machine. This virtual test was essentially a high fidelity, full 3D, nonlinear, FEA simulation of the lab fatigue tests. All parts in the test were modeled as elastoplastic materials. Contacts among all components, as well as large deformations, were considered to accurately predict the stress and deformation in various components. The loads on the part were also exactly the same as those in the tests. The following was considered:

- Internal pressure in the CT
- Force to bend the CT
- Tensile load on the CT caused by close cap condition

The main challenges in the virtual testing included: strong nonlinearity caused by large deformation, multi-body contact, material nonlinearity, large model size because of small features in some parts of the CT assembly, and convergence. The service company developed a modeling procedure and a base model. A user only needs to change the test sample in the virtual test machine and follow the procedure to mesh and to define node sets and surfaces; then the base model is automatically updated yielding a robust FEA model for the new test sample.

In addition to bending fatigue, sealing between CT and the connector was another important aspect of the CT connector design. In fact, if leakage occurred, the connector was considered a failure. For efficiency, this portion of the virtual test was separated from that of the bending-fatigue virtual test. Virtual tests on seals in the connectors were used to test a seal performance during installation and under differential pressure. The virtual test model, in this case, was typically an axis-symmetric nonlinear model, taking into account large deformation and strong, material nonlinearity in elastomers.

4. Virtual Test-Based Design Iterations

A critical issue in the virtual test-based design iteration was how to determine the fatigue life of a newly designed connector or, alternatively, how to determine if one design was better than another. The fatigue life of CT is affected by numerous factors, such as surface damage, wall thinning, ovality, internal pressure, damage during trip in and out, damage by surface equipment, and pits created by corrosion. All of these factors result in a wide range in possible fatigue life of the CT pipe under similar conditions. Estimations of fatigue life for CT and CT connectors are also difficult because of the lack of knowledge regarding fatigue properties for tubing and connector materials (i.e., S-N curves are not available for low and ultra-low cycle fatigue). Even when those properties are available, the variability in fatigue data makes predictions unreliable. Therefore, rather than trying to predict fatigue life, a method was developed to rank relative fatigue lives for different connector designs' reliability. Following many virtual tests on previous connector designs and correlating FEA predictions with physical tests, a proprietary fatigue indicator was developed for CT and CT-connector designs. In the design iteration, virtual tests were first performed on several potential designs. Using the fatigue indicator, the various designs were

compared and the weakest parts in the design were pinpointed, enabling the design to be modified accordingly.

Connector Design Iterations

As in a real test, the CT-connector assembly was pressurized and bent. The force to bend the assembly, Figure 3 for example, was used against the calculated value to check on the virtual tests. In addition to these global responses, virtual tests using FEA provided details not easily available in physical tests, such as local stress/strain; compounded variables, such as the fatigue indicator, helped designers/analysts gain insight into connector performance. A comparison of the contours of the fatigue indicator for two designs of certain-sized connectors is made in Figure 4. Virtual tests showed that the design changes resulted in redistribution of stresses and deformation in the assembly. This change led to an improvement in fatigue life by one order of magnitude.

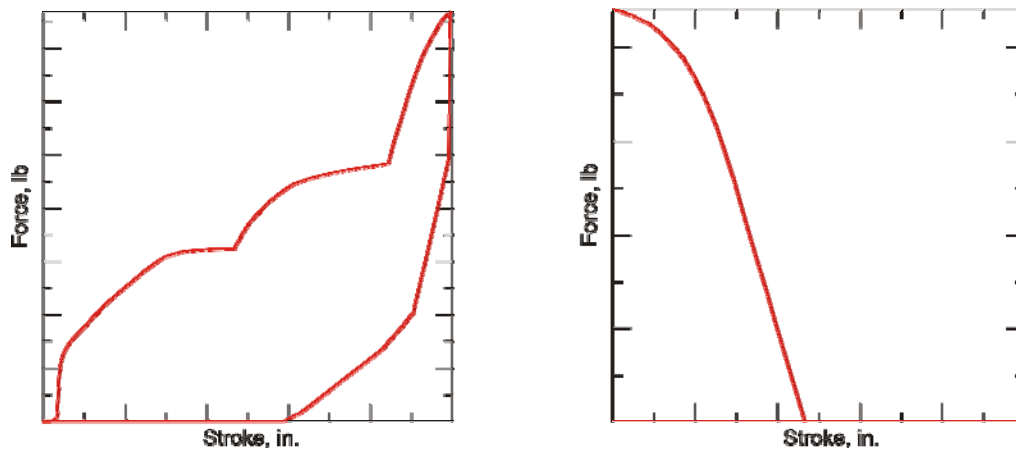


Figure 3. Force—to bend and un-bend the tubing-connector assembly.

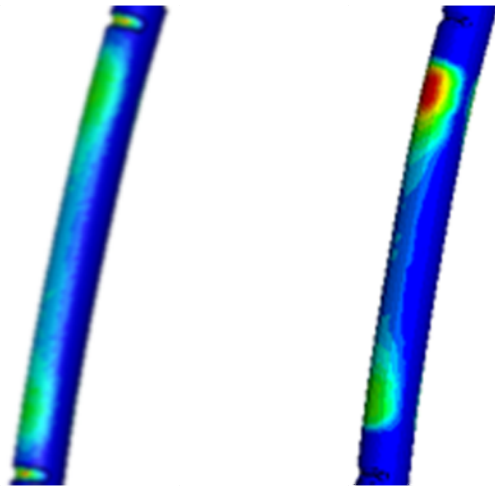


Figure 4. Comparison contours of fatigue indicator for two similar connectors.

Seal Design Iterations

To seal under-ovality of tubing, tubing expansion under high pressure (caused by ratcheting), or under bending, several types of aggressive seal designs were proposed. These designs were screened using FEA, and shortcomings in the new designs were identified. Figure 5 shows an example of simulation of installation of a molded seal during design iteration. In Figure 5a, simulation indicated that the seal would be extruded during installation; while Figure 5b shows that a modified seal would be installed without any problem. Design screening showed that initial design would have been damaged during installation and the modified design should install properly. After several design iterations, a seal with sufficient squeeze and proper sealing capacity was determined.

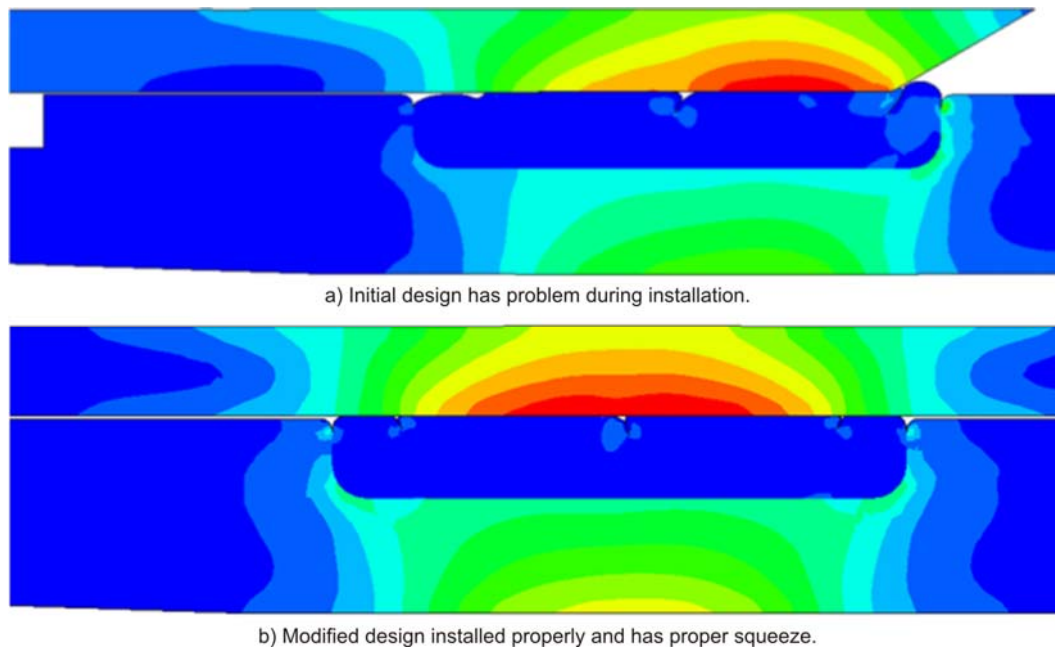


Figure 5. An example of a virtual test-based seal design iteration.

5. Physical Validations—Lab Tests and Yard Tests

Fatigue testing was conducted on the final design of the connector at pressures ranging from 1,000 to 10,000 psi. The 10,000-psi pressure was used to simulate a worst-case scenario, even though the CT connector assembly would rarely be fatigued at such high pressures. Figure 6 shows the results of fatigue machine tests. Several tests at identical test parameters were carried out for statistical fatigue calculation. It can be seen that fatigue life of spoolable connector is better than fatigue life of base pipe with butt weld, tested on fatigue machine, under identical test parameters.

Full-scale testing of spoolable connectors was conducted to further check the viability of the new design under realistic conditions. Six samples were tested at different pressures. Table 1 and Figure 7 show the results of the full-scale yard test results. Individual full scale test results of spoolable connector is presented against 50% median fatigue life of base pipe calculated using fatigue calculator and algorithm developed by Dr V.A. Avakov (Avakov, and Foster 1994).

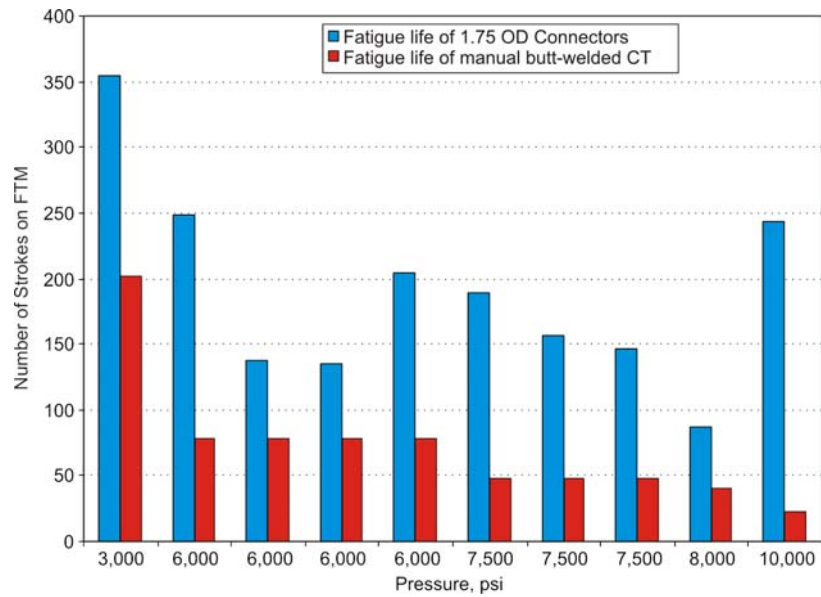


Figure 6. Histogram showing fatigue machine test results.

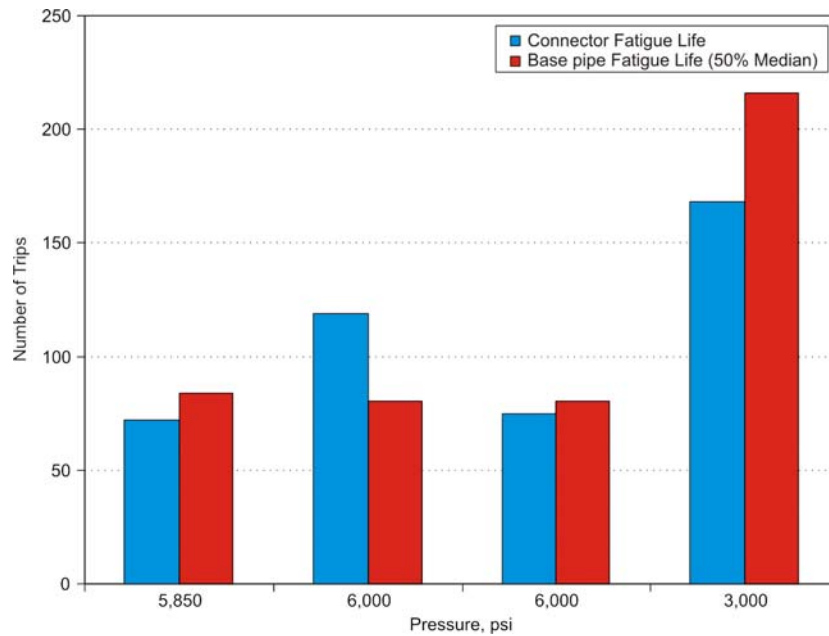


Figure 7. Histogram showing yard test results

Table 1—Full-scale Yard Test Results for 1.75-in. × 0.156-in. Spoolable Connector

Number	1	2	3	4	5	6
Tubing Guide Radius, in.	120	120	120	120	120	120
Drum Radius, in.	65	65	65	65	65	65
Pressure, psi	5,850	6,000	6,000	3,000	1,000	3,000
Number of Trips	72	119	75	168	40	40
Comments re: Failure Mode	No failure. Test stopped for tensile test.	Pressure leak from inside connector.	No failure. Test stopped for torque test.	Broke during spool-off.	No failure. Integrity check at 40 trips to follow.	No failure. Integrity check at 40 trips to follow.
No. of Trips for Base Pipe Calculated from Fatigue Software, (50% Median)	84	80	80	216	NA	NA
Tensile/Torque, lbf, ft-lbf	51,000 lbf	—	950-1330 ft lb	—	950 ft-lb	58,000 lbf
Life Compared to Base Tubing, %	86	149	94	78	NA	NA

Fatigue life calculated using V.A. Avakov Model (Avakov & Foster 1994)

The tensile and torque strength of the CT assembly (with connector) before and after bending are important performance parameters that can be easily determined using virtual tests; however, this type of test was not performed because the focus was on the improvement of bending fatigue life and sealing between connectors and CT. Physical tests, nevertheless, showed that the connector also provided satisfactory tensile and torque strength post-bending.

The tensile test on the connectors after bending typically resulted in 72 to 85% yield load compared to the base pipe. The torque test on the connector typically resulted in a 0.5-in. radial movement at 55 to 78% yield torque compared to the base pipe. For more details of the test results please refer to “Development of a High Performance Spoolable Connector,” Ehtesham, 2008.

6. Conclusion

A robust virtual test method using FEA is developed for CT spoolable connector. Utilizing the virtual test extensively in the development of the spoolable CT connectors and guided by engineering mechanics principles, a CT connector tool with fatigue life greater than butt weld and in some cases close to usable fatigue life of tubing. (an industry-leading fatigue life of spoolable CT connectors) was successfully used. A virtual test for sealing evaluation was developed and applied successfully to developing seals with superior performance for the connector. The virtual

test-based iteration has been successfully applied in the development of several other sized connectors, and in much shorter time than the one discussed in this paper. This case, once again, showed that virtual-test based design iteration helps to shorten development time, reduce development cost, and produce superior products.

7. References

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8. Acknowledgements

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