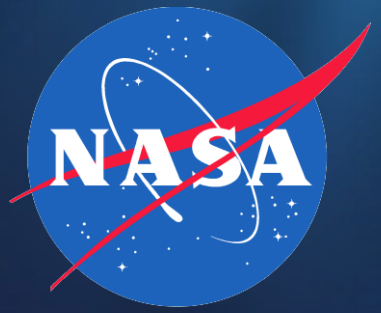
OMAE2015-41305

# Development and Testing of a Post-Installed Deepwater Monitoring System Using Fiber-Optic Sensors



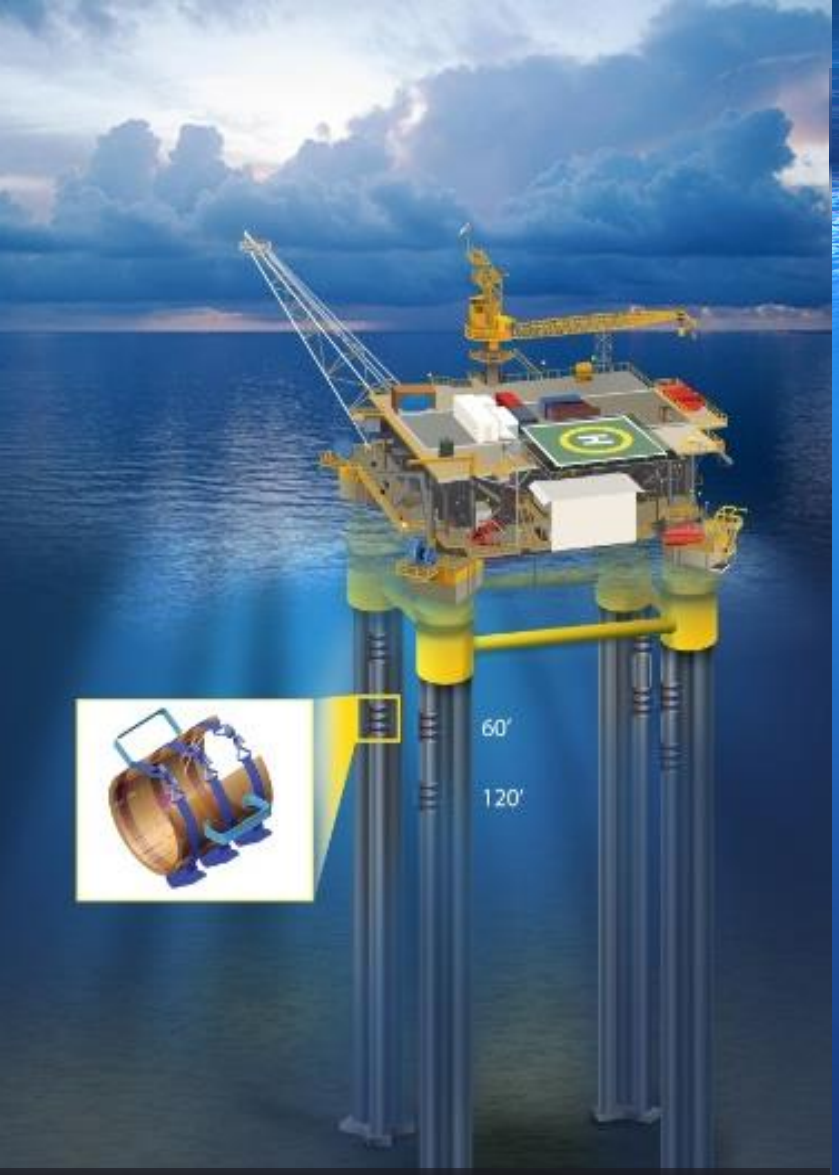



**C. H. Seaman, NASA Johnson Space Center**
D. V. Brower, Astro Technology Inc.
H. H. Tang, Aerodyne Industries, LLC
S. Q. Le, NASA Johnson Space Center

# NASA Involvement with Oil and Gas Industry

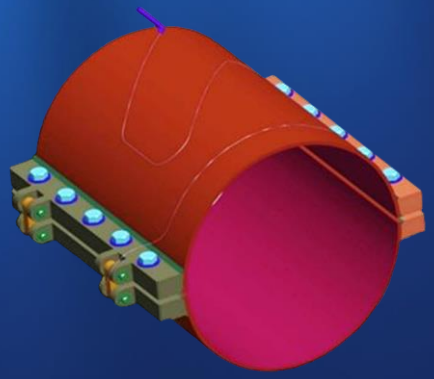

- Improve:
  - Environmental Protection
  - Operational Safety
  - Production Knowledge (Temperature, pressure, flow assurance, etc.)
- Develop structural health monitoring fiber optic sensing devices
- In-situ installation on tendons, pipelines, risers, or other structures deployed in deep water

# Fiber Optic Sensor Devices



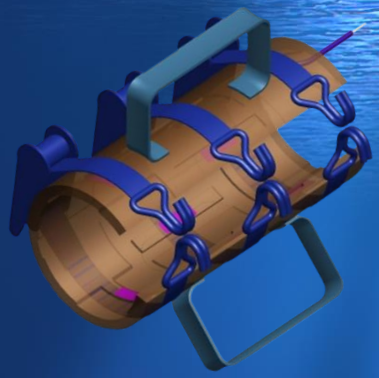

**Tension Leg Platform with Fiber Optic Adhesive Clamps Installed**

**Adhesive Clamp:**
Marine Bonding Adhesive
(Water Column)

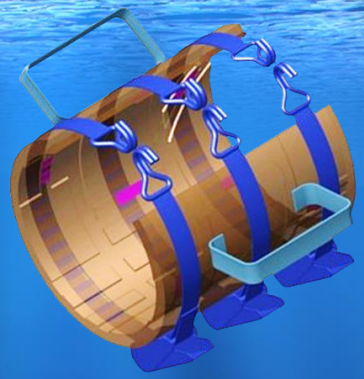


**Friction Clamp:**
Mechanical Friction Clamping Force
(Seabed)

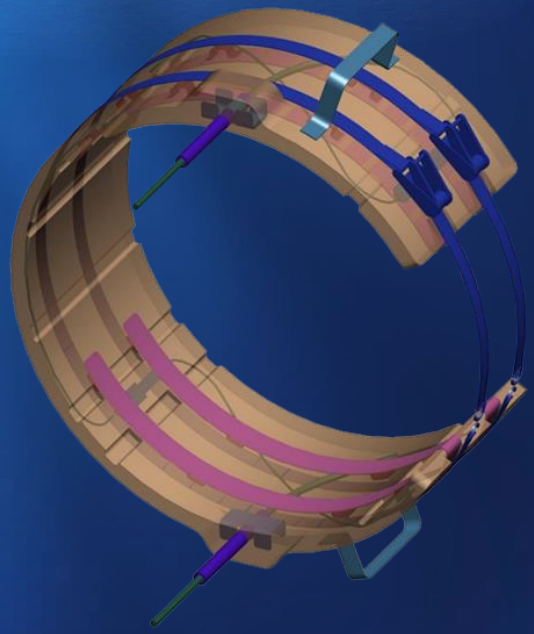
# Adhesive Clamp Design



4-in Adhesive Clamp



8-in Adhesive Clamp



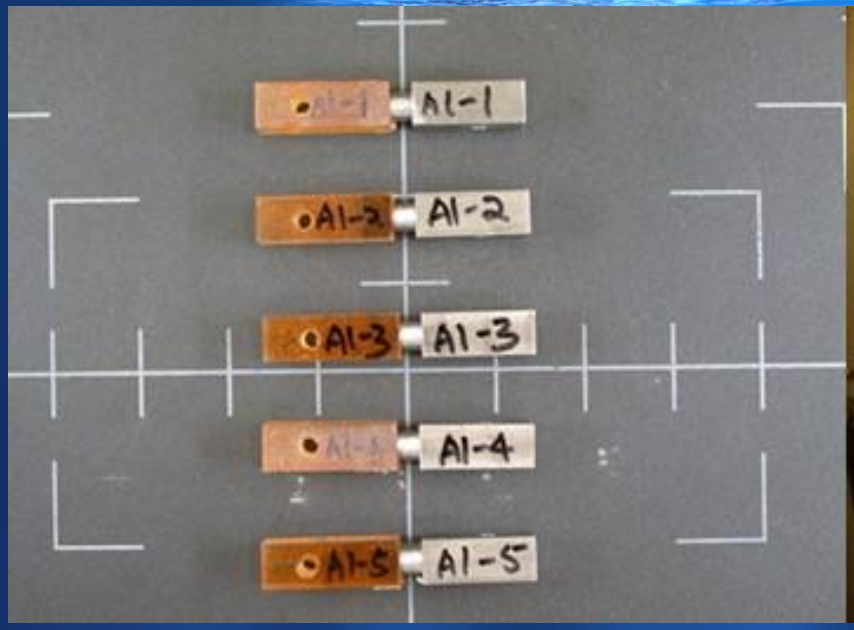
24-in Adhesive Clamp

- **Key Features:**
  - Flexible Polyurethane Body
  - Integrated Fiber Optic Sensors
  - Internal Thin Strip Sensor Shims
  - Built-in Adhesive Leveling Channels
  - 3-D Printed Mold

# Feasibility Evaluation

- **Commercial Marine Adhesive Market Survey Requirements:**
  - Application temperature between 5 and 75 deg C and working pressure around 4,500 psi corresponding to depths of ~10,000 feet
  - Subsea application by commercial divers and/or ROVs
  - Adhesive application time (“pot life”) of no less than 30 minutes
  - Application on sea floor pipelines in the presence of typical environmental contaminants
  - Adhere well to both polyurethane and steel
- **Four commercial adhesives were selected for laboratory testing in both dry ambient air and synthetic seawater environments.**
- **Modified test method ASTM D2095-96, Standard Test Method for Tensile Strength of Adhesives by Means of Bar and Rod Specimens was used to measure adhesive strength.**
  - A total of 40 adhesive tensile tests were conducted at the NASA-JSC Advanced Materials Laboratory.

# Adhesive Tensile Strength




Tensile Test Samples

Test Article in Tensile Test Fixture

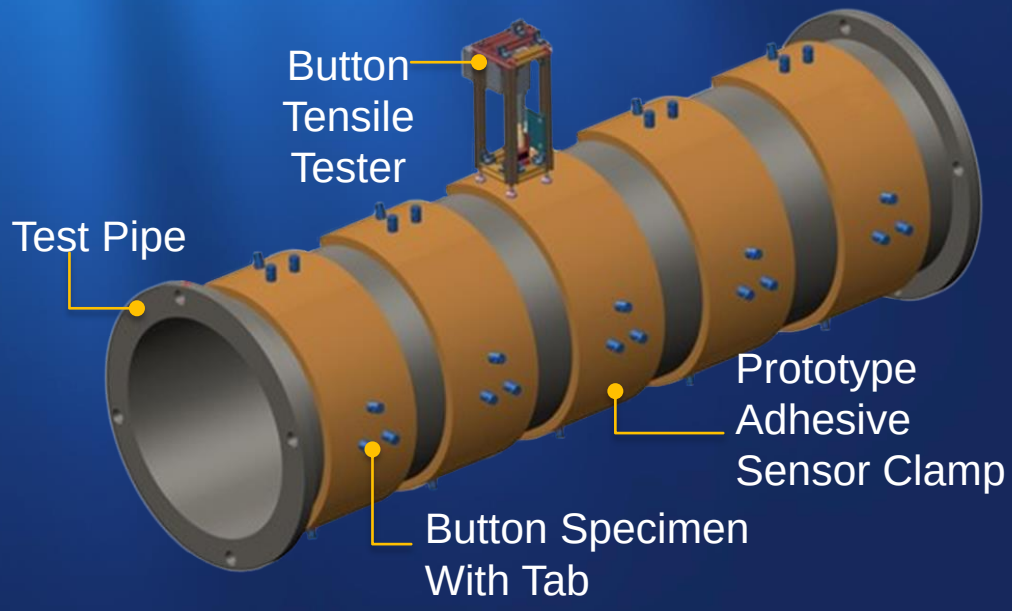
- **Based on the tensile test results, a commercial adhesive which offered the best combination of high average wet bonding strength (507 psi) and overall ease of handling characteristics was chosen for this application.**

# Proof-of-Concept Testing

- **Two-Phase Testing:**
  - **Phase I:** Several full-scale (24-inch dia) prototype clamps were installed onto test pipes. The objectives of Phase I testing were to define the underwater installation procedures in a controlled environment.
  - **Phase II:** Evaluation of the adhesive bonding strength of the prototype clamps installed during Phase I. A portable Button Tensile Tester (BTT) was built by NASA-JSC to conduct the testing.

**Button Tensile Tester**

- Aluminum frame
- Integrated linear actuator and load cell – both rated at 1,000 lbf capacity
- Hand switch controller
- Pin connector at the end of the load cell allowed direct force measurement of button samples



## 24-inch Dia Test Pipe with Seven Adhesive Clamps

## Button and Tab Specimens


Button Tensile Tester

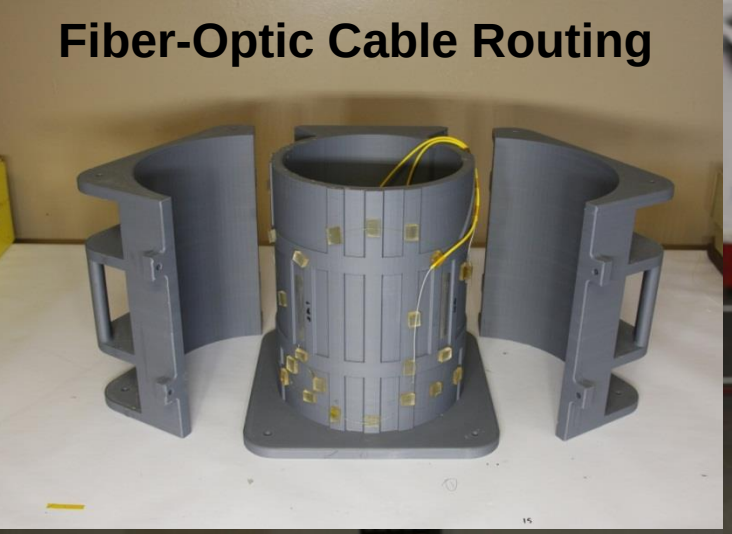
# Results

- The findings from the proof-of-concept testing demonstrated that the underwater adhesive clamp attachment method, by commercial diver, is a viable technique.
- A total of 142 tensile test points were produced and used to assess the adhesive bonding strength of the prototype clamps. The tensile strength values ranged from 91 to 174 psi.
- Test results indicated that a well-controlled installation protocol is needed to maximize the bonding strength of this adhesive clamp system.
- The findings showed that with proper installation technique the subsea adhesive would provide a very strong bond between the polyurethane sensor device and a steel structure.

# Prototype Performance Evaluation

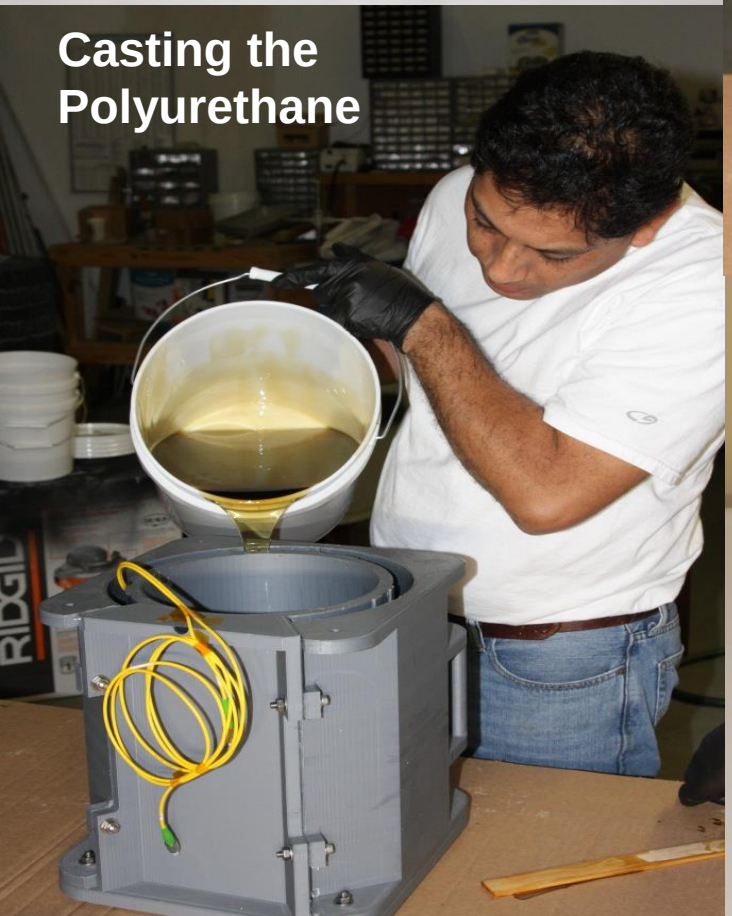
- **These tests were designed to evaluate the strain measuring capabilities of prototype sensor clamps in a configuration comparable to a realistic application in the oil & gas industry (e.g. TLP Tendon Tension Monitoring System).**
- **One 4-inch and two 8-inch diameter adhesive clamp prototypes were built and tested.**
  - The 4-inch adhesive clamp prototype was used for tension/compression tests.
  - One 8-inch adhesive clamp prototype was used for tension/compression tests, and the other was used for 4-point bending tests
- **Test article instrumentation included:**
  - Six fiber optic sensors → 4 axial and 2 transverse
  - Conventional resistance strain gauges
- **The adhesive clamp prototypes were installed onto the steel test pipes in an underwater environment**

## Fiber-Optic Cable Routing



## Polyurethane Allowed to Cure for 72 hours

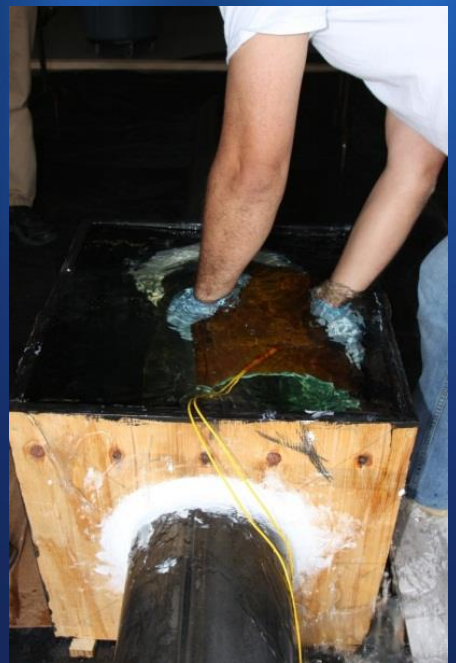
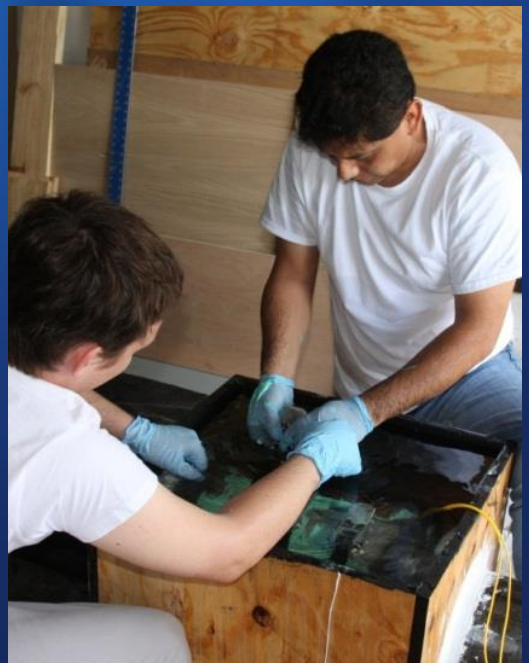
## Casting the Polyurethane



4-in and 8-in Adhesive Clamps




## Adhesive Clamp Installation on 8-inch Test Pipe


# The Adhesive Clamps Were Allowed to Cure Underwater for 48 Hours

# Structural Test Laboratory

**Tension/Compression Testing**
**(±110K lbf cycles)**

**← 4-in Adhesive Clamp**

**8-in Adhesive Clamp →**

**4-Point Bending Test**
**(14K lbf cycles)**

**8-in Adhesive Clamp**

# Tension / Compression Testing

- Conventional resistance strain gauges were installed on all test pipes to provide a control reference to assess the performance of the fiber optic sensor system.

- Tension/Compression cycle tests were conducted at low speed (0.1 in/min) and high speed (0.5 in/min) with up to 10 loading cycles for each test run.

- For each cycle, the test article was subjected to approximately 110,000 lbf of tensile and compressive force which generated approximately ±1250 μin/μin strain.

- At the peak and valley of each cycle, the test machine would hold it's position for a set period of 180 seconds.

# 4-Point Bending Testing

- Conventional resistance strain gauges were installed on all test pipes to provide a control reference to assess the performance of the fiber optic sensor system.
- Bending cycle tests were conducted at low speed (0.1 in/min) and high speed (0.5 in/min) with up to 10 loading cycles for each test run.
- For each cycle, the test article was subjected to approximately 14,500 lbf bending force that generated up to ±1500 μin/μin strain at the middle of the test assembly.
- At the peak of each loading cycle, the test machine would hold it's position for a set period of 30 seconds.
- Rotational test positions ranged from zero to 315 degrees, in 45 degree increments, to vary the strain levels experienced by the different strain gauges.

# Test Summary and Observations

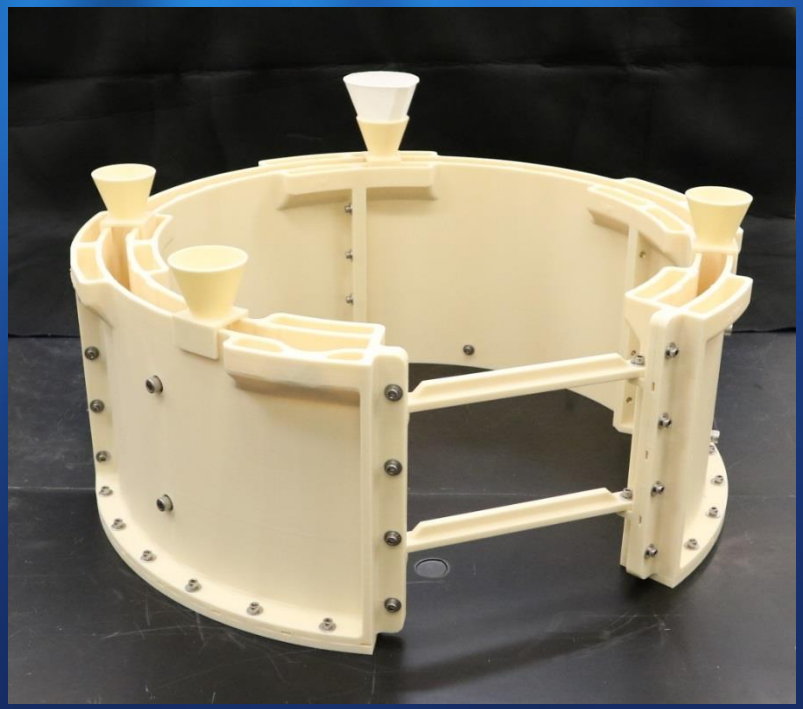
- The underwater installation and curing of the adhesive clamp is a viable method for attaching fiber optic sensors to subsea structures.
- The adhesive clamp demonstrated a very robust sensor coupling interface that can produce high-quality strain measurements (up to 98% correlation in Tension/Compression, and 86% in Bending when compared to the resistance strain gauges).
- Sensor coupling could be degraded by large displacement cycles. As the number of cycles increased, some of the sensor readings decreased correspondingly (worst case: 18% correlation in Tension/Compression, and 17% in Bending when compared to the resistance strain gauges).
- When a sensor lost direct coupling with the pipe surface, it was still capable of providing indirect strain measurement through the coupling between the polyurethane clamp body and the pipe surface.

# Continuous Development & Future Testing

- Improve the fiber optic sensor anchoring and attachment methods, such as using different size and shape metal shims to enhance bonding and surface coupling.
- Improve system reliability by incorporating additional sensors to provide redundancy in case of sensor failure.
- In the event of direct sensor decoupling, investigate the feasibility of converting the indirect strain sensing data, collected through the polyurethane clamp body, into accurate strain measurements. This will provide a secondary monitoring capability.
- Devise a technique for curing the casted polyurethane clamps in a positive pressure environment to reduce offgassing and bubble void formation in the clamp body.

# Continuous Development & Future Testing

- **Improve Design and Streamline the Current Manufacturing Process**
  - Development of a new, full-size, 3-D printed mold which incorporates several of the proposed design improvements
  - Increased number of fiber optic sensor arrays and larger metal support shims
  - Optimized placement of tie-down supports for encapsulated sensors and fibers



*3-D Printed Mold for 24-inch Adhesive Clamp Fabrication*


Task: Cleaning clamp locations T12
DIVER 1
08/02/2013 04:21:54

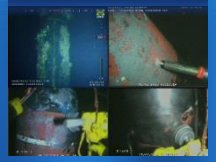

DIVER 2

# Thank You for Your Time and Attention

## Questions?

# Backup Charts

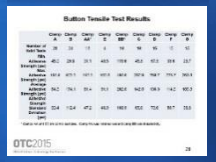
Images



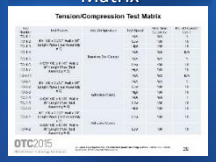
User Interface


Adhesive Tensile Strength Data

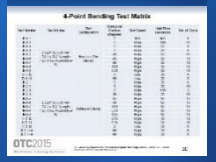

Button Tensile Test Results



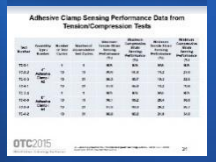

Tension / Compression Test Matrix




4-Point Bending Test Matrix

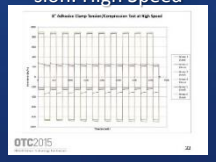



Adhesive Clamp Sensing Performance Data from Tension/Compression Tests

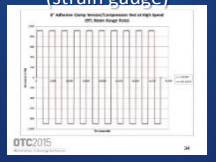



Adhesive Clamp Sensing Performance Data from 4-Point Bending Tests

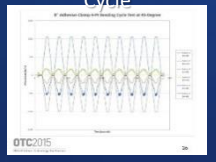

8” Adhesive Clamp Tension/Compression: High Speed



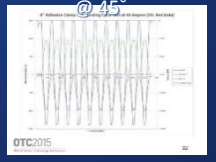
8” Adhesive Clamp Tension/Compression: High Speed (strain gauge)



8” Adhesive Clamp 4-Ft. Bending Cycle



8” Adhesive Clamp 4-Ft. Bending Cycle @ 45°




| SE | | S 199 | SW | | W |
SMIT
DPT
36.1
ALT
0.0
DIVE R027 T12 AS LEFT
OKUME FOXTROT
23:26:40
2/8/2013


Location: OKUME FOXTROT
Dive nr 018S
Task: Cleaning clamp locations T12
DIVER 2
08/02/2013 04:14:19


DIVER 1
08/02/2013 04:21:54


DIVER 1
08/02/2013 04:17:36





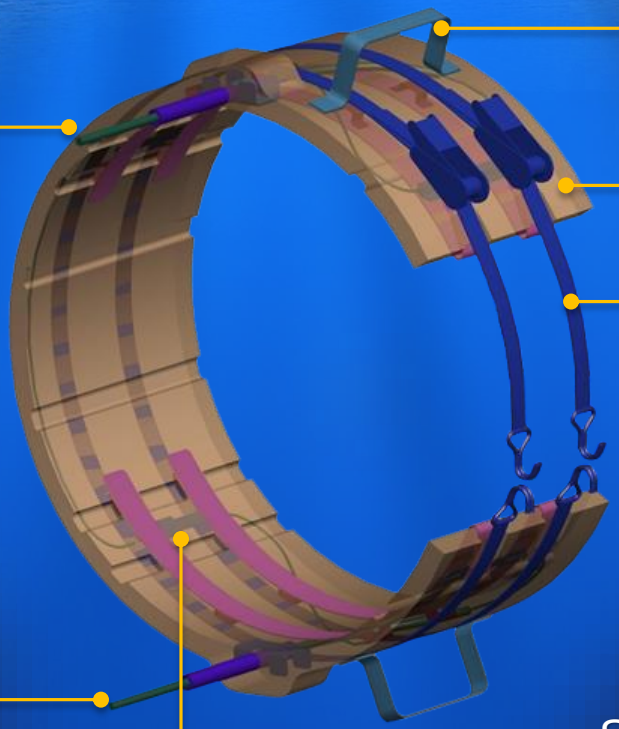
SMIT
DPT
38.1
ALT
0.0
DIVE R027 T12 AS LEFT
OKUME FOXTROT
23:24:08
2/8/2013


DIVER 2
10/02/2013 13:52:40


Task: Clamp installation T12
DIVER 2
10/02/2013 14:21:31


Task: Install Clamps - location T41
DIVER 1
11/02/2013 07:24:12

# Adhesive Clamp Design



Web Handles (2)

Polyurethane Body

Ratchet Straps (2)

Fiber-Optic Cables (2) Routed to Surface Platform

Sensor Elements (4 x 90 deg spacing)

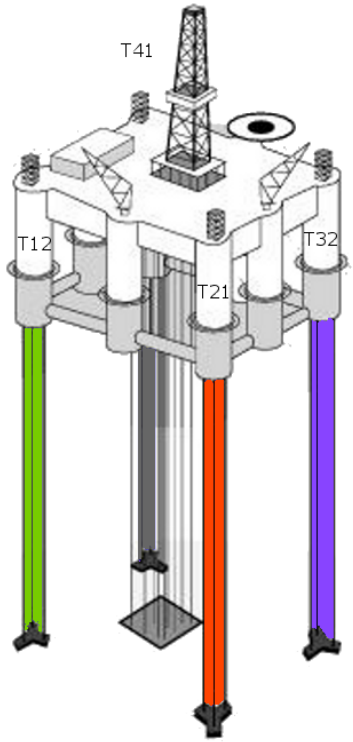
# User Interface

trident.apmonitor.com

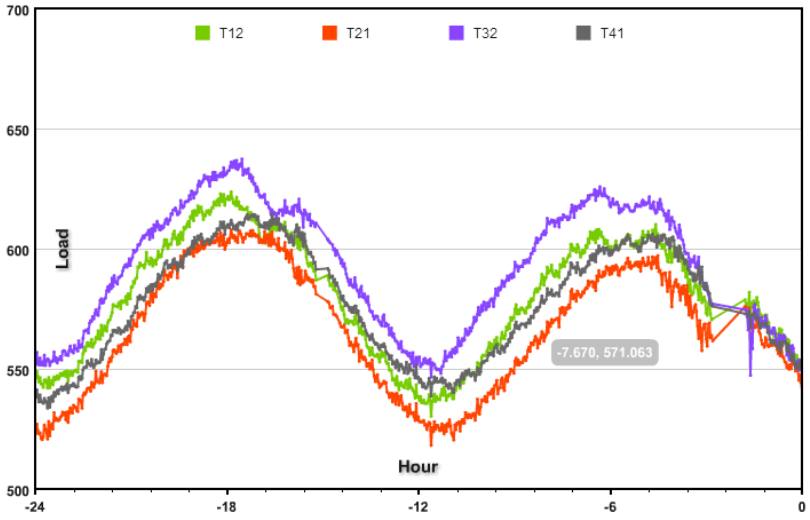
trident.apmonitor.com | foxtrot.apmonitor.com | 192.168.240.41

**Average Load Data (kips) - Live**

| T12 | T21 | T32 | T41 | Past5min |
|---|---|---|---|---|
| 550.805 | 541.589 | 546.999 | 549.552 | Instant |
| 553.476 | 544.789 | 551.265 | 551.974 | AVG |
| 558.919 | 548.729 | 556.441 | 556.073 | MAX |
| 548.439 | 540.370 | 545.023 | 548.457 | MIN |




Past one Hour  Past 24 Hours  Past Month



# Adhesive Tensile Strength Data

| Test Number | Adhesive Tensile Strength - Psi (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Adhesive #1 | | Adhesive #2 | | Adhesive #3 | | Adhseive #4 | |
| | Air | Seawater | Air | Seawater | Air | Seawater | Air | Seawater |
| 1 | 481 (3.32) | N/A | 709 (4.89) | 595 (4.10) | 1054 (7.27) | 792 (5.46) | 846 (5.83) | 379 (2.62) |
| 2 | N/A | N/A | 883 (6.09) | 281 (1.94) | 1000 (6.90) | 435 (3.00) | 807 (5.56) | 475 (3.27) |
| 3 | 434 (2.99) | N/A | 881 (6.07) | 556 (3.83) | 947 (6.53) | 673 (4.64) | 835 (5.76) | 549 (3.78) |
| 4 | 488 (3.36) | N/A | 617 (4.25) | 417 (2.88) | 970 (6.69) | ~~81 (0.56)~~ | 953 (6.57) | 410 (2.83) |
| 5 | 378 (2.61) | N/A | 897 (6.18) | 687 (4.74) | 940 (6.48) | 539 (3.72) | 753 (5.19) | 560 (3.86) |
| Average | **445 (3.07)** | **N/A** | **797 (5.50)** | **507 (3.50)** | **982 (6.77)** | **610 (4.21)** | **839 (5.78)** | **475 (3.27)** |
| S.D. | **51 (0.35)** | **N/A** | **127 (0.88)** | **159 (1.10)** | **46 (0.32)** | **156 (1.07)** | **73 (0.50)** | **81 (0.56)** |

- Red font indicates highest test value recorded.

**Adhesive #2 presented the best combination of high wet bonding strength and overall ease of handling characteristics for this application.**

# Button Tensile Test Results

| | Clamp A | Clamp B | Clamp AA* | Clamp E | Clamp BB* | Clamp C | Clamp D | Clamp F | Clamp G |
|---|---|---|---|---|---|---|---|---|---|
| **Number of Valid Tests** | 20 | 24 | 13 | 4 | 18 | 18 | 15 | 15 | 15 |
| **Min. Adhesive Strength (psi)** | 45.0 | 29.8 | 31.1 | 49.5 | 113.6 | 45.8 | 57.5 | 33.6 | 29.7 |
| **Max. Adhesive Strength (psi)** | 155.8 | 503.3 | 193.5 | 150.8 | 498.6 | 267.9 | 358.7 | 225.7 | 268.8 |
| **Average Adhesive Strength (psi)** | 94.0 | 174.1 | 81.4 | 91.1 | 292.0 | 142.5 | 136.3 | 114.0 | 105.3 |
| **Adhesive Strength Standard Deviation (psi)** | 30.4 | 112.4 | 47.2 | 46.9 | 108.9 | 65.6 | 73.6 | 53.7 | 59.8 |

* Clamps AA and BB are control samples. Clamp AA was installed wet and clamp BB was installed dry.

# Tension/Compression Test Matrix

| Test Number | Test Articles | Test Configuration | Test Speed | Hold Time (seconds) | No. of Repeat / Cycle |
|---|---|---|---|---|---|
| TC-1-1 | 4.5" OD x 0.237" Wall x 36" Length Pipes (Test Assembly # 1) | Baseline (No Clamp) | N/A | N/A | 1 |
| TC-1-2 | | | Low | 180 | 10 |
| TC-1-3 | | | High | 180 | 10 |
| TC-1-4 | | | N/A | N/A | N/A |
| TC-1-5 | 8.625" OD x 0.148" Wall x 36" Length Pipe (Test Assembly # 3) | | N/A | N/A | 1 |
| TC-1-6 | | | Low | 180 | 10 |
| TC-1-7 | | | High | 180 | 10 |
| TC-1-11 | | | N/A | N/A | N/A |
| TC-3-1 | 4.5" OD x 0.237" Wall x 36" Length Pipes (Test Assembly # 2) | Adhesive Clamp | N/A | N/A | 1 |
| TC-3-2 | | | Low | 180 | 10 |
| TC-3-3 | | | High | 180 | 10 |
| TC-3-4 | 8.625" OD x 0.148" Wall x 36" Length Pipe (Test Assembly # 4) | | N/A | N/A | 1 |
| TC-3-5 | | | Low | 180 | 10 |
| TC-3-6 | | | High | 180 | 10 |
| TC-4-1 | 4.5" OD x 0.237" Wall x 36" Length Pipes (Test Assembly # 2) | Adhesive Clamp | Low | 180 | 10 |
| TC-4-2 | 8.625" OD x 0.148" Wall x 36" Length Pipe (Test Assembly # 4) | | Low | 180 | 10 |

# 4-Point Bending Test Matrix

| Test Number | Test Articles | Test Configuration | Rotational Position (Degree) | Test Speed | Hold Time (seconds) | No. of Cycle |
|---|---|---|---|---|---|---|
| B-1-1 | 8.625" OD x 0.148" Wall x 120" Length Pipe (Test Assembly # 5) | Baseline (No Clamp) | 0 | N/A | N/A | 1 |
| B-1-2 | | | 0 | High | 180 | 10 |
| B-1-3 | | | 0 | High | 30 | 1 |
| B-1-4 | | | 0 | High | 30 | 1 |
| B-1-5 | | | 30 | High | 30 | 10 |
| B-1-6 | | | 45 | High | 30 | 10 |
| B-1-7 | | | 90 | High | 30 | 10 |
| B-1-8 | | | 180 | High | 30 | 10 |
| B-1-9 | | | 270 | High | 30 | 10 |
| B-1-10 | | | 0 | Low | 30 | 5 |
| B-1-11 | | | 90 | Low | 30 | 5 |
| B-3-1 | 8.625" OD x 0.148" Wall x 120" Length Pipe (Test Assembly # 6) | Adhesive Clamp | 0 | High | 30 | 1 |
| B-3-2 | | | 0 | High | 30 | 10 |
| B-3-3 | | | 0 | High | 120 | 3 |
| B-3-4 | | | 30 | High | 30 | 10 |
| B-3-5 | | | 45 | High | 30 | 10 |
| B-3-6 | | | 90 | High | 30 | 10 |
| B-3-7 | | | 180 | High | 30 | 10 |
| B-3-8 | | | 270 | High | 30 | 10 |
| B-3-9 | | | 135 | High | 30 | 10 |
| B-3-10 | | | 225 | High | 30 | 10 |
| B-3-11 | | | 315 | High | 30 | 10 |
| B-3-12 | | | 0 | Low | 30 | 5 |
| B-3-14A | | | 90 | High | 30 | 5 |
| B-3-14A | | | 90 | High | 30 | 5 |

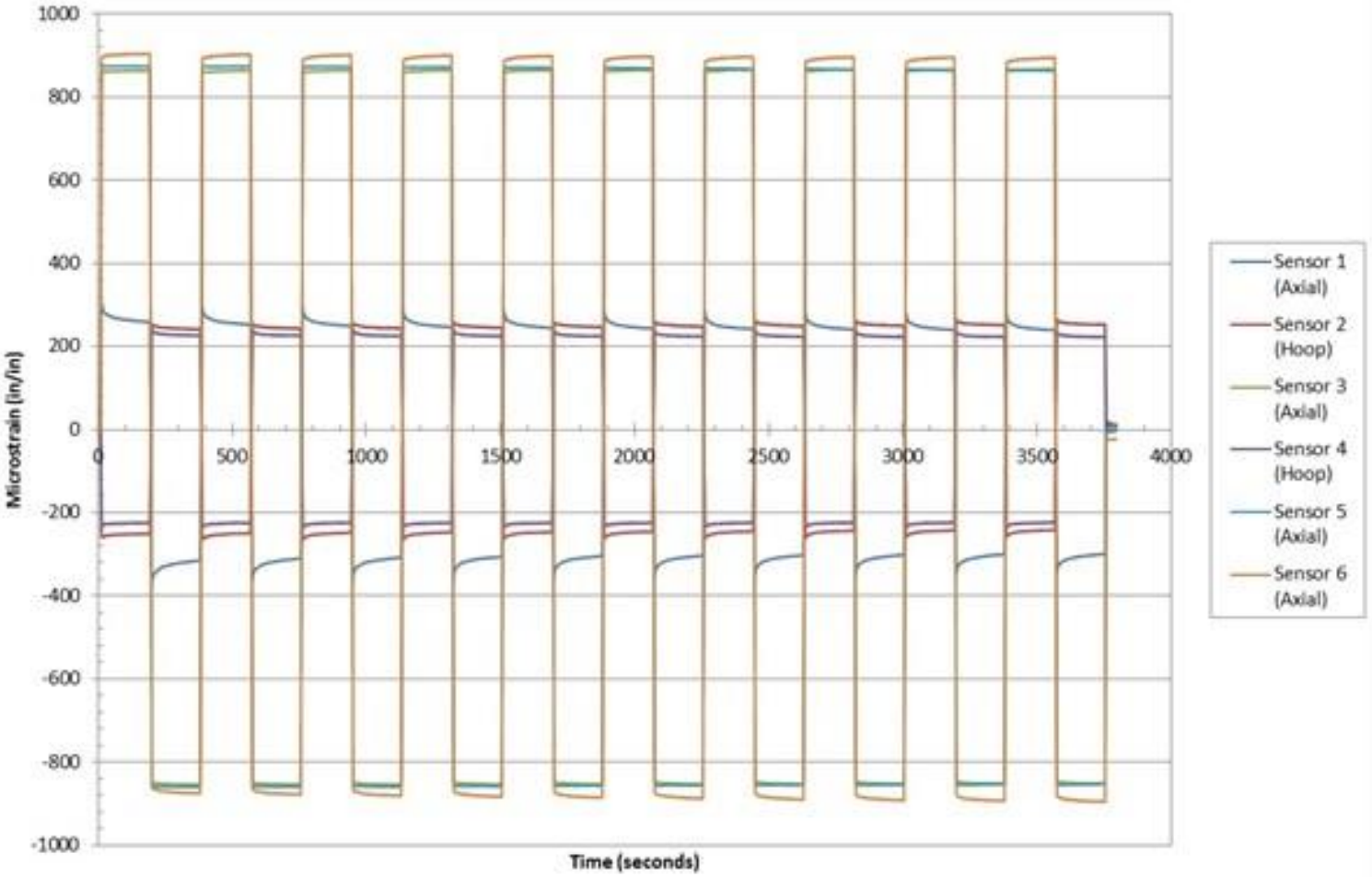
# Adhesive Clamp Sensing Performance Data from Tension/Compression Tests

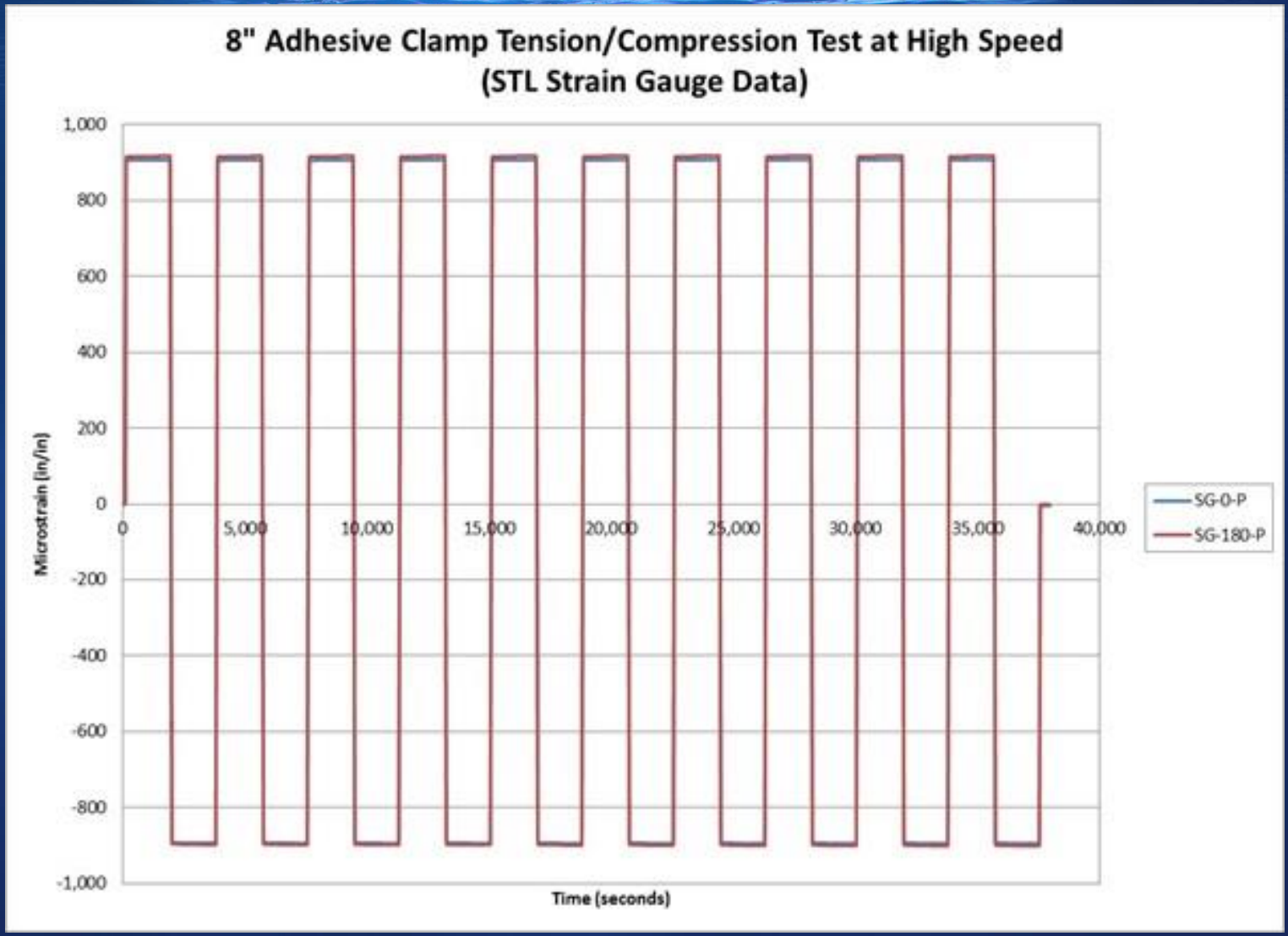
| Test Number | Assembly Type / Number | Number of Test Cycles | Number of Accumulative Test Cycles | Maximum Tensile Strain Sensing Performance (%) | Maximum Compressive Strain Sensing Performance (%) | Minimum Tensile Strain Sensing Performance (%) | Minimum Compressive Strain Sensing Performance (%) |
|---|---|---|---|---|---|---|---|
| TC-3-1 | 4" Adhesive Clamp / #2 | 1 | 1 | N/A | N/A | N/A | N/A |
| TC-3-2 | | 10 | 11 | 89.9 | 91.8 | 19.2 | 27.0 |
| TC-3-3 | | 10 | 21 | 86.5 | 86.7 | 19.3 | 22.6 |
| TC-4-1 | | 10 | 31 | 87.8 | 85.8 | 18.2 | 19.6 |
| TC-3-4 | 8" Adhesive Clamp / #4 | 1 | 1 | N/A | N/A | N/A | N/A |
| TC-3-5 | | 10 | 11 | 96.1 | 95.2 | 26.4 | 35.8 |
| TC-3-6 | | 10 | 21 | 97.3 | 99.3 | 26.2 | 33.7 |
| TC-4-2 | | 10 | 31 | 98.8 | 98.2 | 24.9 | 34.0 |

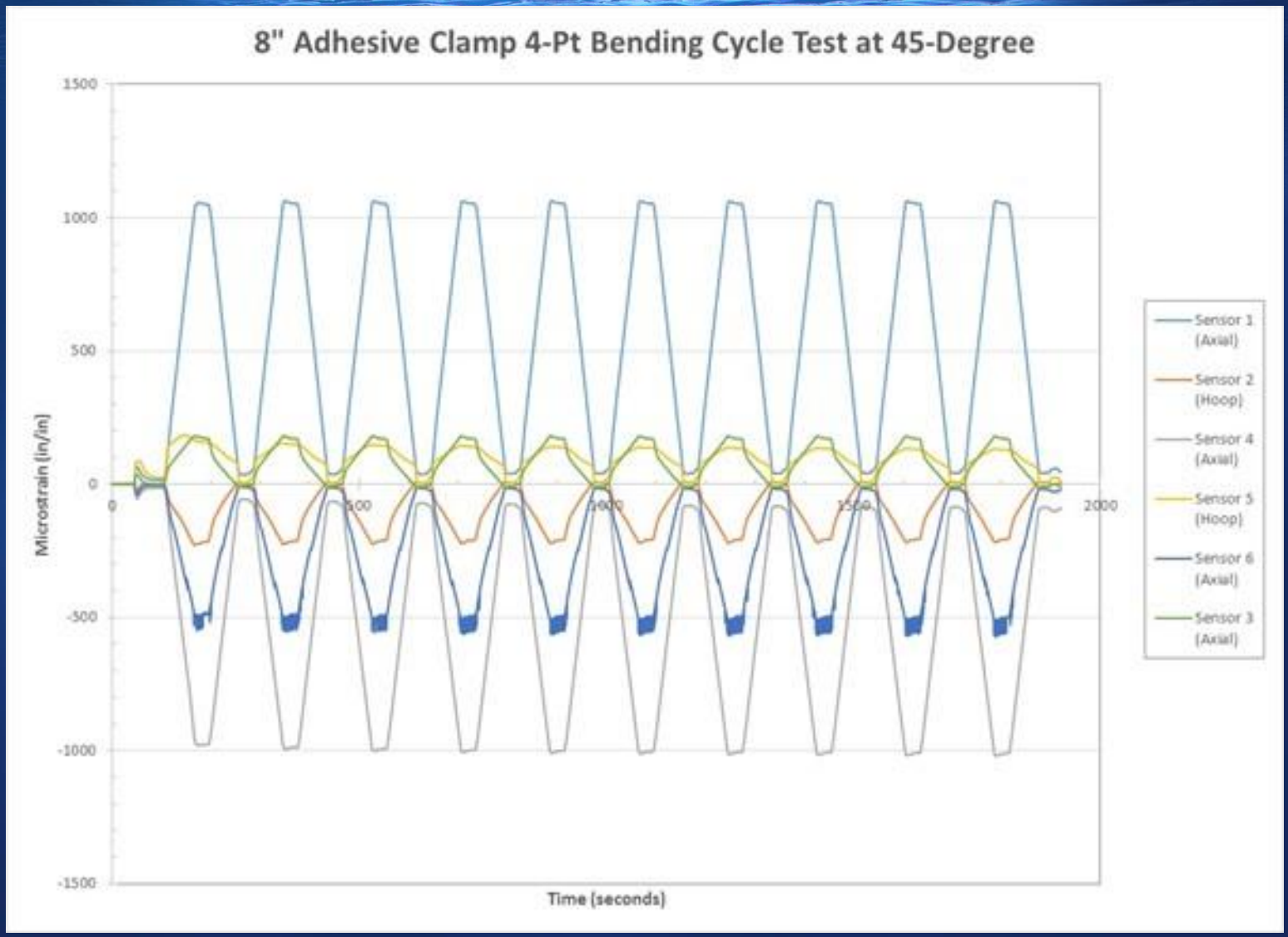
# Adhesive Clamp Sensing Performance Data from 4-Point Bending Tests

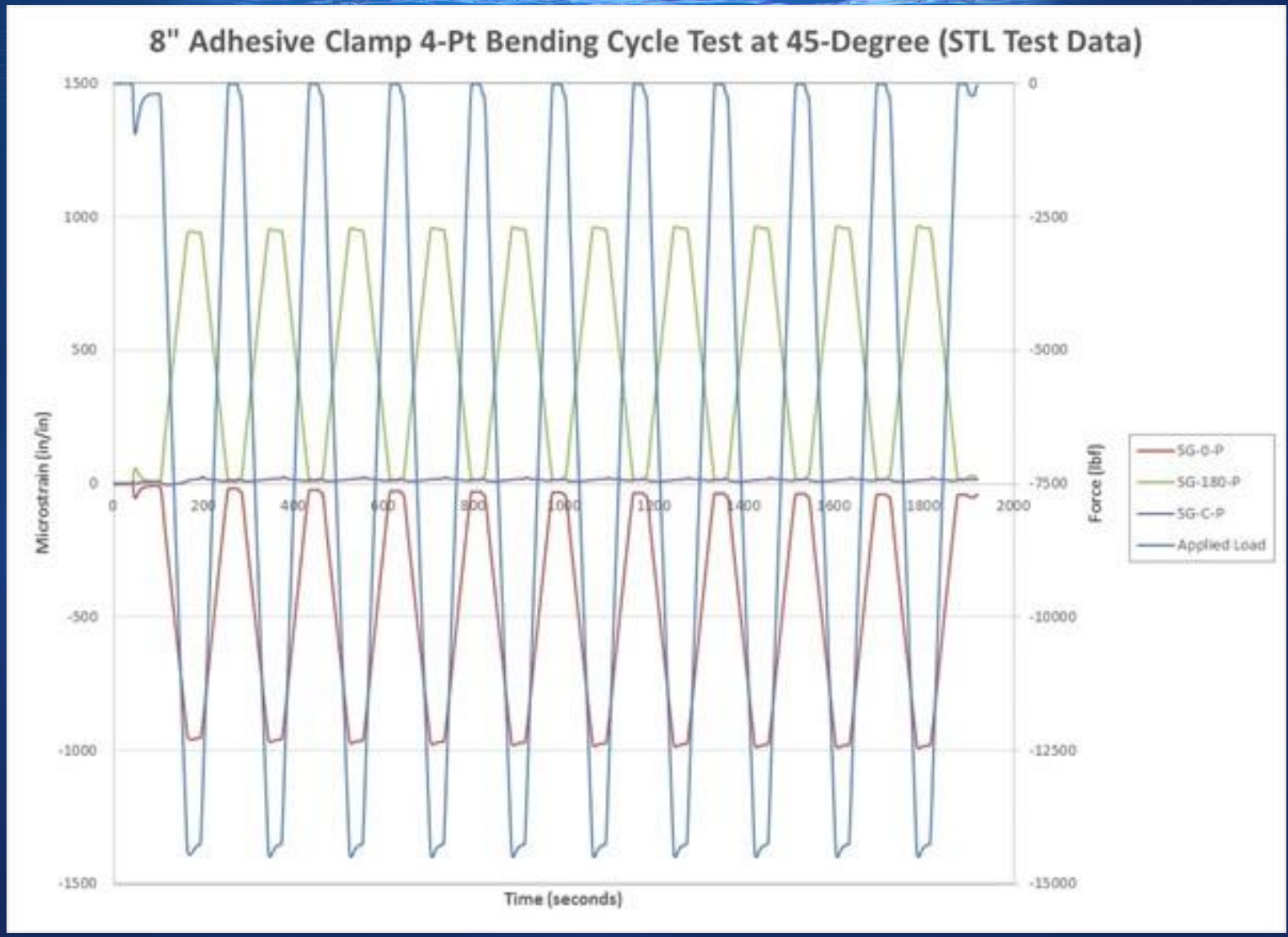
| Test Number | Rotational Position (Degree) | Number of Test Cycles | Number of Accumulative Test Cycles | Maximum Tensile Strain Sensing Performance (%) | Maximum Compressive Strain Sensing Performance (%) |
|---|---|---|---|---|---|
| B-3-1 | 0 | 1 | 1 | N/A | N/A |
| B-3-2 | 0 | 10 | 11 | 22.6 | 69.5 |
| B-3-3 | 0 | 3 | 14 | 21.6 | 63.2 |
| B-3-4 | 30 | 10 | 24 | 19.0 | 57.8 |
| B-3-5 | 45 | 10 | 34 | 17.8 | 56.8 |
| B-3-6 | 90 | 10 | 44 | 85.9 | 82.2 |
| B-3-7 | 180 | 10 | 54 | 25.2 | 19.8 |
| B-3-8 | 270 | 10 | 64 | 83.2 | 17.4 |
| B-3-9 | 135 | 10 | 74 | 20.2 | 17.8 |
| B-3-10 | 225 | 10 | 84 | 21.8 | 19.7 |
| B-3-11 | 315 | 10 | 94 | 17.2 | 21.5 |
| B-3-14A | 90 | 5 | 104 | 25.7 | 56.6 |
| B-3-14B | 90 | 5 | 109 | 24.8 | 42.3 |

## 8" Adhesive Clamp Tension/Compression Test at High Speed




8" Adhesive Clamp Tension/Compression Test at High Speed
(STL Strain Gauge Data)
1,000
800
600
400
200
0
-200
-400
-600
-800
-1,000
Microstrain (in/in)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
Time (seconds)
SG-0-P
SG-180-P


8" Adhesive Clamp 4-Pt Bending Cycle Test at 45-Degree
1500
1000
500
0
-500
-1000
-1500
Microstrain (in/in)
0
500
1000
1500
2000
Time (seconds)
Sensor 1 (Axial)
Sensor 2 (Hoop)
Sensor 4 (Axial)
Sensor 5 (Hoop)
Sensor 6 (Axial)
Sensor 3 (Axial)


8" Adhesive Clamp 4-Pt Bending Cycle Test at 45-Degree (STL Test Data)
Microstrain (in/in)
Force (lbf)
Time (seconds)
1500
1000
500
0
-500
-1000
-1500
0
-2500
-5000
-7500
-10000
-12500
-15000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
SG-0-P
SG-180-P
SG-C-P
Applied Load