Buckling and Failure Tests of a Subscale Composite Cylinder

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**A subscale solid laminate composite cylinder 31.5-in. diameter and 47.8 in. long with a [23/0/-23]4S layup known as NDL-1 was designed to fail in buckling and tested in axial compression to collapse twice. The proposed paper will focus on comparing the behavior of NDL-1 from the first test to failure (TTF-1) and the second test to failure (TTF-2). NDL-1 had a peak load of 466.3 kips during TTF-1 and a peak load of 390.4 kips, 15.5% lower, but with a similar stiffness during TTF-2. Failure initiated at the 200º circumferential location in TTF-1, and at the 30º circumferential location in TTF-2. Though, failure initiated at different locations, a similar radial deformation pattern was present just prior to collapse in TTF-1 and TTF-2. A shallow delamination occurred due to the initial failure event in TTF-1, and the damage has no influence on the response of NDL-1 during TTF-2. In the end, it was determined that NDL-1 failed in buckling during TTF-1 and TTF-2, and the second test to failure of NDL-1 highlighted interesting observations with respect to the effect of damage.**

**Nomenclature**

SBKF = Shell Buckling Knockdown Factor Project

TUDelft = Delft University of Technology

NDL-1 = Considered cylindrical composite test article

LaRC = Langley Research Center

MSFC = Marshall Space Flight Center

IML = Inner mold line

OML = Outer mold line

DIC = Digital image correlation

DCDT = Direct current differential transducers

TTF-1 = First test to failure

TTF-2 = Second test to failure

1. **Introduction**

The NASA Engineering and Safety Center (NESC) established the Shell Buckling Knockdown Factor Project (SBKF) in 2007 with the primary objective of developing new analysis-based buckling design guidelines for selected classes of metallic and composite cylindrical shells.1 Experimental validation testing is being performed at the subcomponent, panel, and cylinder levels as part of this development. A secondary objective is to develop a scaling methodology for composite shells. To achieve this secondary objective, SBKF has an on-going collaboration with the Delft University of Technology. As a part of the scaling effort, a solid laminate composite test article 47.8 inches in length and 31.5 inches in diameter called NASA-Delft Laminate-1 (NDL-1) was designed, manufactured, and tested in axial compression. The layup of NDL-1 was [23/0/-23]4S and was based on a composite scaling methodology and designed to fail in buckling.2

The focus on the proposed paper will not be the scaling methodology, but rather an investigation and comparison of the prebuckling and buckling behavior of NDL-1 during the first test to failure in June 2019 and second test to failure in September 2019. The test article design and manufacturing of NDL-1 will be discussed in Section II. The test set up and results for the first test to failure, the second test to failure, and compares the performance of the test article from the first and second test are discussed in Section IV. Finally, a summary of the findings will be given in Section V.

1. **Test Article Design and Manufacturing**

Test article NDL-1 is a laminated composite cylinder fabricated from the Hexcel IM7/8552-1 (190 gsm) graphite-epoxy material system.3 This is a toughened 350 °F cure material system and is a unidirectional tape with an average thickness of 0.0071 in. The in plane lamina tensile and compressive elastic moduli, and failure stresses for IM7-8552 (190gsm) material system are listed in Table 1.4 Assuming linear elastic behavior, the elastic moduli and failure stresses were used to calculate failure strains, Table 2. Without laminate material properties, the lamina properties provide a suitable reference point for material failure.

Table 1. IM7-8552 in plane lamina elastic moduli and failure stresses.4

|  |  |  |  |
| --- | --- | --- | --- |
| **IM7-8552 Material Properties** | | | |
| Longitudinal Tension | E1t | 23.51 | Msi |
| Transverse Tension | E2t | 1.3 | Msi |
| Longitudinal Compression | E1c | 20.44 | Msi |
| Transverse Compression | E2c | 1.41 | Msi |
| Longitudinal Tension | F1tu | 371.08 | ksi |
| Transverse Tension | F2tu | 9.29 | ksi |
| Longitudinal Compression | F1cu | 251.13 | ksi |
| Transverse Compression | F2cu | 41.44 | ksi |

Table 2. Calculated IM7-8552 lamina failure strains.

|  |  |  |  |
| --- | --- | --- | --- |
| **IM7-8552 Calculated Failure Strains** | | | |
| Longitudinal Tension | ε1t | 15784 | με |
| Transverse Tension | ε2t | 7146 | με |
| Longitudinal Compression | ε1c | 12286 | με |
| Transverse Compression | ε2c | 29390 | με |

This test article was fabricated using an advanced fiber placement robot at the NASA Marshall Space Flight Center Composites Technology Lab and designed to fail in buckling. The unidirectional plies were laid on the outer surface of an aluminum cylindrical mandrel in the desired fiber orientation, with the 0° direction being parallel to the longitudinal axis and the 90° direction being oriented circumferentially. The inner mold line diameter was nominally 31.50 in, and the test article had a final trimmed length of 47.8-in. The acreage laminate was [23/0/-23]4S (24 plies, nominally 0.1704-in. total laminate thickness). Additional padups were included at the ends of the test article to assist with load introduction. Design details are included in Figure 1 and Table 3.

The ends of the composite cylinder were encased with an epoxy grout material (Micor Microx Slow Standard) to prevent end brooming and attempt to simulate clamped boundary conditions. This grout is 1.0-in. thick on each end and extends approximately 0.90 in. away from the IML and OML surfaces of the composite cylinder. The IML and OML surfaces of the potting are encased in aluminum rings 0.25-in. thick to contain the grout material. The ends of the test article are machined flat and parallel (with the shell exposed on either end) to ensure uniform compressive load introduction.



Figure 1. NDL-1 geometry and design details.

Table 3. NDL-1 acreage and padup layup details.

|  |  |
| --- | --- |
| **Region** | **Layup** |
| Acreage | [(23/0/-23)]S4 |
| Pad up 1 | [(23/0/-23)S3/(23/0/-23/)S] |
| Pad up 2 | [(23/0/-23)S3/-/(23/0/-23/)S] |
| Pad up 3 | [(23/0/-23)S2/(23/0/-23/)S/-45/(23/0/-23/)S] |

1. **Testing**

## First Test to Failure

The objective of the first test to failure (TTF-1) was to load NDL-1 in uniform axial compression at various load levels to interrogate the prebuckling, buckling, and postbuckling response. The test was conducted in the Dr. James H. Starnes, Jr. Structures and Materials Research Laboratory at the NASA Langley Research Center, Hampton, VA. Loading of the test article was performed in the Satec Systems/Instron 600,000-lb load frame. A number of measurement systems were used to monitor the test article such as, direct current displacement transducers (DCDTs), strain gages, low-speed Digital Image Correlation (DIC), high-speed video/DIC, and standard video.

On both the inner and outer surfaces, 12 axially oriented strain gages were spaced at regular intervals of 0, 90, 180, and 270 degrees around the circumference with axial positions of -22.0 in., 0 in. (midlength), and 22.0 in. Eight digital image correlation (DIC) systems were used to observe the experiment: four low-speed and four high-speed systems, with each system being comprised of two cameras. NDL-1 was painted with a black and white speckle pattern for the DIC systems. Pairs consisting of one low-speed and one high-speed system were positioned facing circumferential positions of the shell at 45, 135, 225, and 315 degrees. Data from the low-speed DIC systems was recorded at one frame per second. Prebuckling radial and axial displacements were derived from this data. High-speed DIC was used to capture the buckling event at 20,000 frames per second. The experimental setup is shown Figure 2.

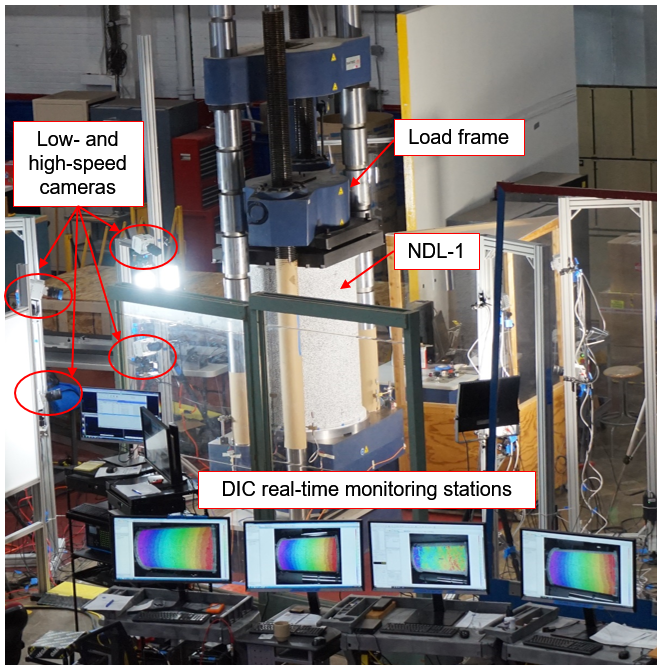
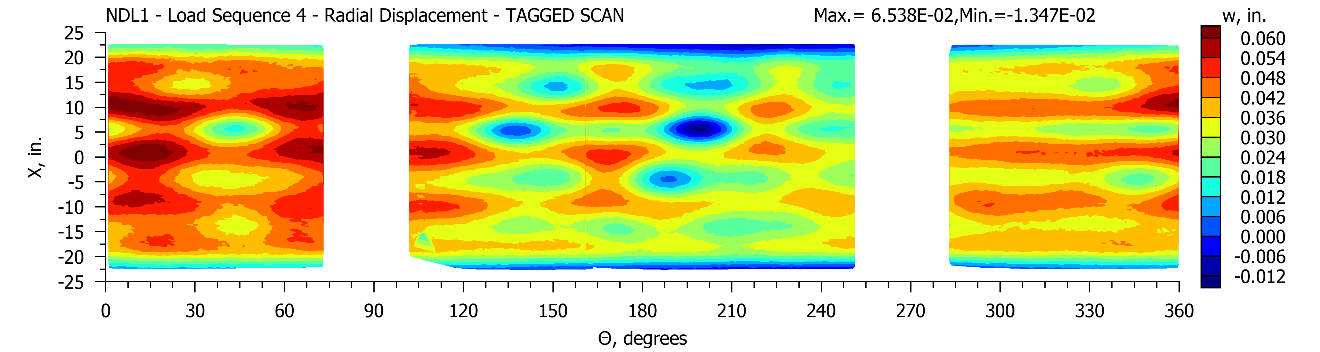
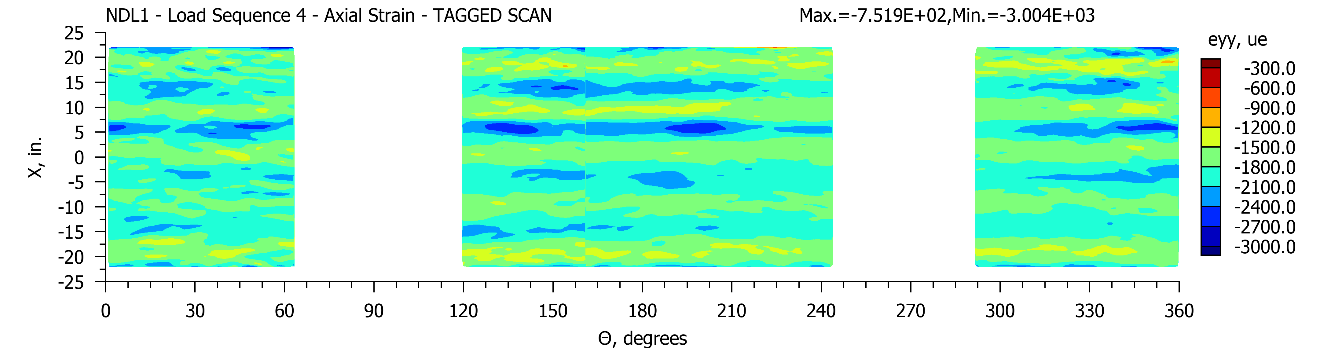


Figure 2. NDL-1 experimental setup.

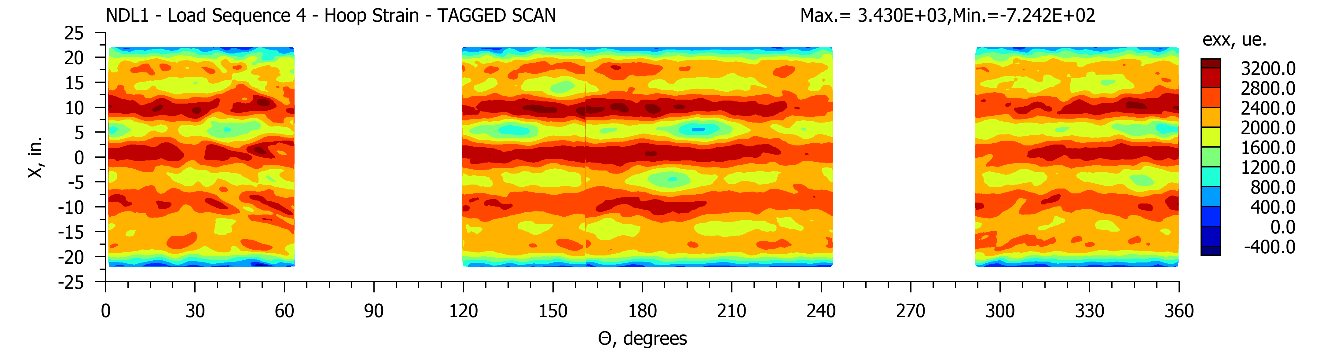
Prior to TTF-1, three subcritical load sequences were conducted. The fourth load sequence was TTF-1, in which the test article was loaded to buckling failure—to a maximum axial load of 466.3 kips at an axial displacement of 0.085 in. Failure initiated at a dimple approximately 5-in. above the midlength of the test article at the circumferential position of 200-degrees as seen in the radial displacement plot in Figure 3a. Figure 3a represents an unrolled view of the test article where the red colors indicate relative outward displacements and blue color indicate relative inward displacements. The axial and hoop strains measure just prior to buckling, Figure 3b and 3c, were less than the calculated failure strains in Table 2. Based on maximum strain criterion, it is concluded that the test article failed in buckling rather than a strength failure.



a.) Radial displacements.



b.) Axial strain.



c.) Hoop strain.

Figure 3. NDL-1 at TTF-1 incipient failure.

A shallow delamination approximately 6-in. long and 2-in. wide was found after TTF-1 at midlength and a circumferential location of 170-degrees, as indicated by the red outline on NDL-1 in Figure 4. The delamination occurred at an inflection point between the inward dimple where buckling initiated, and an adjacent outward dimple as seen in Figure 3a. The angle of the delamination is +23-degrees which is the angle of the outer most ply. The depth of the delamination was not conclusive, but visual and ultrasonic inspection determined it was close to the OML. A detailed description of the pretest predictions, test setup, and posttest analysis correlation for TTF1 has been published.5

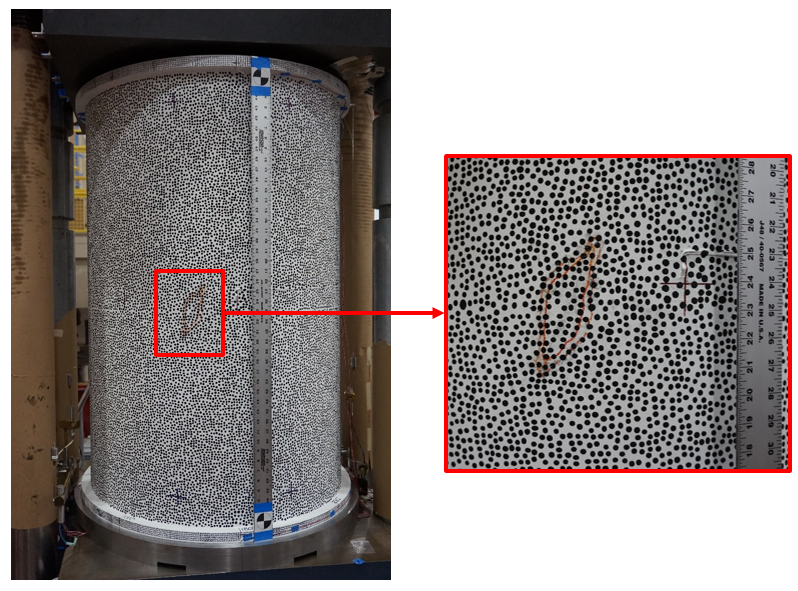
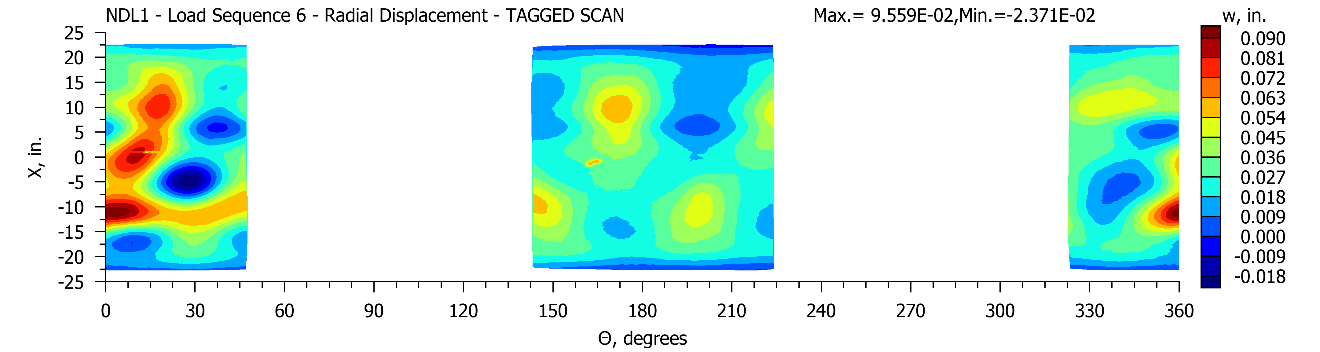


Figure 4. Damage during the TTF-1 buckling event.

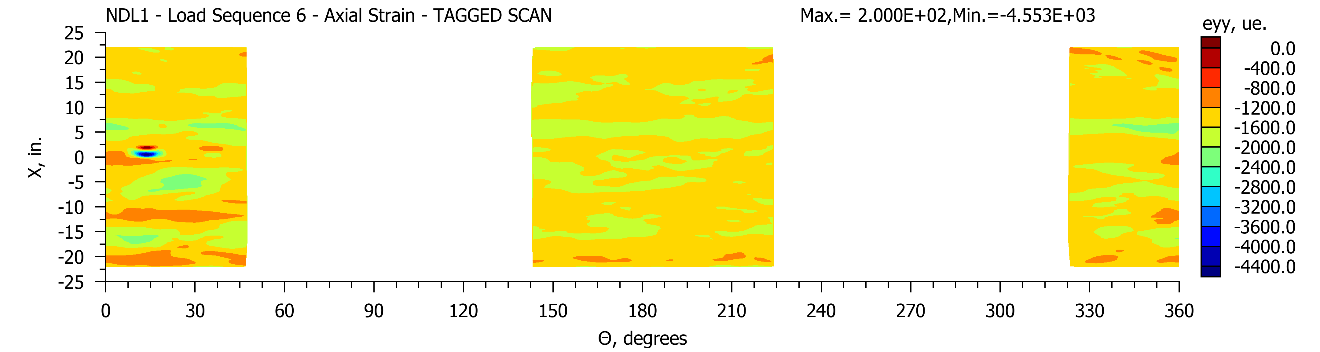
## Second Test to Failure

NDL-1 was loaded for a second time in the same load frame several weeks after TTF-1. While postprocessing the data from TTF-1, it was noted that the axial displacements measured by the DCDTs were different from the extensometer data determined by DIC. Specifically, the DCDT-measured axial displacements were smaller than the DIC-measured axial displacements. Therefore, the main purpose for reloading NDL-1 a second time was to collect more data to determine the source of this discrepancy, but it was decided to load to failure again to assess the repeatability of the response with the damage present. Since this second test to failure, or TTF-2, was originally unplanned, only DCDTs and two low-speed DIC camera systems were utilized. It was determined that the deformation of the loading platen along with the positioning of the DCDTs underestimated the axial displacement of the barrel. For this reason, displacement data from the DIC systems will be presented.

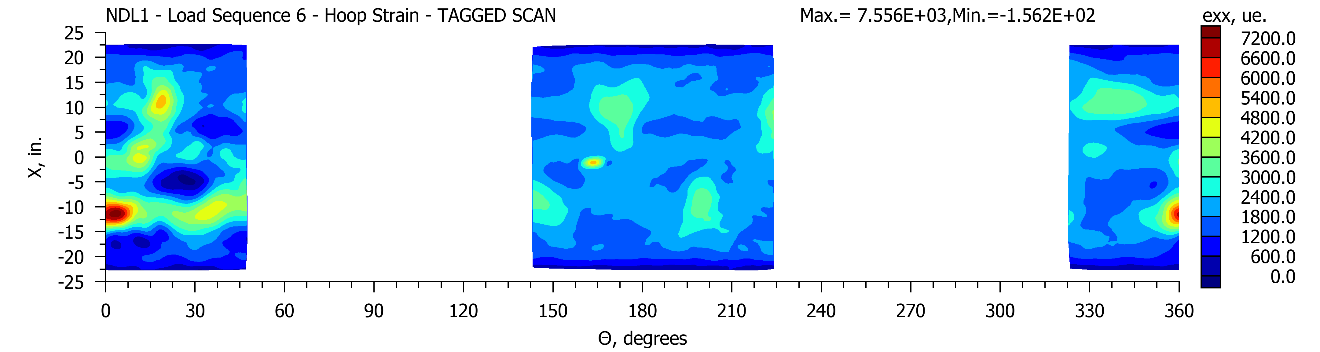
The NDL-1 failure load during TTF-2 was 390.4 kips at an axial displacement of 0.073 in. The radial displacements, axial strains, hoop strains just prior to failure are shown in Figure 5a, 5b, and 5c, respectively. The damage observed after TTF-1 can be seen in the hoop strain plot. The feature in the axial strain plot (Figure 5b) at midlength and 15° is associated with a strain gage wire that came off due to the buckling event in TTF-1. The maximum inward radial deformation occurs at 30°, 5-in. below the midlength. It is suspected that failure initiated at this dimple. The maximum hoop strain just prior to failure in TTF-2 occurs approximately at 0°, 10-in. aft of the midlength. While the maximum hoop strains is 7556 με, which is greater than calculated failure strains based on maximum strain criterion, the location this maximum strain is different than the location with the maximum inward radial deformation.



a.) Radial displacements.



b. Axial strain.



c.) Hoop strain.

Figure 5. NDL-1 at TTF-2 incipient failure.

Visual inspection after the test article failed determined the damage was more substantial than the delamination from TTF-1. A V-shaped through cracks appears in the same orientation as the 23-degree plies, Figure 6. The shape of the crack implies that failure initiated at the bottom of the “V” and the cracks propagated towards the top end of the test article. The bottom of the V-shaped crack is centered on the blue dimple, which is located at a circumferential position of 30-degrees and centered at approximately 17.5-in. below the midlength of the test article, as shown in the DIC contour just after failure (Figure 7). Given the fact that the most inward radial deformation just prior to buckling, the maximum strain just prior to buckling, and the material failure did not all occur in the same location, it was concluded that the test article failed in buckling.

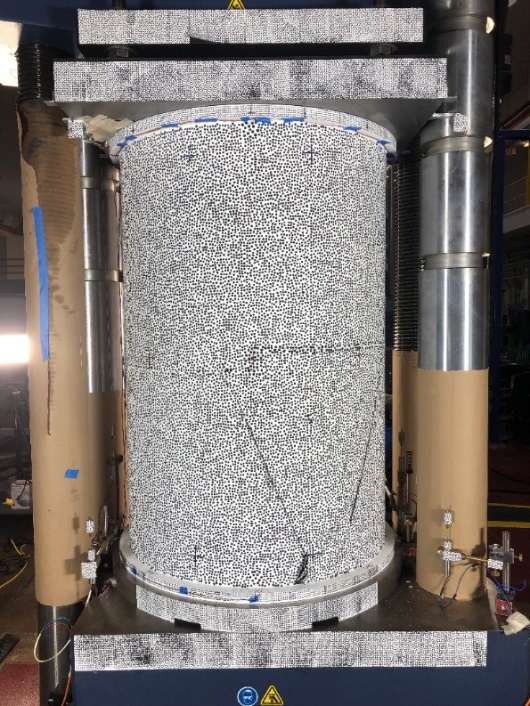


Figure 6. Damage during the TTF-2 buckling event.

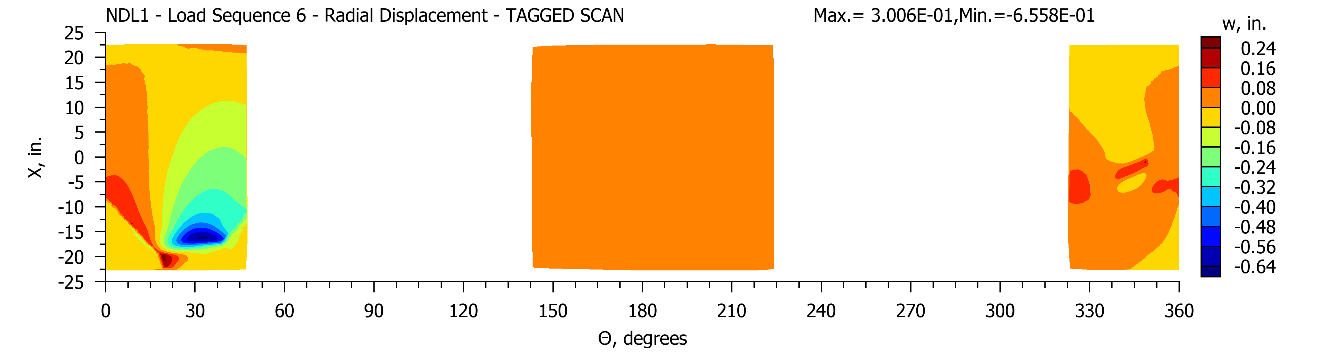


Figure 7. Radial displacements after the buckling event from TTF-2.

## Comparison

In general, the test article maintained a lot of its structural integrity despite the damage that occurred during the first buckling event (TTF-1). The stiffness was nearly unchanged between the undamaged and damaged test article; however, there is a slight nonlinearity present in the TTF-2 load versus end shortening curve, Figure 8. During TTF-1, the test article failed in a global buckling event at a load of 466.3 kips at 200-degrees approximately 5 in. above midlength. During TTF-2, the test article carried a maximum axial load of 390.4 kips, approximately 15.5% less than TTF-1, and failure occurred at approximately the 30-degree circumferential location, 5 in. below the midlength.

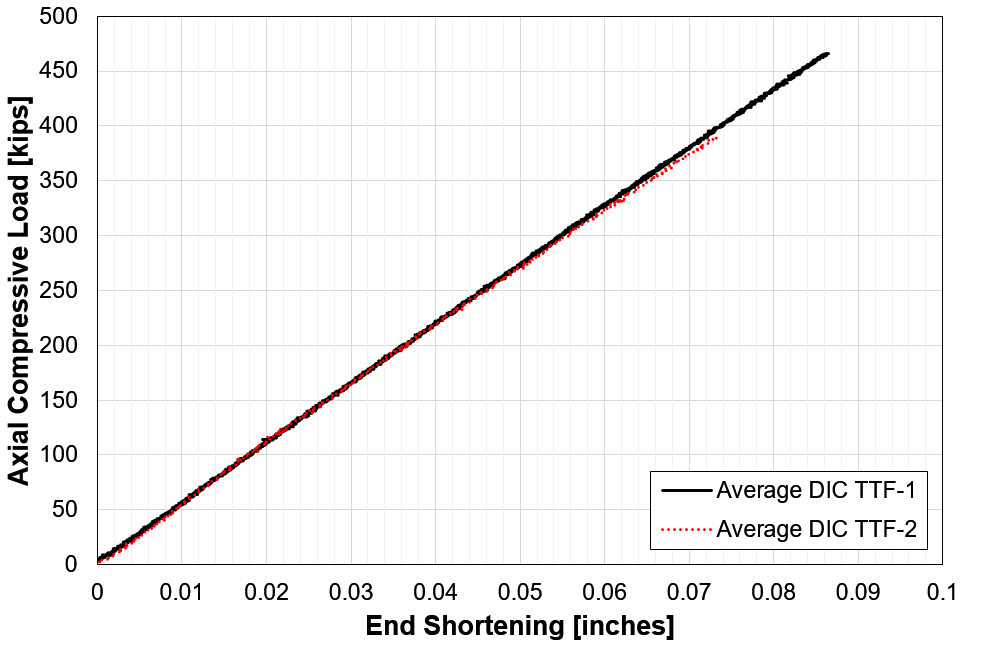
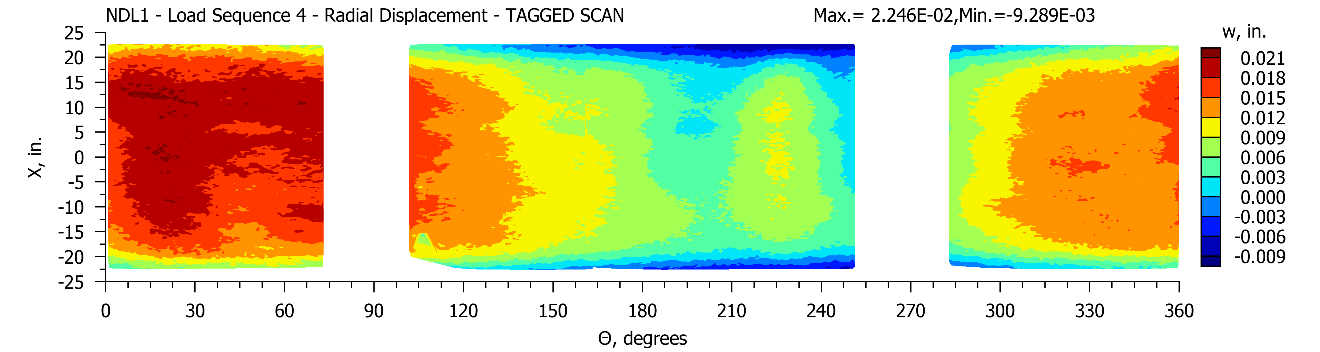


Figure 8. Axial compressive load versus end shortening for TTF-1 and TTF-2.

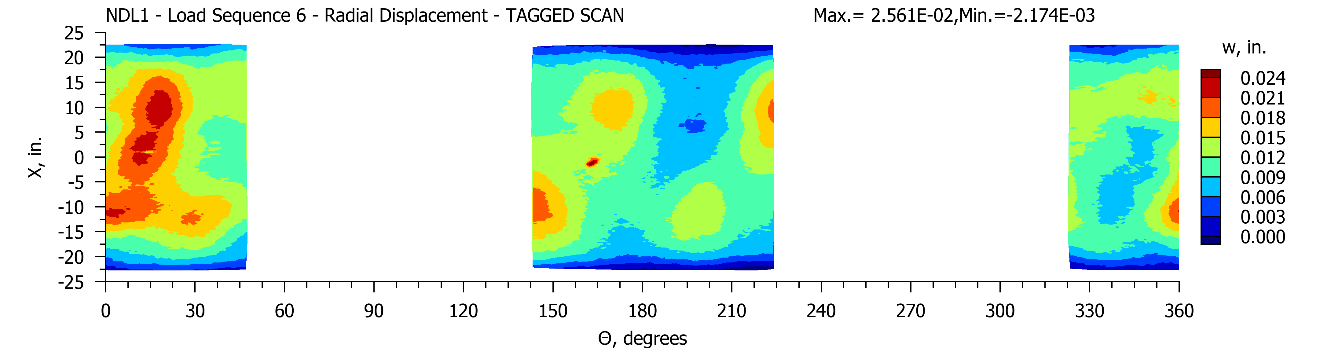
An interesting observation is the damage which occurred during TTF-1 did not appear to influence the behavior of NDL-1 during TTF-2. It should be noted that the crosshead of the load frame was balanced for TTF-1, but not for TTF-2, which may have contributed to the fact that the test article failed in a different location. Also, during TTF-1 shims were placed between the crosshead and the test article to ensure even load introduction. Even load introduction into the test article was not verified for TTF-2.

Comparison of the low-speed DIC data leading up to failure for TTF-1 and TTF-2, shows that the prebuckling shapes are relatively consistent. A major difference is that the dimples that began to form just prior to buckling in TTF-1 appeared at much lower load levels in TTF-2. The radial displacements at 150 kips during TTF-1 and TTF-2 are shown in Figure 9a and Figure 9b, respectively. In Figure 9a, there are no indications of the prebuckling shape at 150 kips during TTF-1. On the other hand, in Figure 9b there are three outward dimples vertically aligned at the 15-degree circumferential position, coinciding with a similar feature observed just prior to buckling in TTF-1, Figure 3a.

In addition, the growth of the radial displacement is greater in TTF-2 than in TTF-1. In Figure 9a and Figure 9b, though the radial deformation shape is different, the maximum and minimum magnitudes of the radial displacements are similar. Looking at the radial displacements prior to buckling at 466.3 kip during TTF-1, the most inward dimple measured -0.013 in. (Figure 3a), whereas the most inward dimple measures -0.024 in. just prior to a buckling load of 390.4 kips during TTF-2 (Figure 5a). It is thought that the increased growth of the radial deformations in TTF-2 may have contributed to the nonlinearity present in the load versus displacement curve and for the decrease in load carrying capability.



a.) TTF-1.



b.) TTF-2

Figure 9. NDL-1 radial deformations at 150 kips.

# Conclusion

Composite test article NDL-1 was tested to failure twice. The first test was to interrogate the prebuckling, buckling, and postbuckling behavior of the pristine test article. The second test to failure (TTF-2) was not originally planned, but carried out to investigate a discrepancy between the axial shortening data from the DCDTs and DIC. During the first test to failure (TTF-1), the test article was fully instrumented with strain gages, displacement sensors, four low-speed DIC systems and four high-speed DIC systems. For the unplanned TTF-2, only two low-speed DIC systems, and displacement sensors to monitor the crosshead’s axial displacement were used to collect data.

It was concluded that NDL-1 failed in buckling in both TTF-1 and TTF-2. NDL-1 failed at 466.3 kips during TTF-1, and buckled at a load 15.5% lower in TTF-2, 390.4 kips. Buckling initiated different locations in TTF-1 and TTF-1. In TTF-1 buckling occurred at a circumferential position of 200-degrees and 5-in. above the midlength, and a circumferential position of 30 degrees and 20-inches below the midlength during TTF-2. Comparing the radial displacement plots just prior to failure in TTF-1 and TTF-2, it was observed that the magnitudes were very similar even at different load levels, therefore the rate of growth of the radial displacement was larger in TTF-2. It is believed this behavior potentially contributed to nonlinearity seen in the load versus displacement plot and the reduction in load carrying capability during TTF-2. The buckling event during TTF-1 caused a shallow delamination that did not seem to affect the buckling behavior in TTF-2. While the original objective was to understand the prebuckling, buckling, and postbuckling behavior of the pristine NDL-1 with just one test, the second test to failure highlighted some interesting observations with respect to prebuckling and buckling response, as well as the effects of damage.

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