STRUCTURAL BEHAVIOR OF DAMAGED ANISOTROPIC STIFFENED PANELS UNDER COMPRESSIVE LOADS

Giacomo Frulla*
***Politecnico di Torino, Dipartimento di Ingegneria Aeronautica e Spaziale**

Keywords: *buckling, post-buckling, damage effect, stiffened composite panels*

Abstract

Stiffening concepts are frequently used to increase buckling characteristics of a thin plate. A skin delamination or a stiffener de-bonding in a stiffened panel can cause buckling prior to the designed critical condition and can cause a reduction in global strength. The presence of cyclical loading and fatigue effect can have important consequence on damage propagation and structural integrity. The static structural behavior of a damaged stiffened composite panel is presented as a preliminary activity for the introduction of the subsequent fatigue case. Uniaxial and biaxial loading condition are applied to the panel in order to point out the damage effects. Strain distribution under critical and post-critical (local-global) static test condition are reported. Very preliminary load cycling test is performed and presented[1].

1 Introduction

The use of composite materials in aerospace engineering is ever increasing . Properties such as low weight, high performance, high stiffness and the ability for it to be tailored specifically for different structural uses, has increased its importance in recent years. However, compared to the traditional aerospace material, metal, the use of composites is still very much limited. This is due to the fact that knowledge of the behavior of composites in the post-buckling regime, especially with occurrences of delamination and micro-cracking, is still not very established connected to the presence of cyclical loading and fatigue effect on damage propagation and structural integrity[1,4]. Delamination may occur due to different reasons, such as low energy impact, manufacturing events, high stress concentrations or material discontinuities (free edge effects etc..). Delamination is known to degrade the overall stiffness and strength of the structures, severely reducing the load-carrying capacity of the laminate under compressive loads [10,11]. A skin delamination or a stiffener de-bonding in a stiffened panel can cause buckling prior to the designed critical condition. The ability to evaluate this effect is essential for predicting composite performance and developing more safe/reliable structures [2,3]. Stiffening concepts are used to increase buckling characteristics of a thin plate. Several type of buckling have to be taken into account such as: overall buckling, skin buckling, stiffeners buckling and torsional or twisting buckling[5,6]. Local/global critical behavior is modified as a damage effect in terms of de-bonding between skin and stiffeners, delamination between skin layers and between stiffeners layers and so on. In these cases it is important to assess and characterize damage, as well as how to identify the progression of damage and the convenient design procedures [8,4]. On this basis an anisotropic stiffened panel is considered, with an artificially induced damage: stiffener de-bonding. Damage position and dimension are chosen according to preliminary numerical analysis. The damaged panel is studied in order to evaluate and compare its structural behavior. Strain distribution under critical and post-critical (local-global) static condition are determined. A comparison between undamaged and damaged case is obtained by numerical FE analysis. Biaxial and uniaxial compression static tests are performed and presented. Specific damage effects are pointed out. A subsequent experimental activity, considering cyclical compressive loading condition, is performed as a preliminary test set-up phase. Fatigue experimental evaluation is in progress.

2 Preliminary analysis of damage effect in stiffened panel

A carbon/epoxy stiffened panel with a artificially simulated defect (skin-stiffener debonding) is investigated. A flat panel with four T-type stiffeners is considered. Stiffener width and height of 30mm is assumed. M40/epoxy material with standard properties and the following laminate lay-ups are introduced: $[(+-45)_2/0/(+-45)/90]_S$ for the panel, $[(+-45)_2/0_6/(+-45)/0]_S$ for the stiffener cap and $[(+-45)_2/0_6/(+-45)/0_5]_S$ for stiffener web. Panel average thickness of 2.8mm is considered. Overall panel dimensions are 1000x700mm. The dimensions were reduced according to the assumed clamping condition adopted for the experimental phase [5,7]. Uniaxial compression and two biaxial cases were considered in this preliminary numerical analysis with an overall load per unit length ratio of 0.15 and 0.2. Different numerical model can be found in the open literature in order to analyze a de-bonding configuration [9,11]. A preliminary structural definition of the stiffened panel was introduced according to [9]. A de-bonded length of the order of the stiffener distance is considered. Three types of damages are initially analyzed: type A introduces a de-bonding length of 100mm in the central part of one stiffener, type B duplicates the same de-bonding in the central part of two stiffeners, while type C considers a de-bonding length of 200mm in the central part of one stiffener. Other types of defects could be possible in stiffened panel such as delamination in the outer panel surface or near stiffener connection. They are typical of different operative damages or impacts and they will be included in further analyses and investigations. In figure 1 a qualitative sketch of the three damages types are presented. Type C revealed an early initiation of the damage buckling phenomenon. For this reason a damage extension of more than 200mm is considered in the subsequent analysis and experimental configuration. A specific FE model was developed including a panel/stiffener de-bonding of 220mm. The panel is considered clamped along four edges. The applied longitudinal load was twice the critical load of the panel between two stringers [5,6] for the biaxial cases, while the uniaxial one was limited to 400kN considered sufficient for damage activation. Since this load level is under the local panel buckling, undamaged configuration was not studied for this case. Qualitative buckling shape is reported in figures 2 for the undamaged first biaxial case. The numerically determined local buckling level is little higher than the analytical one, due to a different stiffener-panel interface condition. Non linear static analysis was performed in order to obtain the post-critical panel behavior.

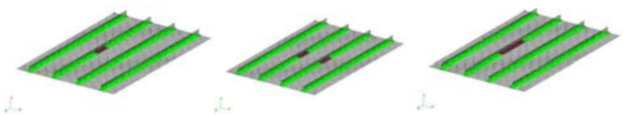

Figure 1: Damage types: A-B-C

Three half-waves are clearly developed in transversal direction. A displacement comparison is reported in figures 3 and 4. The localized buckling in the damaged area is evident in the first biaxial case but at a load level ratio of about 0.8 the deflection tends to be reduced and the undamaged case is followed. The mid-bay displacement in figure 4, clarifies the situation. Strain comparison is reported in figure 6. The damage deflection is very clear. The strain distribution is also shown in figures 5a and 5b for the first biaxial case. 60% and 80% load level are reported. The local buckling of the defect area is evident in figure 5a with the corresponding strain concentration at the interface. That deflection tends to be eliminated at higher load, as in figure 5b, where the three half-waves mode seems to be developed. The uniaxial case in summarized in figure 7 where the strain behavior demonstrate an evident damage buckling at a load level ratio of about 0.72. In this case the maximum applied load was limited to a similar level used for the other cases in order to emphasize the defect deflection. As a conclusion of this preparatory activity, it is important to point out that in the uniaxial case a damage buckling is expected to occur in a well behaved shape. In the biaxial one the damage buckling is not so evident and a damage-global buckling coupling seems to occur at high transversal load.

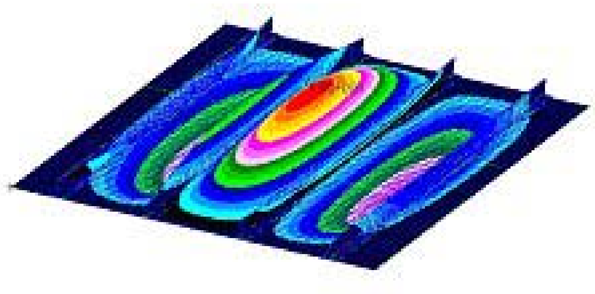

Figure 2

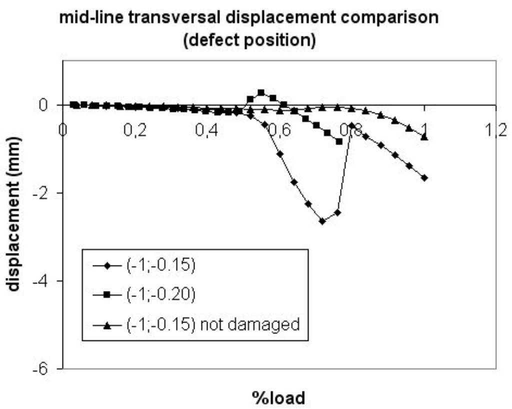

Figure 3

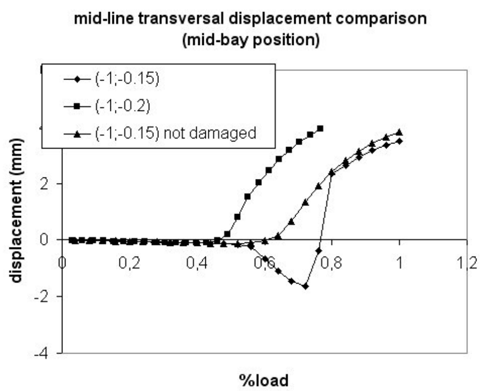

Figure 4

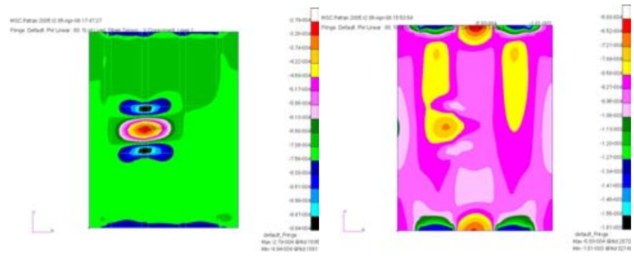

Figure 5a, 5b

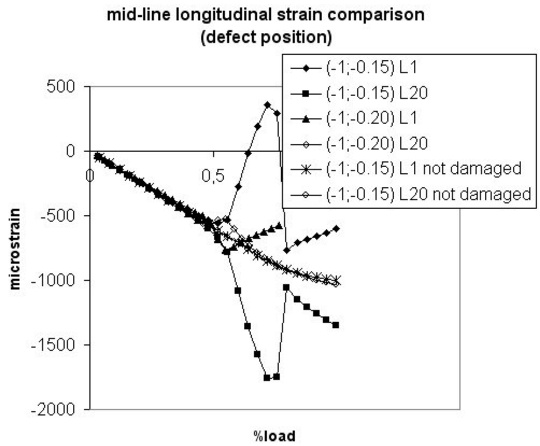

Figure 6

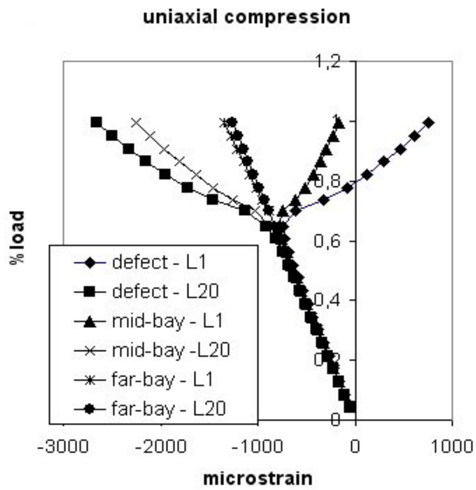

Figure 7

4 Experimental static behavior

Considering the preliminary evaluation, a testing sample was manufactured. It is a flat stiffened panel shown in figure 8a (flat side) and in figure 8b (stiffened side). Several strain gages (SG) are bonded back-to-back along mid-line and quarter-line panel position. The stiffened side is plotted in figure 9 with SG positions. Dashed and dotted lines indicate damage (253mm wide) position and back SG position respectively. The panel was prepared as shown in figure 10a. Two metal rails were used to obtain two opposite clamping terminals and lateral boundary conditions.

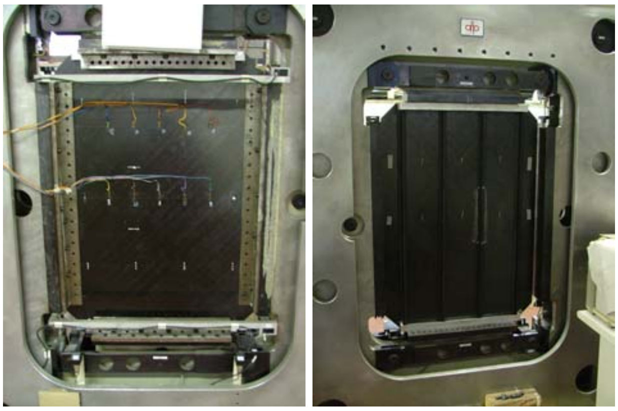

Figure 8a, 8b

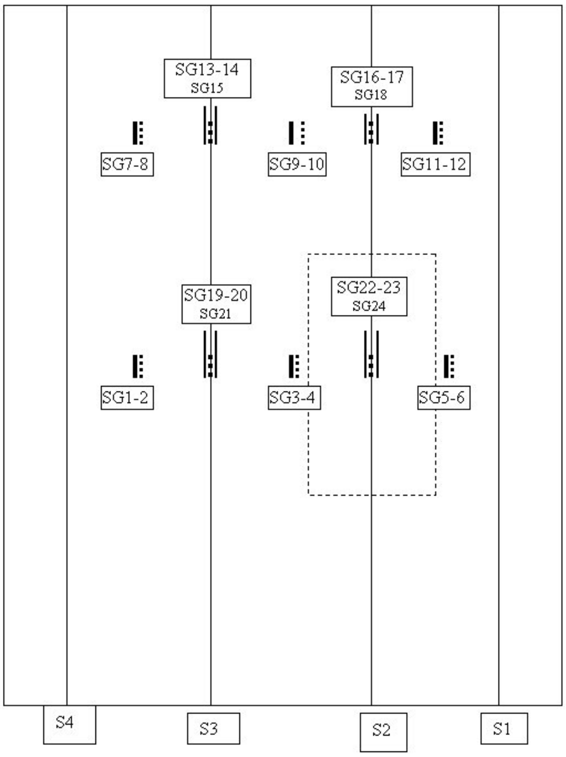

Figure 9

Figure 10a

Figure 10b

No initial imperfection seems detectable on the panel as in figure 10b. Biaxial compression test is considered at first. A load per unit length ratio *Ny/Nx* of 0.15 is applied. This load level introduces higher load ratio on the panel skin due to presence of the stiffeners. Transversal displacements are qualitatively detected by Shadow-Moirè method. The loading phase is reported in figures 11a, 11b (10kN and 200kN)

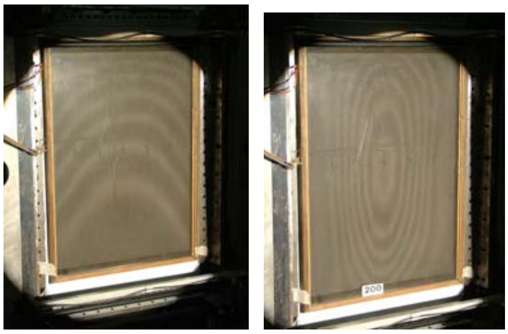

Figure 11a, 11b

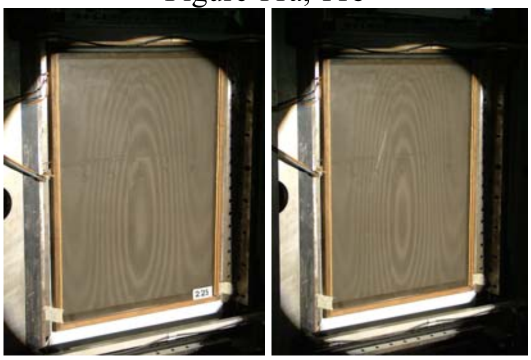

Figure 12a, 12b

and figures 12a and 12b (225kN and 250kN). The lateral buckle, next to the defect position (left on the figure), seems more pronounced also if the plot is not so clear. However the central buckle is quite evident maintaining its shape up to the maximum applied load. The load level reached during the test was maintained low. The scope of the static test, in fact, was the activation of the panel deflection in the damage position in order to determine the mean load level for a subsequent cyclical loading phase. The longitudinal experimental strain distribution is shown in figure 13 and figure 14 for mid-line and quarter-line positions. While the quarter-line distribution is quite close to the expected shape (three half-waves), the mid-line distribution reveals an unexpected behavior. The SG positioned on the damaged area tends to be strained higher than the near points. This fact can be considered as a tendency of the panel to move toward the stiffener avoiding the buckling of the damaged area. A buckle can be detected by SG5-6 reversal in the next-bay position (figure 15).

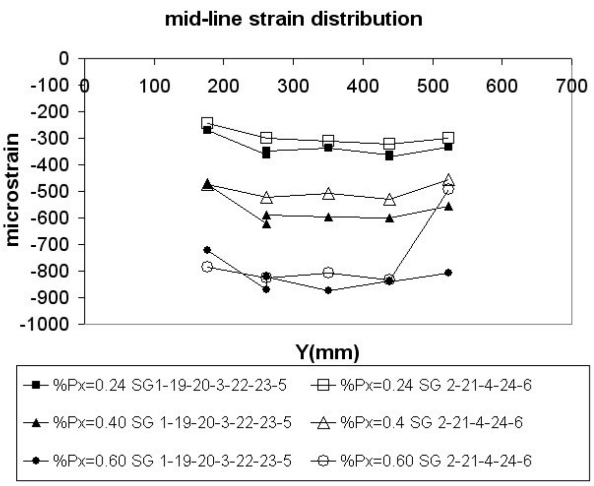

Figure 13

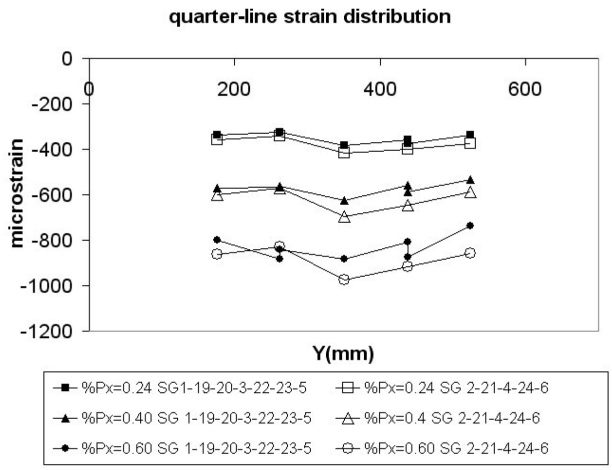

Figure 14

The average value follows the numerical undamaged one. The defect position is shown in figure 16. In this case the strain reversal due to the local panel buckling is not determined at all in contrast to the numerical expectations. The SG24 tends to the opposite direction revealing a combined stiffener-panel overall behavior. The SG22 and 23 are quite close to the undamaged results confirming the previous conclusion. A subsequent uniaxial compression was applied to the panel. In figure 17, the SG5-6 are reported. The graph indicate a loading phase and a restoring one. It is quite evident in this situation, the presence of a local damage buckling activation at a load ratio of about 0.52.

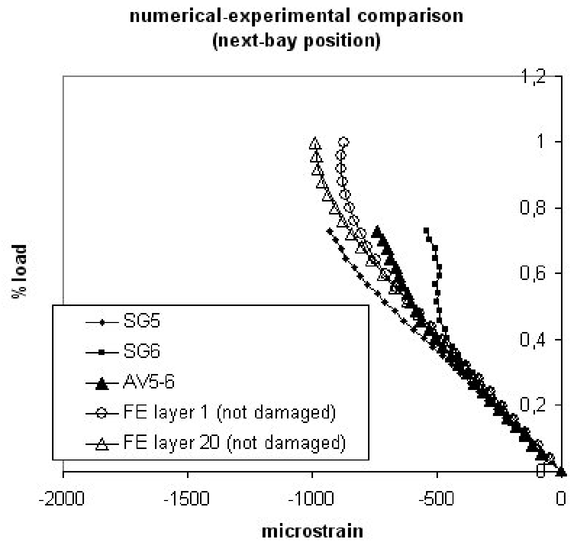

Figure 15

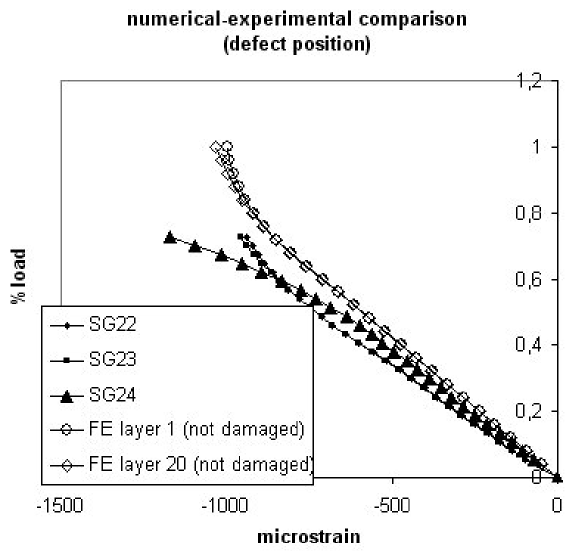

Figure 16

The restoring curve proceeds along a different path up to a load ratio of about 0.42 where it remains over the previous loading one. This "snap" phenomenon is also pointed out in figure 18 where the SG 22,23 and 24, are presented. The damage position demonstrates very clearly the snap local buckling effect. It is repetitive as the load is increased over the 0.52 value. In figure19 the Shadow –Moirè of the uniaxial case confirm the local buckling configuration. The strain distribution along the mid-line is presented in figure 20. Flat side and stiff side strains are reported. Buckling at defect position and snap effect are pointed out.

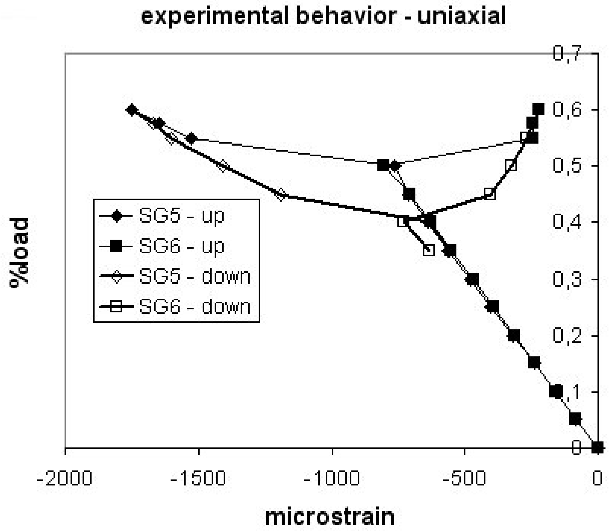

Figure 17: uniaxial case: snap buckling

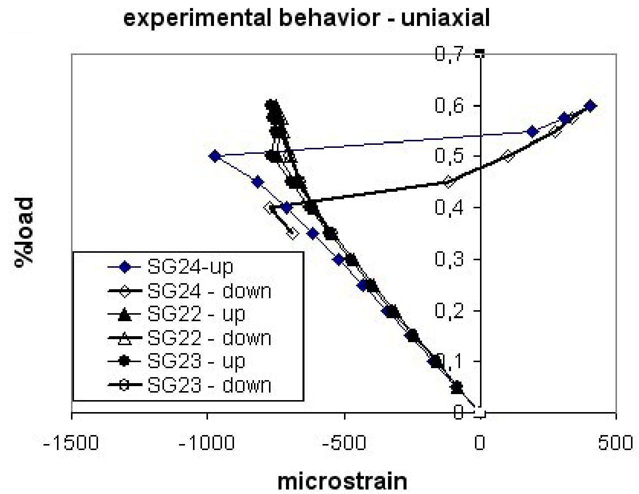

Figure 18: defect position

Figure 19: Load level ratio of 0.55

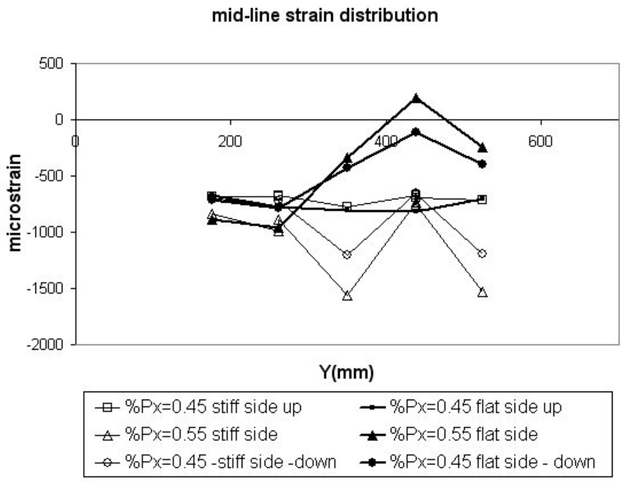

Figure 20

A numerical comparison is not possible in the post-buckling case due to the presence of snap situation that suggests the presence of a certain level of imperfection during test. A possible initial induced deflection at low load level seems evident as in figure 21. An improved FE analysis is requested. The presence of a “snap” buckling suggests the possibility to operate over the same load levels during fatigue loading condition: an amplification of the damage effect could be determined.

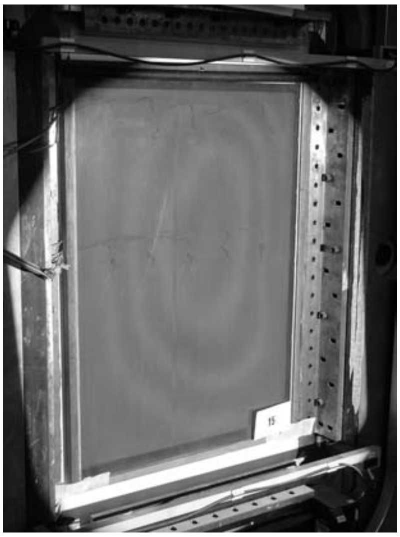

Figure 21: Imperfection at low load level

4 Preliminary fatigue test

The uniaxial compression case is considered for this preliminary fatigue test. A low frequency (0.1Hz) loading condition is performed in order to evaluate the behavior of the damage and in order to asses the testing equipment. SG5, SG6 and SG 24 are retained during test assumed as the most representative of the situation. A first loading phase is presented in figure 22 showing the "snap" effect at 0.52 load level as previously determined. The damage buckling is quite evident following SG24 curve. Figure 23 presents the rough preliminary detected data after cycling. The load cycle is characterized by a maximum load ratio of 0.6 , a minimum load ratio of 0.5 and an amplitude of 0.05. The cycling curves follow the "after snap " path as indicated during static phase. The time history of the test case is presented in figure 24. A stiffness parameter is evaluated according to [7] in order to detect the damage effect. The stiffness parameter experimentally determined, is reported in figure 25 showing the damage behavior at the considered life. The stiffness parameter evaluation can be considered just one of the experimental method for damage detecting. It is easy to apply during test without any intrusive effect. However some improvements in the damage evaluation under fatigue has to be done in order have a better indication of the possible damage variation.

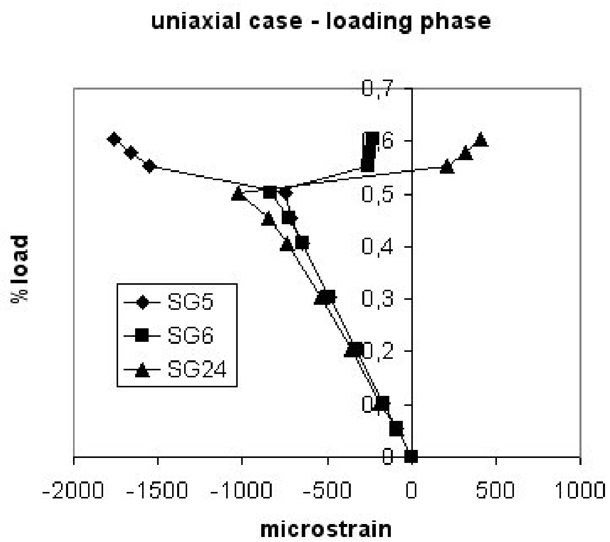

Figure 22

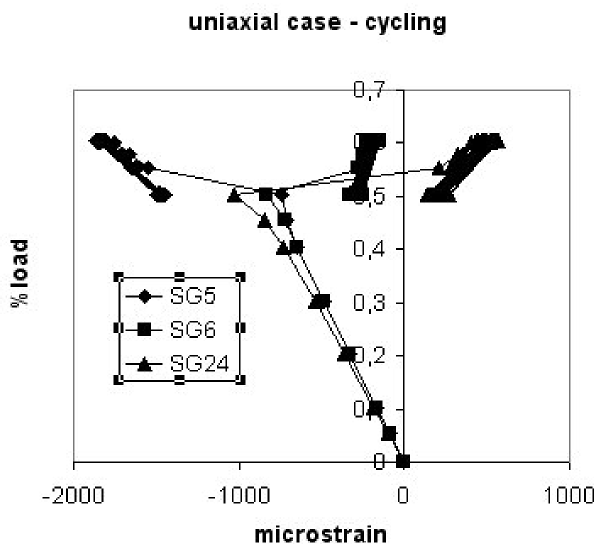

Figure 23

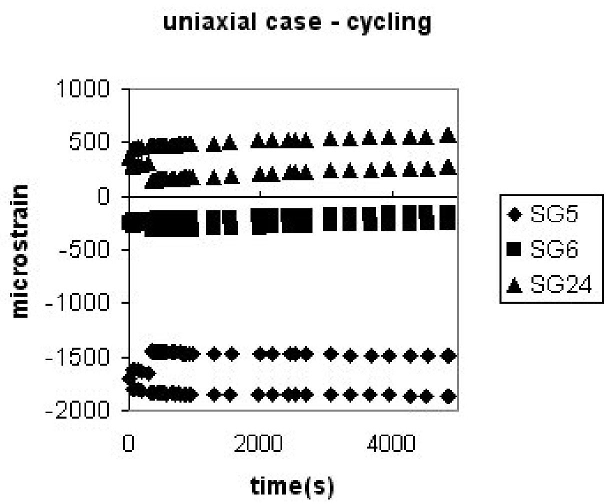

Figure 24

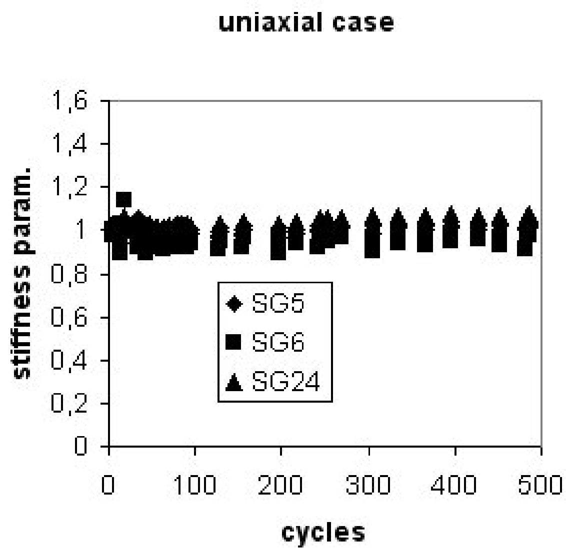

Figure 25

5 Conclusions

Damage effect on critical and post-critical behavior of a stiffened panel is studied. Stiffener de-bonding is introduced in the panel, as representative of an operative condition. Preliminary numerical analysis showed local panel buckling in the defected area for uniaxial and biaxial considered cases. In the biaxial cases the local buckling tends to reduce at high load due to a local/global panel buckling interference. This behavior is confirmed by the preliminary biaxial experiments where local defect buckling does not occur. A snap buckling phenomenon seems to be experimentally determined under uniaxial compression. The presence of a transversal deflection under low load level can influence the snap condition. An improved FE analysis is necessary in order to have a better description of the experimental case. On the basis of the preliminary static tests, a subsequent cyclic load activity is started. The stiffness parameter is introduced as a measure of damage variation during cycles. Just preliminary data are reported as a first set-up of the experimental equipment. Fatigue experimental activity is in progress in order to reach a reasonable life.

Acknowledgements. The presented activity was a part of the PRIN2004 (MURST) research project.

6 References

[1] Chai, H. and Babcock, C. D. “Two-dimensional modelling of compressive failure in delaminated laminates”. *J. Comp. Mater.* **19**, 1985. pp. 67-97.
[2] Chen D.J., Chan W.S., Wang B.P. “ An efficient method to simulate one and two-dimensional delamination growth in composite laminates”. *Journal of Reinforced Plastics and Composites,* Vol.15, September 1996, pp. 944-957.
[3] Withcomb J.D. “Predicted and observed effects of stacking sequence and delamination size on instability related delamination growth”. *Journal of Composite Technology & Research,* Vol. 11, 1989, pp. 94 – 98.
[4] Whitworth H.A. “ Evaluation of the residual strength degradation in composite laminates under fatigue loading”. *Composite Structures*, Vol. 48, 2002, pp.261-264.
[5] Romeo, G. and Frulla, G. Nonlinear analysis of anisotropic plates with initial imperfections and various boundary conditions subjected to combined biaxial compression and shear loads. *Int. J. Solids Structures* **31**, 1993, pp.763-783.
[6] Romeo G., Frulla G., “Post-buckling behaviour of graphite/epoxy stiffened panels with initial imperfections subjected to eccentric biaxial compression loading”. *Int. J. Non-Linear Mechanics* , Vol.32, No.6, 1997, pp.1017-1033.
[7] Frulla G., “ Experimental behavior of damaged anisotropic rectangular panels under cyclic compressive loads”. *XVIII AIDAA National Congress* , 19-22 September 2005, Volterra (PI).
[8] Greenhalgh E., Meeks C., Clarke A., Thatcher J. “The effect of defects on the performance of post-buckled CFRP stringer-stiffened panels”. *Composites Part A*, Vol. 34, 2003, pp.623-633.
[9] Yap J.W.H., Scott M. L., Thomson R., Hachenberg D. , “ The analysis of skin-to-stiffener de-bonding in composite aerospace structures”. *Composite Structures*, Vol. 57, 2002, pp.425-435.
[10] Woo-Min K., Chun-Gon K., Chang-Sun H. “ Buckling and post-buckling behavior of composite cross-ply laminates with multiple delaminations”. *Composite Structures*, Vol.43, 1999, pp.257-274.
[11] Yap J.W.H., Thomson R., Scott M. L., Hachenberg D. , “ Influence of post-buckling behaviour of composite stiffened panels on the damage criticality” *Composite Structures*, Vol. 66, 2004, pp.197-206.