CYCLIC BUCKLING TESTS OF CFRP CURVED PANELS

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Abstract

Experimental results obtained on three carbon fibre composite stiffened curved panels subjected to static and cyclic compression and shear loadings are presented.

The results obtained from static tests performed on two panels are described in terms of global axial load vs. shortening curve, torque vs. rotation curve, and strain measurements.

A third panel was subjected to a cyclic loading, at 2 Hz, from above zero till 1.6 times its static buckling load, allowing the investigation of the effect of cyclic buckling in terms of axial load vs. shortening behaviour and strain measurements.

The obtained results show that this kind of structures can well work in the post-buckling field even if during their operative life the buckling load is reached thousands of times.

1 Introduction

Fibre reinforced composites are an important class of engineering materials due to their high specific mechanical properties. Unlike isotropic materials, they have a complex response to loading and offer a not well-known behaviour in the post-buckling field [1]. The main reason is that the presence of several laminae, with different lay-up and properties, makes composite material performances in a non-linear field very difficult to predict. This leads to the necessity to conduct an intensive investigation of the damage onset in composite structures subjected to several load conditions.

This paper highlights some results obtained during the COCOMAT (Improved MATerial Exploitation at Safe Design of COmposite Airframe Structures by Accurate Simulation of Collapse) European project [2], on stringer stiffened composite panels subjected to static and cyclic buckling under compression and shear. In particular, the presented data report the first results of an investigation regarding the post-buckling field of such a structure after the buckling load was reached thousands of times.

2 Test specimens

The three reported panels were fabricated by Israel Aeronautical Industries [3-4]. They are 720 *mm* in high, with a radius of curvature of 938 *mm*, and made with unidirectional carbon composite material. The panels present five blade stringer stiffeners, which are directly co-cured to the skin. The length of the blades is 20 *mm*, while the part in contact with the skin is 60 *mm* width. Besides, the panels are provided with two ending tabs for allowing the clamping into the loading machines. Table 1 summarizes the geometrical properties of the panels.

At the beginning, two similar panels were tested statically and individually under axial compression at the Faculty of Aerospace Engineering of Technion (Israel). Then twin panels were assembled in a closed box and statically tested at the Department of Aerospace Engineering of Politecnico di Milano (Italy).

The box is built by connecting two stiffened curved panels with two flat lateral aluminium panels, as shown in Figure 1, where only half a structure is reported. Figure 1 illustrates also the position and the numeration of the strain gauges placed internally. Each strain gauge has also a corresponding strain gauge on the other side of the panel, in a back to back position. Applying torque on the box, each panel results in being tested under shear.

After static tests, one similar panel was tested under cyclic axial compression at the Faculty of Aerospace Engineering of Technion (Israel), while further cyclic tests under shear are planned in the near future at the Department of Aerospace Engineering of Politecnico di Milano (Italy).

Number of stringers	5
Radius of curvature	938 *mm*
Total height	720 *mm*
Arc-length	660 *mm*
Stringer blade length	20 *mm*
Stringer thickness	3 *mm*
Skin thickness	1 *mm*
Skin lay-up	$[0°,+45°,-45°,90°]_S$
Stringer lay-up	$[+45°,-45°,0°_2]_{3S}$

Table 1. Geometrical properties of the panels.

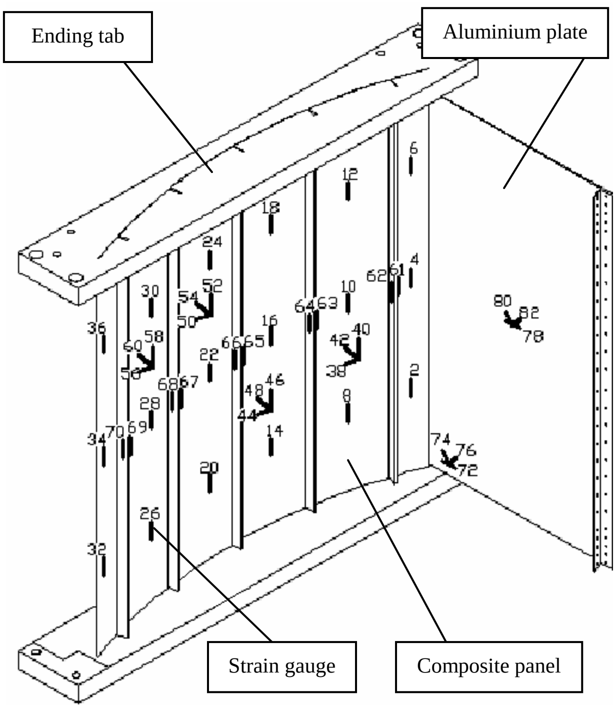


Fig 1. CFRP curved panel, lateral aluminium plate and strain gauges positions.

3 Static test

During the static tests the curved panels are tested until post-buckling field, measuring the axial compression vs. shortening and the torque vs. rotation curves, by a load cell and LVDTs transducers. Strains are also measured, by means of the 82 strain gauges applied on the panels in a back-to-back configuration. Moreover buckling deformations are visualized using Moiré fringes.

3.1 Static tests facilities

Static tests were performed in two different laboratories using two different testing equipments.

At Technion (Israel), single panels were tested under compression using a MTS equipment. Basically, it is a servo-hydraulic test systems which can be easily configured to perform virtually any type of test, from fatigue life studies, to fracture or crack growth studies and to tension, bending and compression tests. A photo of the testing equipment with a panel under test is reported in Figure 2.

Fig 2. Testing equipment at Technion.

At Politecnico di Milano (Italy), the panels were tested in a closed box configuration using a dedicated equipment with displacement control [5-6]. A sketch of the testing equipment is shown in Figure 3.

This facility allows the application of an axial compression load by a hydraulic raw pushing a load platform against four ball screws connected to four stepping motors. The user can control the displacement of each screw, one by one or all together, so to gradually transfer the load to the specimen.

Torque is obtained using a fifth stepping motor connected, through a ball screw, to a torsion lever fixed on a bearing on the top of which the specimen is clamped. Controlling the rotation of the lever, the user determines the rotation introduced into the testing structure.

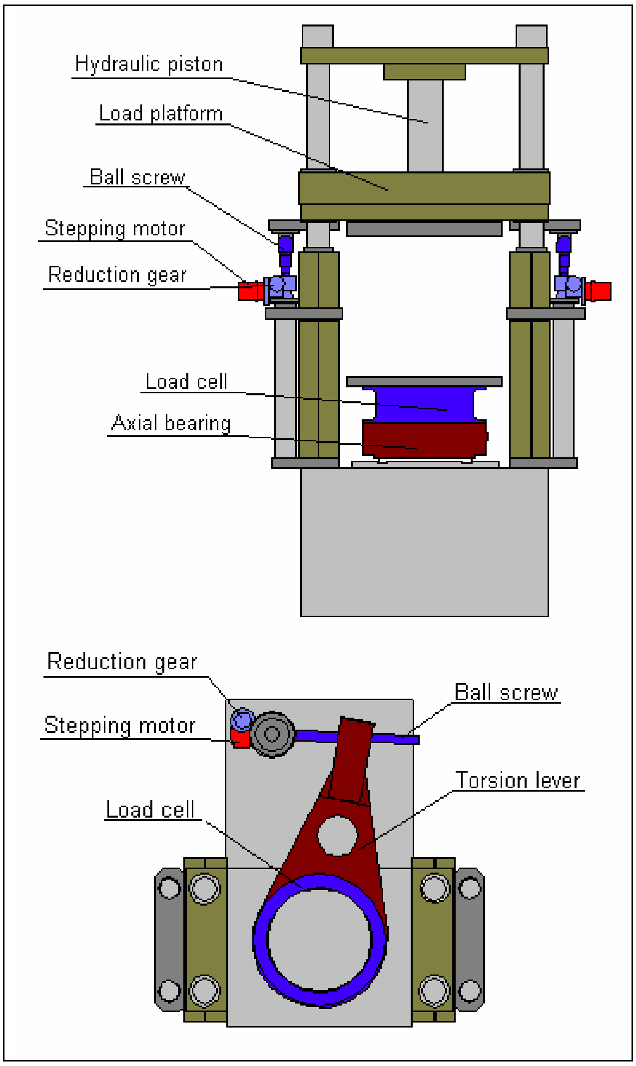


Fig 3. Static test equipment of Politecnico di Milano.

3.2 Static test results

Static tests under compression were performed at first on two single panels at the Technion, then on a closed box at Politecnico di Milano. The results obtained in both cases are in a good agreement.

Figure 4 presents the axial compression vs. shortening curve of the box.

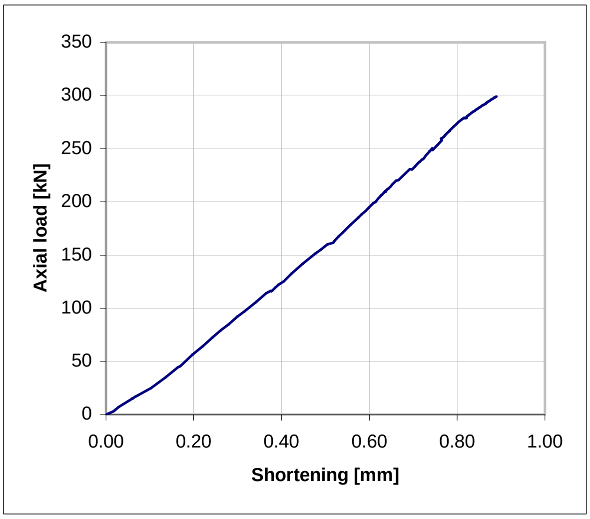


Fig 4. Axial load vs. shortening curve of tested box.

The first buckling load of the box is 231 *kN*, as it is shown in Figure 5, which depicts the micro-strain vs. axial load curves obtained for the strain gauges number 27 and number 28.

Assuming that the load is uniformly distributed on the two panels (being the lateral aluminium plates disconnected from the loading machine), the buckling load achieved for each panel is 115.5 *kN*.

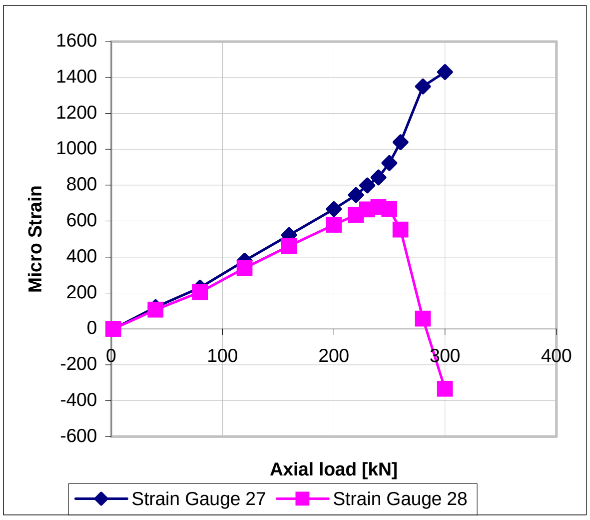


Fig 5. Two strain gauge measurements taken during the compression test on the box.

Figure 6 presents a photo of the panel taken during the test at the maximum axial applied load (300 *kN*). The buckling waves are visualized using the Moiré fringes and highlighted using the yellow arrows.

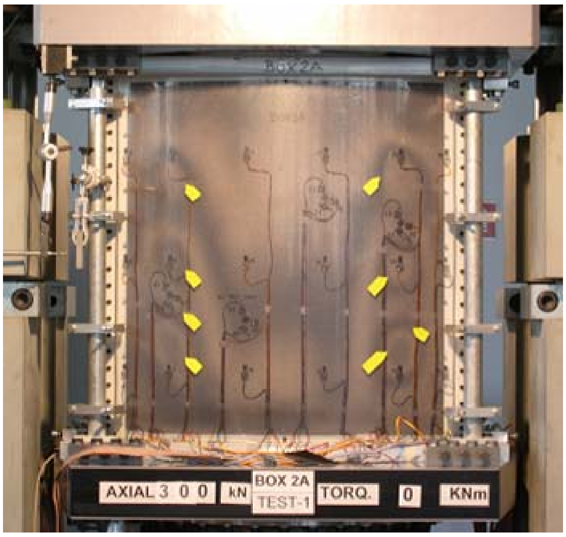


Fig 6. Photo of the box during compression test (300 kN).

After that, the panels were collapsed in a combined axial compression and torque test.

To prevent tearing of the bolts connecting the box aluminium end pieces to the loading machine, it was decided to keep constant the axial load on the box at a value of 180 *kN* and to reach the collapse by increasing the torsion loading in the counter clockwise direction. In reality, because of the torque, the axial compression load is not completely constant throughout the test, but it is fluctuating around the nominal load.

In Figure 7, the torque vs. rotation curve is reported. The highlighted points correspond to some photos of the specimen taken during the test and presented in Figure 9. Figure 8 reports the recorded micro-strain vs. torque curves of the strain gauges number 55 and 56.

The first wave appeared at a combination of torque and axial compression of 6 *kNm* and 180 *kN*, respectively (Figure 9a). As the torque was increased, waves began to spread all over the surface (Figure 9b and Figure 9c), until, at a load of 16 *kNm* in torsion and 180 *kN* in compression, the whole surface was completely buckled (Figure 10a).

Further increasing the torsion, waves become deeper and deeper (Figure 10b), until, at a torque of 40 *kNm* and a compression of 180 *kN*, Moiré fringes are removed because they were touching the buckled surface (Figure 10c).

At a load of 43 *kNm* and 178 *kN* a visible local damage appeared simultaneously at the upper left corners of the two panels (Figure 11). The torsion is further increased till the collapse at a torque of 48 *kNm* with an axial load of 182 *kN*. The box held this combination of loads for 15 minutes, then, after a big noise, the loads fell to 45 *kNm* and 180 *kN*.

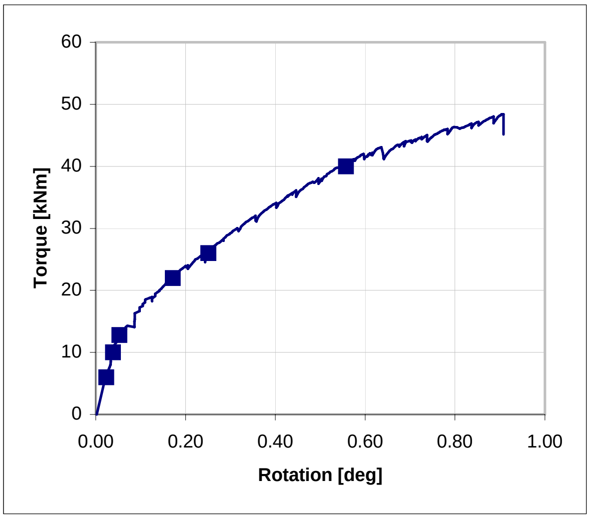


Fig 7. Torque vs. rotation curve during static collapse test.

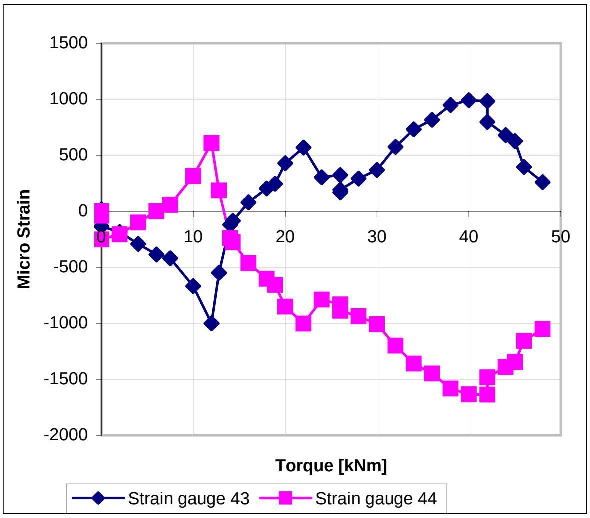
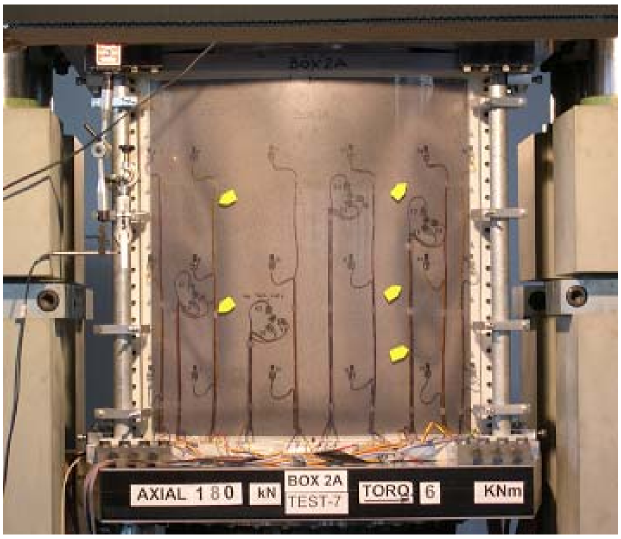
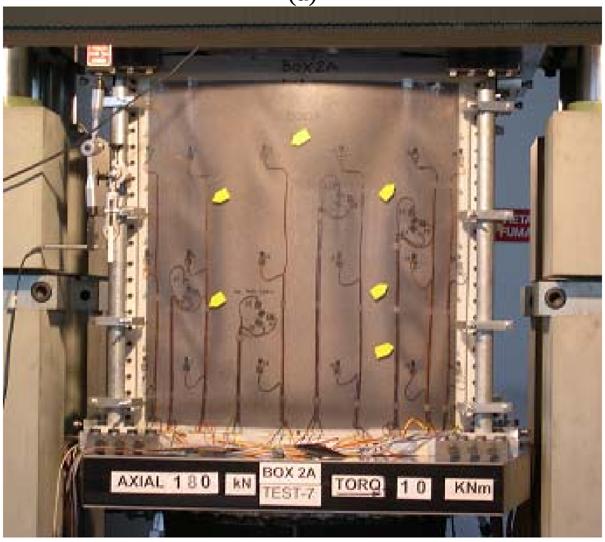


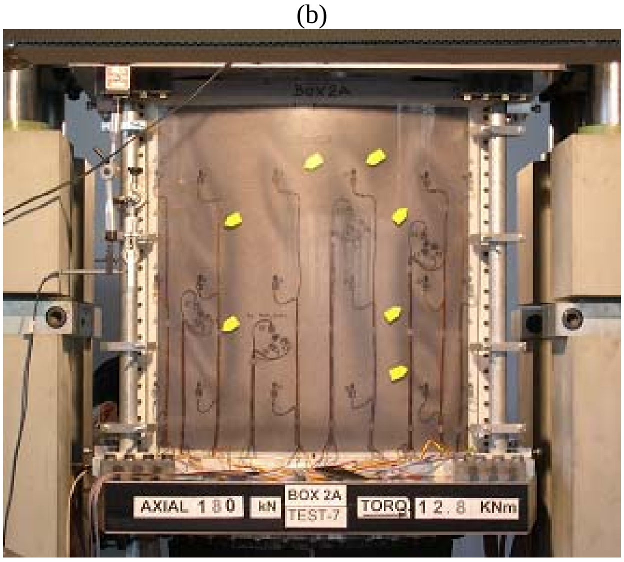
Fig 8. Two strain gauge measurements during static collapse test.



(a)

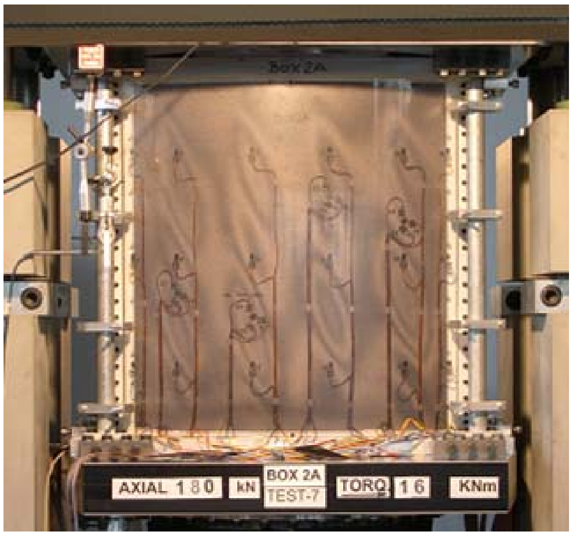


(b)

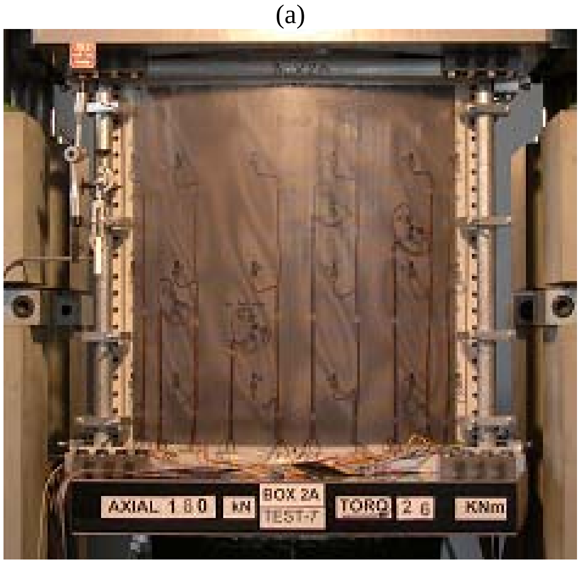


(c)

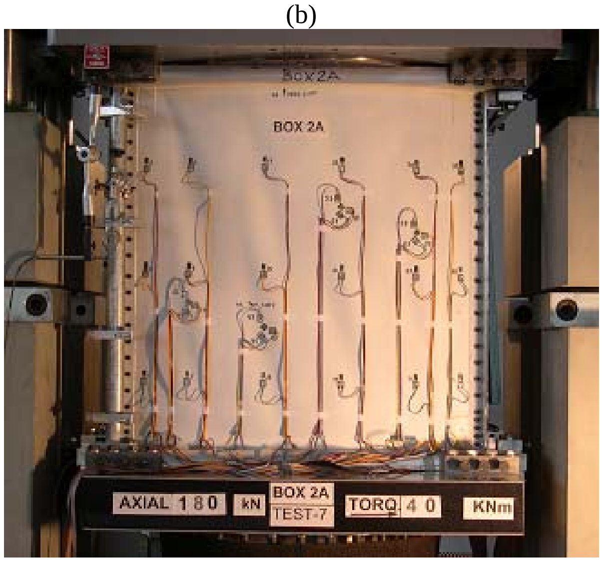
Fig 9. Evolution of the deformation during collapse test: first part of the test.



(a)



(b)



(c)

Fig 10. Evolution of the deformation during collapse test: second part of the test.

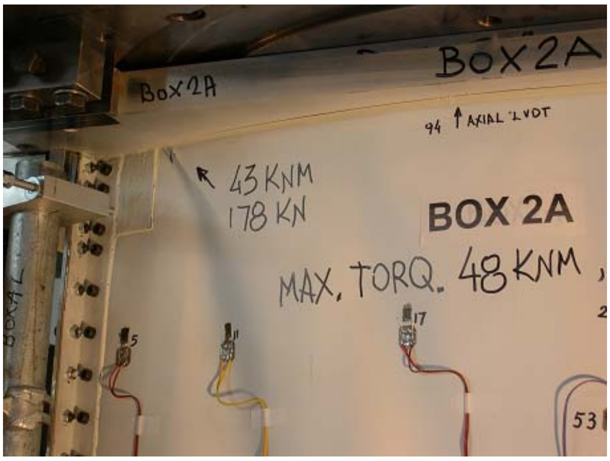


Fig 11. Visible damage on one panel during collapse test.

4 Cyclic tests

A third panel, nominally identical to the previous two ones, was tested under axial compression loading cyclically at the Technion (Israel).

For this case, the compression vs. shortening curve was measured using a load cell and LVDTs, and 70 strain gauges in back-to-back configuration were used to get the strains. Finally, Moiré fringes were employed to visualize buckling deformations during the test.

Cyclic torsion tests have not yet been completed, but they will be performed in the near future at Politecnico di Milano (Italy).

4.1 Cyclic tests facilities

Cyclic tests are planned in two different laboratories using two different testing equipments. Unfortunately only the first tests under cyclic compression were performed until now.

The used equipment is the MTS system available at the Technion. In this case, each panel is tested individually, and the results are compared to the ones obtained during static tests in terms of global response and strain measurements.

For cyclic torsion tests, the equipment that will be used is the one used in the static tests at Politecnico di Milano, modified as reported in the sketch of Figure 12.

In particular, the torsion stepping motor used during static buckling tests in position control mode is substituted with a hydraulic actuator piloted by a servo-valve.

Moreover, an ad hoc PC based software is used to control the test. The software, named SISIFO, was fully home-developed using hard and soft real time capabilities of RTAI [7]. It uses the load cell signal as input data and then calibrates the output from the servo-valve, using a PID controller.

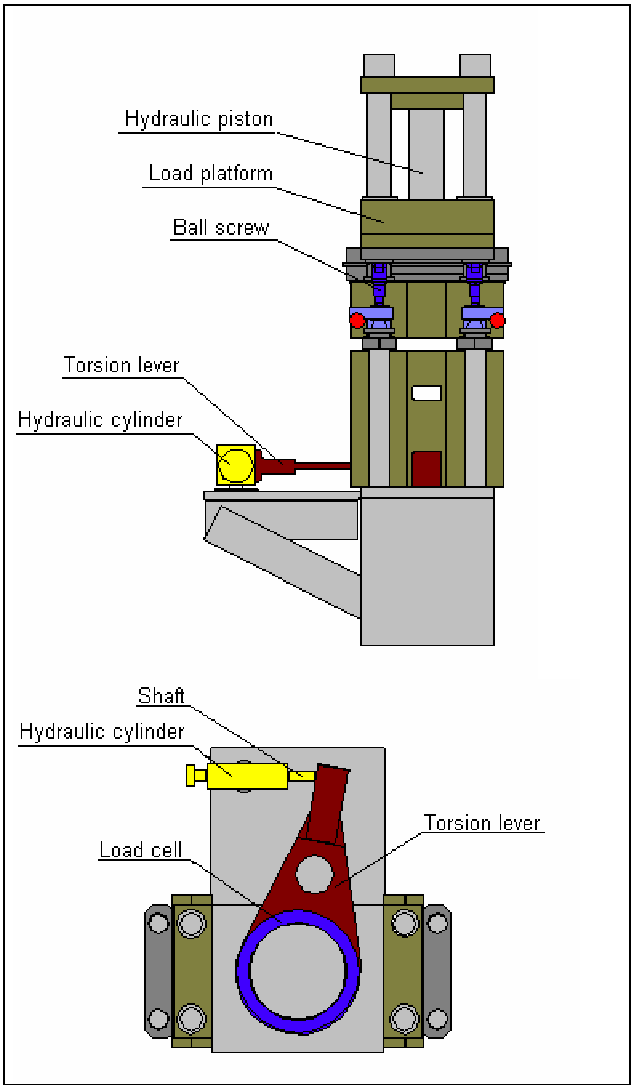


Fig 12. Cyclic test equipment at Politecnico di Milano.

4.2 Cyclic tests results

The third panel was tested at Technion.

The panel was initially tested statically until the post-buckling field. Figure 13 reports the axial compression vs. shortening curve, while Figure 14 shows the axial compression vs. micro-strains curves for the strain gauge 7 and 8.

Experimentally, the first buckling load is found equal to 75 *kN*.

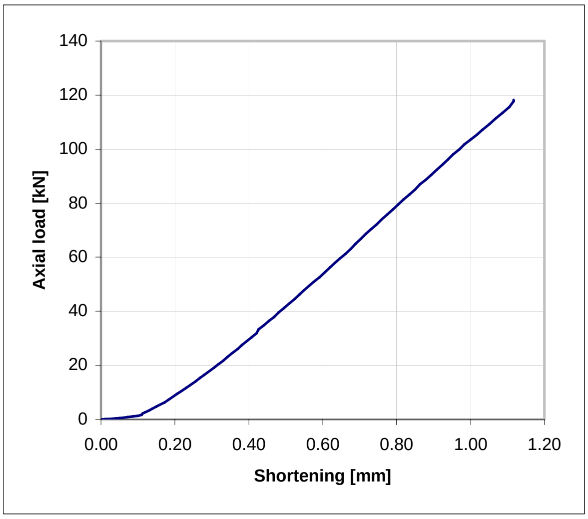


Fig 13. Third panel: strain gauge measurements during the axial load test.

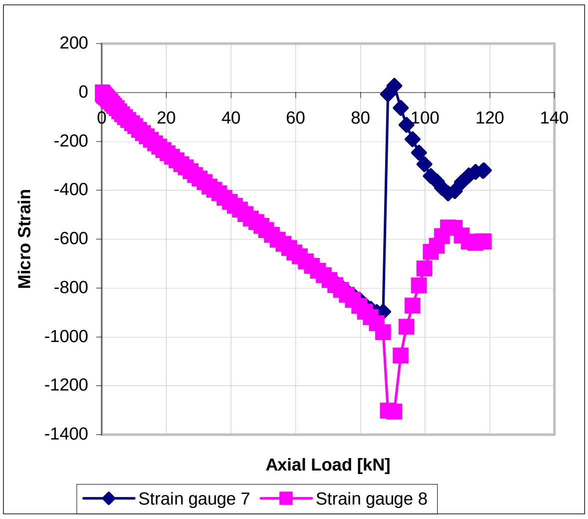


Fig 14. Third panel: bending and compression strains.

Then, the panel was tested under 2000 cycles, at 2 Hz, from above zero axial load till 120 kN, thus till 1.6 times its original first buckling load.

After 500 cycles the test was stopped and the strain gages readings and the lateral and axial displacements were recorded.

The procedure was repeated again for 1000 cycles, 1500 cycles and 2000 cycles. Figure 15 reports a photo taken during the cyclic test.

Then the panel was tested for another 50000 cycles under an alternating axial load of $0 \pm 120\ kN$, after which it was again tested for more 10000 cycles under $0 \pm 150\ kN$, without any visible damage. Finally, a collapse test was performed obtaining a collapse load equal to 211.43 *kN*.

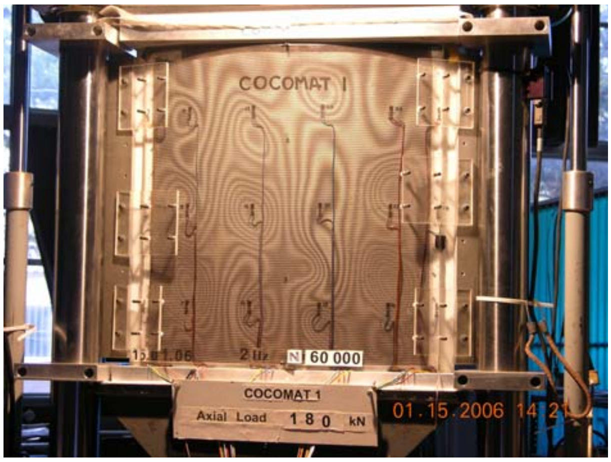


Fig 15. Cyclic test at Technion.

5 Conclusions

Experimental results obtained on three carbon fibre composite stiffened curved panels subjected to static and cyclic axial compression and shear loadings are presented.

In particular, two panels were at first individually tested at Technion under static axial compression tests. After that, twin identical panels were assembled in a closed box, tested again at Politecnico di Milano under axial compression, and then collapsed under torsion.

An important observation is that the results obtained in the two different labs are practically the same.

The third panel was tested under axial compression, both statically and cyclically, at Technion, while cyclic tests on a box configuration are planned in next months at Politecnico di Milano.

Reported results appear very important as they concern the behaviour of composite stiffened panels under cyclic pre-post buckling loads. In particular, they confirm that this kind of structures can well work overcoming during their life thousands of times the buckling load without significant damages, so extending their operating loads well above the limit actually adopted. More data will be allowable once the cyclic test series will be completed including the box configuration.

Acknowledgment

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