[11]Johnson, F. T., and Rubbert, P. E., "Advanced Panel-Type Influence Coefficient Methods Applied to Subsonic Flows," AIAA Paper 75-50, Jan. 1975.

[12]Johnson, F. T., Rubbert, P. E., and Ehlers, F. E., "A Higher Order Panel Method for General Analysis and Design Application in Subsonic Flow," *Proceedings of the 5th International Conference on Numerical Methods in Fluids Dynamics* (Enschede, The Netherlands), Springer–Verlag, Berlin, 1975, pp. 247–253.

[13]Ehlers, F. E., Johnson, F. T., and Rubbert, P. E., "Advanced Panel-Type Influence Coefficient Methods Applied to Subsonic Flows," *LaRC Aerodynamic Analysis Requiring Advanced Computers*, NASA Langley Research Center, Hampton, VA, 1975, pp. 939–984.

[14]Bristow, D. R., and Grose, G. G., "Modification of the Douglas Neumann Program to Improve Efficiency of Predicting Component Interference and High Lift Characteristics," NASA CR-3020, June 1978.

[15]Nathman, J. K., "Precision Requirement for Potential-Based Panel Methods," *AIAA Journal*, Vol. 32, No. 5, 1994, pp. 1089, 1090.

[16]Ardonceau, P. L., "Computation of the Potential Flow over Airfoils with Cusped or Thin Trailing Edges," *AIAA Journal*, Vol. 24, No. 8, 1986, pp. 1375–1377.

[17]Yon, S., Katz, J., and Plotkin, A., "Effect of Airfoil (Trailing-Edge) Thickness on the Numerical Solution of Panel Method Based on the Dirichlet Boundary Condition," *AIAA Journal*, Vol. 30, No. 3, 1992, pp. 697–702.

[18]Girardi, R. M., and Bizarro, A. F., "Modification of the Hess and Smith Method for Calculating Cascades and Airfoils with Cusped Trailing Edge," Instituto Tecnologico de Aeronáutica, Sào José dos Campos, Brazil, April 1994.

[19]Lakshminarayana, B., *Fluid Dynamics and Heat Transfer of Turbomachinery*, Wiley-Interscience, New York, 1995.

[20]Hunt, B., "The Panel Method for Subsonic Aerodynamics Flows," von Kármán Inst. for Fluid Dynamics, Lecture Series 1978-4, 1978.

[21]Hess, J. L., "Review of Integral-Equation Techniques for Solving Potential-Flow Problems with Emphasis on the Surface Method," *Computer Methods in Applied Mechanics and Engineering*, Vol. 5, July 1975, pp. 145–196.

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# Experimental Buckling of Thin Composite Cylinders in Compression

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## Introduction

THE thin, circular, cylindrical shell has been used extensively as a structural configuration, mainly in the aerospace industry. The specific concern of its behavior when subjected to external loads and in particular the buckling phenomena has, therefore, received significant attention.[1] Recently, the increasing need for lightweight efficient structures has driven research in the field of structural optimization and simultaneously to the use of fiber-reinforced composites, which are attractive because of their high stiffness-to-weight ratios. Many studies have been conducted on the buckling of composites; however, these studies have not yet led to systematic and widely applicable design criteria. This is primarily due to the multitude of parameters that influence the instability but also to the lack of available representative tests results. The buckling of composite shells, in addition to the initial geometric imperfections, also typical for isotropic shells, depends on a large number of input parameters, such as lamina properties and orientations, and can be influenced by several types of imperfections, consequences of the manufacturing process, such as thickness variations[2] and local delaminations.[3] To develop appropriate methods for predicting the buckling loads of thin shells, it is important to increase the available data on the shape and amplitudes of initial imperfections,[4] as well as the results of experimental buckling tests on composite shells of different materials and layup orientations.[5,6] In fact, the experimental results have proven to be extremely useful for tuning analytical[7] and numerical[8,9] models.

This Note describes the experimental equipment and the methodologies used for performing buckling tests under position control on composite cylindrical shells subject to axial compression, measuring the development of the geometric imperfections and of the buckling pattern. The results of tests on 16 thin shells in carbon fabric, carbon unidirectional laid down, and carbon roving tape wrapped with different layup orientations are reported and evaluated. Typical results, showing variations of compressive load with axial displacement and postbuckling patterns, are presented to demonstrate the reliability and accuracy of the experimental setup.

## Cylindrical Shells

The cylindrical specimens are characterized by a length and an internal diameter of 700 mm. Two tabs are provided at the top and bottom surfaces for attaching them to the loading rig. The actual length is, therefore, limited to the central part and is equal to 540 mm.

Testing has been conducted on 16 specimens, made of carbon fabric, of carbon unidirectional laid down, and of carbon roving tape wrapped in epoxy matrix (Table 1). They are of different staking sequences and have a total thickness equal to 1.32, 1.20, and 1.50 mm for the carbon fabric, the carbon unidirectional, and the carbon roving tape wrapped specimens, respectively. The lamina properties of the carbon fabric cylinders are $E_{11} = E_{22} = 52{,}000$ N/mm$^2$,

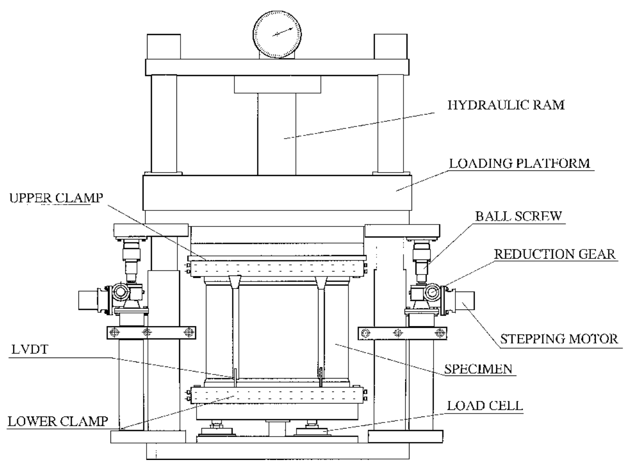


**Fig. 1a Loading rig to perform axial compression buckling tests under position control.**

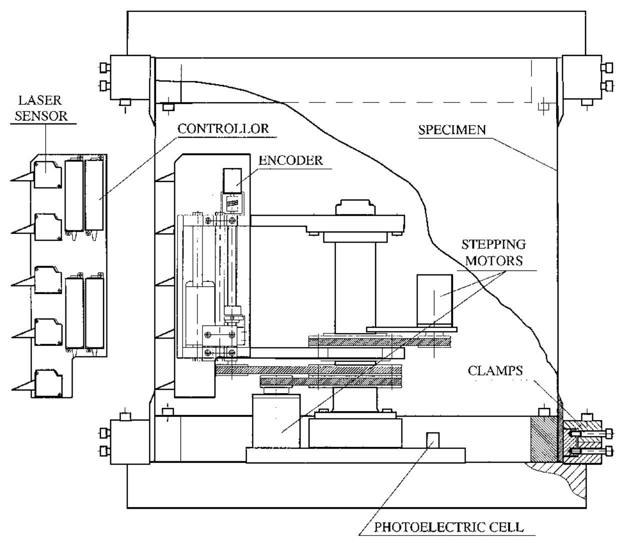


**Fig. 1b Equipment to record the specimen's internal surface during the tests.**

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**Table 1 Results of buckling tests**

| Material layup | Experimental buckling load/stress, N/N/mm$^2$ | Analytical buckling load/stress, N/N/mm$^2$ | Experimental load/ analytical load | Postbuckling pattern |
|---|---|---|---|---|
| Carbon fabric [0/45/−45/0] | 172,877/59.55 | 240,000/82.67 | 0.72 | 9 × 2 |
| Carbon fabric [0/45/−45/0] | 151,618/52.23 | | 0.63 | 10 × 2 |
| Carbon fabric [0/45/−45/0] | 155,676/53.63 | | 0.65 | 10 × 2 |
| Carbon fabric [0/45/−45/0] | 164,702/56.74 | | 0.69 | 10 × 2 |
| Carbon fabric $[45/-45]_s$ | 120,236/41.42 | 120,580/54.83 | 0.99 | 8 × 1 |
| Carbon fabric $[45/-45]_s$ | 116,454/40.12 | | 0.97 | 7 × 1 |
| Carbon fabric $[45/-45]_s$ | 102,447/35.29 | | 0.85 | 8 × 1 |
| Carbon fabric $[45/-45]_s$ | 112,632/38.80 | | 0.93 | 8 × 1 |
| Carbon unidir. $[45/-45]_{2s}$ | 96,269/36.48 | 173,676/65.81 | 0.55 | 8 × 1 |
| Carbon unidir. $[45/-45]_{2s}$ | 92,859/35.19 | | 0.53 | 8 × 1 |
| Carbon unidir. $[90/0]_{2s}$ | 92,049/34.88 | 170,022/64.43 | 0.54 | 10 × 2 |
| Carbon unidir. $[90/0]_{2s}$ | 99,541/37.72 | | 0.59 | 10 × 2 |
| Carbon wrapped [90/±30/90] | 196,230/78.27 | 289,025/115.28 | 0.68 | 10 × 2 |
| Carbon wrapped [90/±30/90] | 185,936/74.17 | | 0.64 | 10 × 2 |
| Carbon wrapped [±45] | 159,055/63.44 | 159,840/63.76 | 0.99 | 8 × 2 |
| Carbon wrapped [±45] | 155,353/61.97 | | 0.98 | 8 × 2 |

$G_{12} = 2350$ N/mm$^2$, and $\nu_{12} = 0.302$; whereas the lamina properties of the carbon unidirectional and carbon-wrapped cylinders are $E_{11} = 113{,}000$ N/mm$^2$, $E_{22} = 9000$ N/mm$^2$, $G_{12} = 3820$ N/mm$^2$, and $\nu_{12} = 0.73$.

## Equipment

The geometric imperfections on the specimen's internal and external surfaces and the thickness variations are measured before the tests, using two linear variable differential transformer (LVDT) transducers.[10,11]

The axial compression buckling tests are performed by a loading rig under position control (Fig. 1a). During the tests, a hydraulic ram pushes the loading platform against four ball screw supports, placed at the four corners of the platform. At the beginning, the load from the ram is completely released on the four screws, which distribute the real applied load on the specimen during the test. The screw motion is computer controlled by means of four stepping motors through four reduction gears, producing exactly the desired displacement of the loading platform. The load level, which is transferred smoothly to the cylinder, thus depends only on the platform displacement and on the cylinder elastic response and does not substantially depend on the load magnitude due to the hydraulic ram acting on the platform. During the tests, the compression load and the axial displacement of the specimen are measured by means of three load cells and three LVDT transducers, equally spaced to ensure accuracy and uniformity of the loading process. To avoid the occurrence of internal stress during the clamping of the specimen to the loading rig, a mechanical clamping system is used.[11]

Equipment[11] (Fig. 1b) was designed to measure the development of geometric imperfections and the buckling pattern on the specimen internal surface during the tests. It employs five laser displacement sensors, having a resolution of 15 $\mu$m, placed at a distance of 40 mm from the specimen. Therefore, any contact with the specimen surface is avoided, and the buckling behavior is not influenced.

## Tests Results

Before the tests, the internal and external surfaces of the shells are scanned to measure their initial geometric imperfections and thickness variations. Next the compressive load is applied and the load vs axial displacement data are recorded. The cylinder internal surface is checked immediately before the test and about 15–20 times during the buckling test, to follow the development of geometric imperfections, as well as the buckling pattern. The time required to measure a complete surface is limited to 4 min.

The values of the measured buckling loads are given in Table 1, compared to the analytical buckling loads obtained from a classical linear theory, not including the effect of the initial imperfections.[11] Table 1 also reports the postbuckling pattern in terms of number of waves in the circumferential and axial directions, respectively. Variations in material properties and layup orientations show significant differences in the postbuckling pattern.

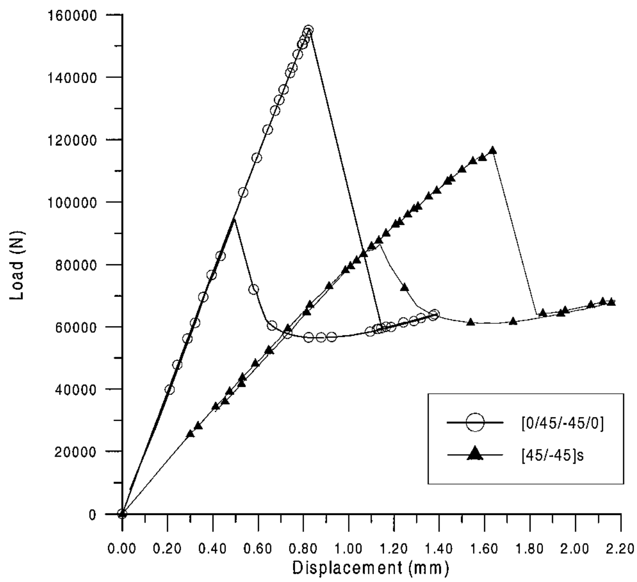



**Fig. 2a Carbon fabric cylinders.**

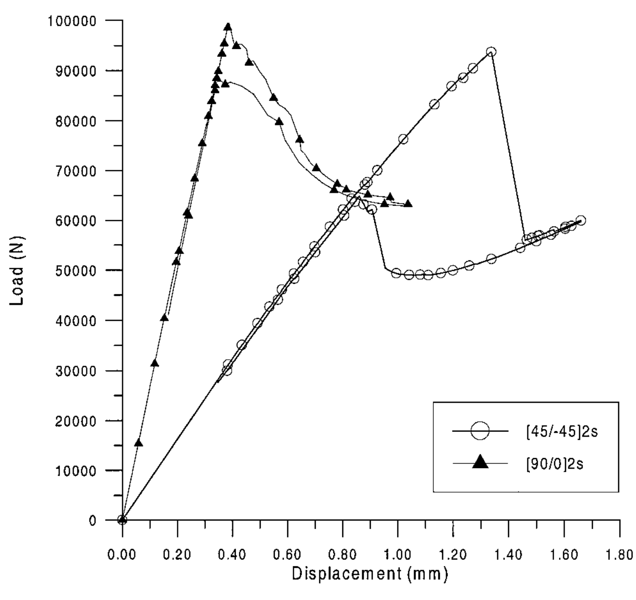
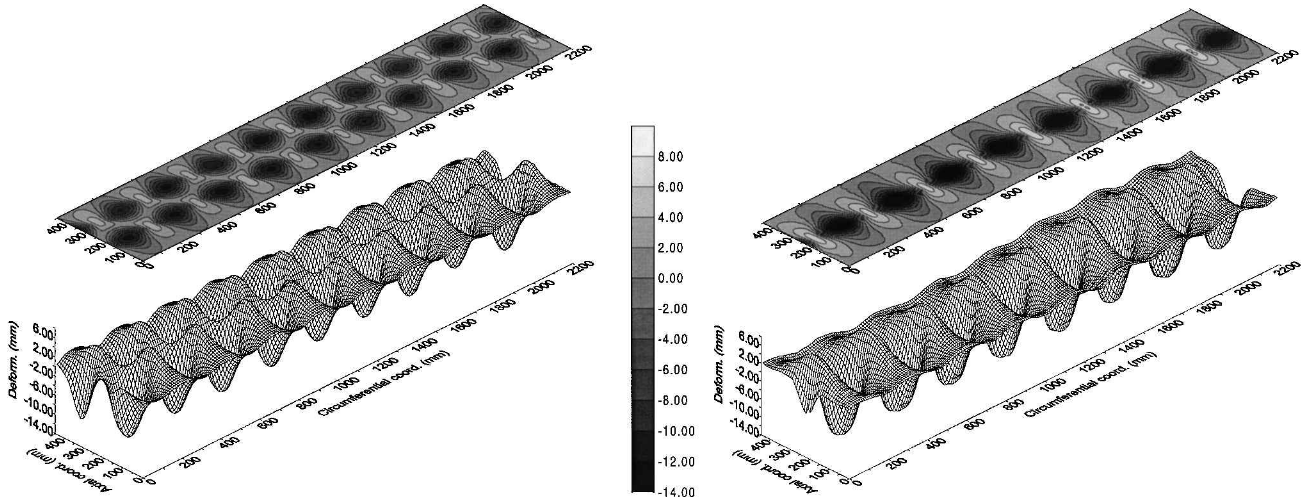



**Fig. 2b Carbon unidirectional cylinders.**




**a) Carbon fabric cylinder [0/45/− 45/0]** **b) Carbon fabric cylinder [45/− 45]s**

**Fig. 3 Typical postbuckling patterns.**

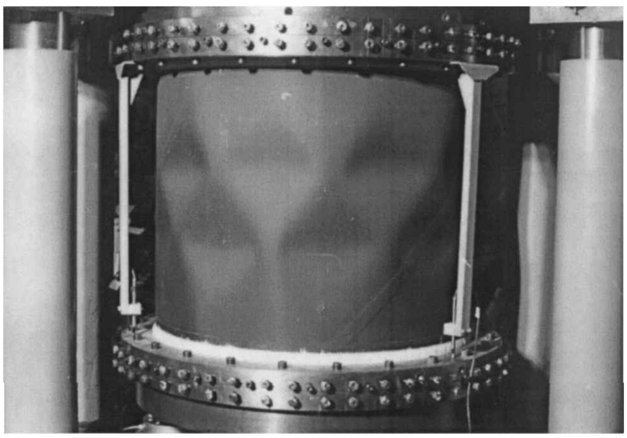


**Fig. 4 Typical postbuckling pattern for carbon fabric cylinder.**

Representative variations of compressive load with axial displacement are presented in Fig. 2, where both loading and unloading sequences are shown. In almost all of the tests performed, buckling occurs suddenly. In only the case of carbon unidirectional $[90/0]_{2s}$ specimens is the load reduction gradual, and the pattern changes in the postbuckling field. During the unloading phase, the results agree with the theoretical curve until the buckling patterns disappear, and the values of both load and displacement become equal to those of the loading sequence.

Figure 3 shows two typical postbuckling patterns recorded during tests on carbon fabric cylinders. The patterns are well defined and regular. Although the patterns do not change during the tests, the amplitude (that is, the displacement normal to the surface) increases in the postbuckling region. A photograph of a typical postbuckling pattern for a carbon fabric cylinder, as it appears during a test, is shown in Fig. 4.

## Conclusions

Experimental equipment is described that is used for performing buckling tests, under axial compression, on composite cylindrical shells, and the results are reported of tests on 16 thin shells in carbon fabric, carbon unidirectional laid down, and carbon roving tape wrapped with different layup orientations. Typical results, showing variations of compressive load with axial displacement and postbuckling patterns, are presented. A comparison between experimental and analytical linear buckling loads is performed, showing that, in most cases, the ratio between the buckling loads (measured and analytical) is significantly high.

The experimental equipment is reliable and accurate, allowing the establishment of a significantly large database of experimental results, which can be used to correlate numerical models. This represents a fundamental step toward the correlation of measured imperfections with respect to the corresponding buckling loads.

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## References

[1]Simitses, G. J., "Buckling and Postbuckling of Imperfect Cylindrical Shells: A Review," *Applied Mechanics Reviews*, Vol. 39, No. 10, 1986, pp. 1517–1524.

[2]Koiter, W. T., Elishakoff, I., Li, Y. W., and Starnes, J. H., Jr., "Buckling of an Axially Compressed Cylindrical Shell of Variable Thickness," *International Journal of Solids and Structures*, Vol. 31, No. 6, 1994, pp. 797–805.

[3]Gu, H., and Chattopadhyay, A., "Delamination Buckling and Postbuckling of Composite Cylindrical Shells," *AIAA Journal*, Vol. 34, No. 6, 1996, pp. 1279–1286.

[4]Abramovich, H., Yaffe, R., and Singer, J., "Evaluation of Stiffened Shell Characteristics from Imperfection Measurements," *Journal of Strain Analysis*, Vol. 22, No. 1, 1987, pp. 17–23.

[5]Meyer-Piening, H.-R., Geier, B., and Rohwer, K., "Remarks on the Effective-Width Concept for Orthotropic Thin Shells," *Buckling of Shell Structures on Land, in the Sea and in the Air*, edited by J. F. Jullien, Lyon Symposium, Elsevier Applied Science, London, 1991, pp. 102–113.

[6]Geier, B., Klein, H., and Zimmermann, R., "Buckling Tests with Axially Compressed Unstiffened Cylindrical Shells Made from CFRP," *Buckling of Shell Structures on Land, in the Sea and in the Air*, edited by J. F. Jullien, Lyon Symposium, Elsevier Applied Science, London, 1991, pp. 498–507.

[7]Elishakoff, I., and Arbocz, J., "Reliability of Axially Compressed Cylindrical Shells with General Nonsymmetric Imperfections," *Journal of Applied Mechanics*, Vol. 52, No. 1, 1985, pp. 122–128.

[8]Huyan, X., Simitses, G. J., and Tabiei, A., "Nonlinear Analysis of Imperfect Metallic and Laminated Cylinders Under Bending Loads," *AIAA Journal*, Vol. 34, No. 11, 1996, pp. 2406–2413.

[9]Bisagni, C., "Carbon-Epoxy Laminated Cylindrical Shells Under Axial Compression," *Proceedings of 23rd European Rotorcraft Forum* (Dresden, Germany), DGLR, Bonn, Germany, 1997, pp. 100.1–100.10.

[10]Chryssanthopoulos, M. K., Giavotto, V., and Poggi, C., "Characterization of Manufacturing Effects for Buckling-Sensitive Composite Cylinders," *Composites Manufacturing*, Vol. 6, No. 2, 1995, pp. 93–101.

[11]Bisagni, C., "Instabilità e Comportamento Post-Critico di Gusci in Materiale Composito," Ph.D. Thesis, Dept. of Aerospace Engineering, Politecnico di Milano, Milan, Italy, Feb. 1997 (in Italian).

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