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BEHAVIOUR OF A LOCAL DELAMINATION UNDER COMPRESSIVE LOAD*

S. Maison and D. Guedra-Degeorges
Aerospatiale. Louis Bleriot Joint Research Center
Suresnes, France

Abstract

This paper presents results of a study aiming the following objectives:
- experimental identification of sensitivity to local buckling of a delamination in a plate under compression
- correlation of buckling loads computed by Finite Element Method and test results.

Three shapes of defect (circle, square, elliptic) and two stacking sequences of a 32 plies laminate in T300/914 material have been investigated. Artificial delaminations have been located in the thickness at 4th and 8th ply.

An experimental device to assess accurately buckling load and shape of the blister has been developed. Comparison with computation showed a good agreement.

Results analysis reveals that for realistic delamination size ($S=350mm^2$), a surface delamination seems more damageous than an "in thickness" defect because local buckling appears before overall buckling of the sample.

Introduction

Many researches into buckling-compression behaviour of composite materials are running at the moment because of the compression design of aeronautical stuctural parts.

Delaminations can occur during the material processing (compactness lack) or under external loading during service: impact of foreign bodies or mechanical loading of the structure.

The aim of this study was to set up a methodology and to provide data allowing a better knowledge of the local buckling phenomena around a delamination in a carbon-epoxy composite under compressive load. Tests and computations were achieved and showed a good agreement.

In particular computations and tests showed the local buckling behaviour depended of delamination nature (shape, in thickness position) and of the stacking sequence of the laminate.

The development of an experimental device and of a numerical method to assess accurately buckling load and shape of blister allowed to define a methodology able to predict the possible propagation of the delamination.

Experimental

Materials

The laminates of this study are made of the following pre-preg:
-Fibre TORAY T300B 6k/ Resin CIBA GEIGY 914

Stacking sequences

Two stacking sequences of a quasi-isotropic 32 plies laminates were studied:
- type 1: $[(0/-45/90/45)_4]_{sym}$
- type 2: $[(0/45/0/-45/90/45/90/-45/0/45/90/-45/0/-45/90/45)]_{sym}$.

Choice was made in order to get two different bending stiffness laminates with the same "in plane" stiffness.

Sample dimensions

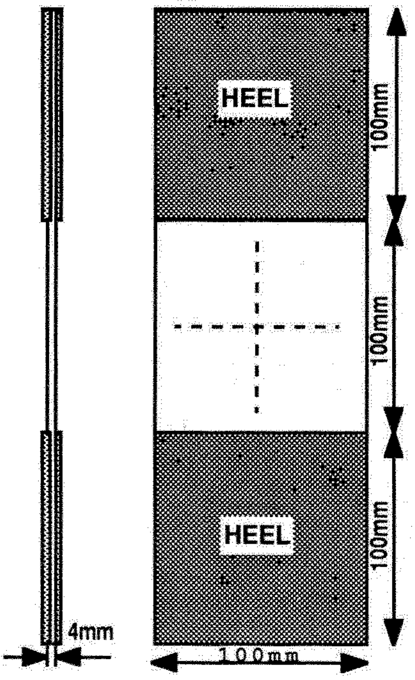

fig 1: sample dimensions

Nota: the heels are made of 3 (±45) glass plies.

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Defect simulation

For each stacking sequence, we considered:

- 4 defect shapes:
  - square
  - circular
  - elliptic main axis oriented O°
  - elliptic main axis oriented 90°
- 1 defect size (different for each shape)
- 2 "in thickness" location
  - between 4th and 5th ply (level 2)
  - between 8th and 9th ply (level 1)

at the middle plane of the sample.
Defects were created with thick film of TEFLON (25 μm)

Test and equipment description

Tests were performed at ambient temperature with an 25000 N capacity INSTRON machine. For each compressive test, a special device was set up to avoid the overall flexion of the sample. Two different test fixture were used:

- test fixture 1: set up of two LVDT captors located at the middle of each face of the sample (fig 2).
- test fixture 2: set up of two strain gages located at the middle of each face of the sample (in the loading direction) and of an electronic dial indicator (fig 3).

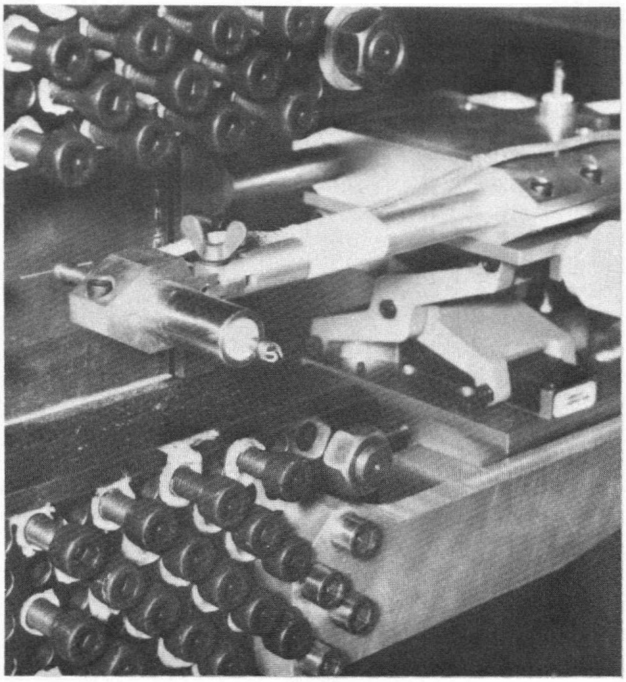


fig 2: test fixture 1

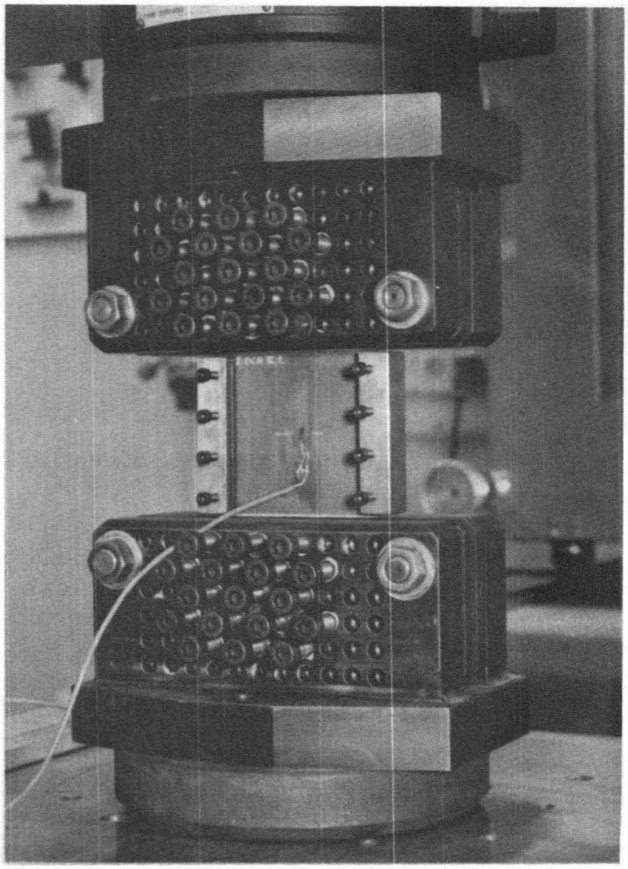


fig 3: test fixture 2

Determination of the local buckling load

Experimental curve gives outer and upper skin displacements versus applied load.

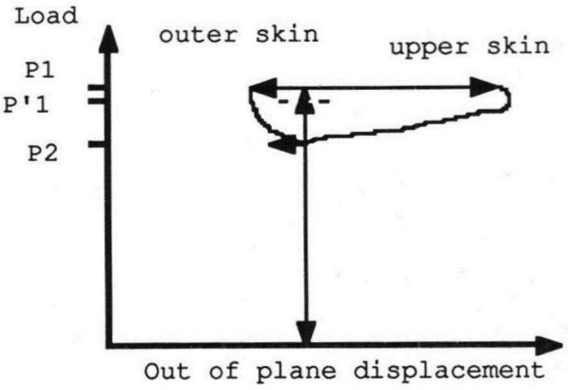


fig 4: schematic of experimental curves

So there is an out of plane deflection for the P1 load and an in plane return when reducing the load to P2. Then, when increasing again the load, an out of plane deflection is obtained for the P'1 load lower than the P1 when P2 load is the same. This can be explained by the addition of energy necessary to completely separate the TEFLON defect from the material. The P2 load seems more representative of the local buckling load because it doesn't change during the load-unload cycle. Therefore the local buckling load will be the average of the P2 load given for the 2nd and 3rd cycle.

Non destructive investigations

A C-SCAN inspection was performed for each tested sample in order to validate the local buckling load by verifying the no-propagation of the defect.

Experimental results

Main results are the following:

- Whatever the stacking sequence and the defect shape there is no local buckling when the delamination is located between 8th and 9th ply.
- There is always local buckling when the defect is located between 4th and 5th ply.
- The stacking sequence 1 blisters for load greater than the stacking sequence 2 (meanigfull difference) for all defect shapes.
- The sensitivity of defect to blister versus its shape is the same for both sequences

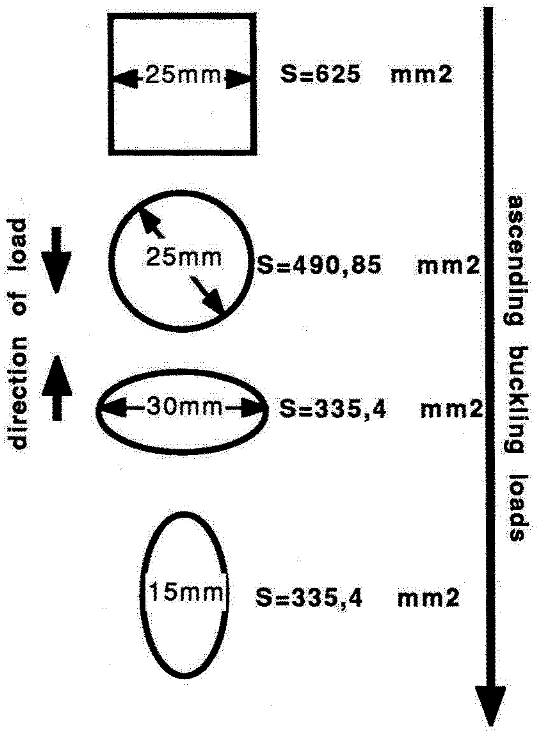


fig5: sensitivity of defect to blister versus its shape

Shape of the blister

Experimental shape of the blister was determined for different loading levels by moving an electronic dial indicator along the width of the sample (test fixture 1).

Finite element computations

Buckling load computations

In this part, the problem is considered geometrically linear. The three-dimensionnal multi-layers elements of SAMCEF code were used.

Mesh. and boundary conditions

Several configurations of mesh refinements were analyzed as a part of this study and a systematic convergence of the local buckling load was performed. The described configuration is the elliptic defect one:

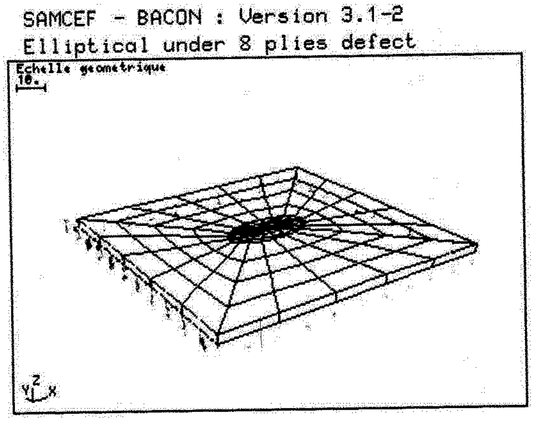


fig 6: Mesh and boundary conditions

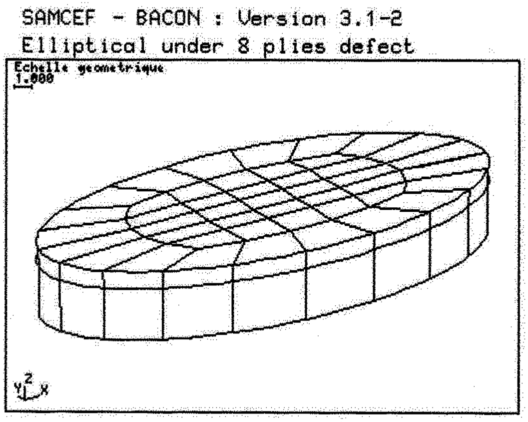
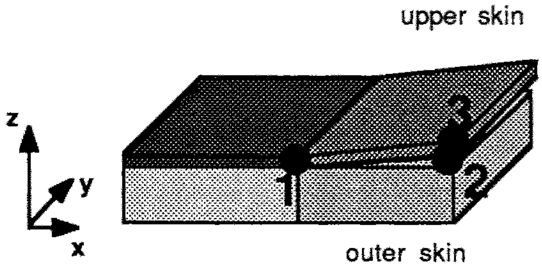


fig 7: Zoom of the defect mesh

Defect modelling

Two three-dimensional multi-layers elements (8 nodes, 60 degrees of freedom) are disposed in the thickness of the sample: one for the upper skin (4 or 8 plies) and the other for the outer skin (28 or 24 plies). Lower nodes of upper element are the same as upper nodes of lower element in the "no defect" region.
Lower nodes are different from upper nodes in the defect region. They have the same co-ordinates but there is no link between the respective degrees of freedom which allow the defect to blister:



■ 4 plies element
▩ 4 plies element
▨ 28 plies element
□ 28 plies element

fig 8: mesh strategy for modelling the defect

<u>Mechanical properties of the unidirectionnal tape</u>

E_{11}= 140000 MPa ν_{12}=0.31
G_{12}= 5700 MPa
E_{22}= 10000 MPa ν_{23}=0.48
G_{13}= 5700 MPa
E_{33}= 10000 MPa ν_{13}=0.31
G_{23}= 3600 MPa

1: fibre direction
2: transverse direction
3: thickness direction

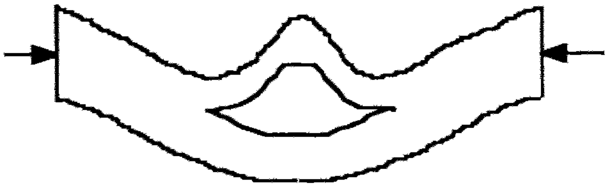
Ply thickness: 125 µm

<u>Computation results</u>

Main results are the following:
- Mode shape is not the same for a defect located under 4 plies and a defect located under 8 plies:

4 plies: local buckling
8 plies: local + overall buckling

4 plies: local buckling



8 plies : local + overall buckling

fig 9: Schematic of the both buckling modes

It explains the higher buckling loads obtained for the type 1 samples.
- The sensitivity of defect versus its shape to blister is the same as experimentally.
- It's always easier for the defect to blister when it is in the 2nd lay-up than when it is in the first one.
This leads comments:
A simple beam analysis says the buckling load of a structure increases with the inertia. For the 4 plies located above defect, the second lay-up gets a 0° ply instead of a 90° ply for the first lay-up. So the inertia of the 4 plies is greater for the second lay-up and it should lead to a greater buckling load for the second lay-up: the opposite is observed; this shows that coupling between compression and bending can not be neglected in such a problem
Otherwise the stiffness of the "under defect" plies seems to be important in the buckling load computation (local boundary conditions of the defect).

<u>Sensitivity to modulus and to ply thickness</u>
Results are the following:

parameter	parameter variation	buckling load variation
E11	1%	0.6%
thickness of a ply	1%	2.9%

Both parameters have a slight effect upon the buckling load.

Parametric study on the insertion level of the defect

The experiments and computations showed a great difference of behaviour between the two locations of the defect.

The numerical method allows a parametric study of this phenomena by modifying ply to ply the location of the defect:

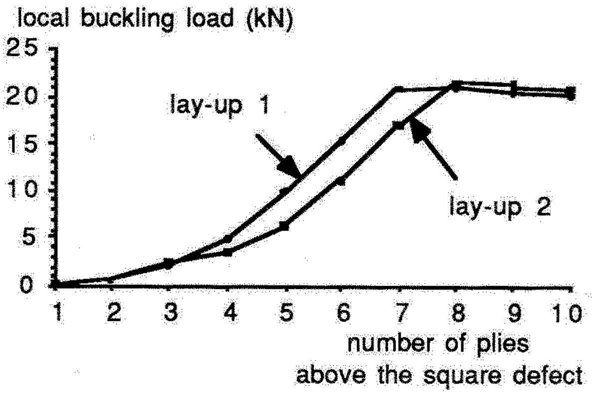


fig 10: Local buckling load versus number of plies above defect

- Up to 7 plies there is only local buckling and the load increases with the number of plies. Beyond 7 plies, overall buckling adds to local buckling for a constant load slightly lower than buckling load of a plate without defect: experimentally only overall buckling will be observed.
- The loads are the same for the both sequences up to 3 plies. Beyond 3 plies and up to 7 plies, loads are different because coupling between compression and bending is different.

Shape of the blister

The objective was to determine by Finite Element computations the shape of the blister in order to make a comparison with the experimental shape. So geometrically non-linear computations were achieved. Results of this study will be described in the following part.

Test and computation results comparison

Local buckling loads

A qualitative comparison of results shows a perfect agreement between tests and computations. In particular:

- Influence of the stacking sequence (fot the same lay-up)

Two different stacking sequences don't have the same compression-bending coupling allowing more or less the local buckling.

- Influence of the shape of the defect with regard to loading.
- Influence of the "in thickness" location of the defect.

Local buckling for a defect under 4 plies, no local buckling for a defect under 8 plies.

- Influence of boundary conditions

All developments achieved (experiments and computations) during this study showed a great sensitivity to boundary conditions.

A quantitative comparison of the local buckling loads for the different configurations revealed a good agreement (figure 11). In particular:

- The evolution of the buckling load when changing the stacking sequence or defect shape is the same between experiments and computations.

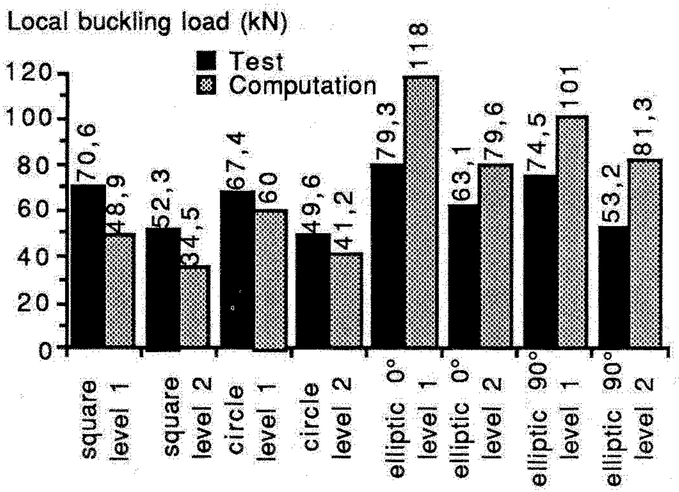


fig 11: Summary of the computed and experimental buckling loads

Shape of the blister

Computed and experimental shape of the blister for square defect (load=73500 N) is showed in figure 12.

This particularly good agreement between the both plotted curves indicate the modelisation validity.

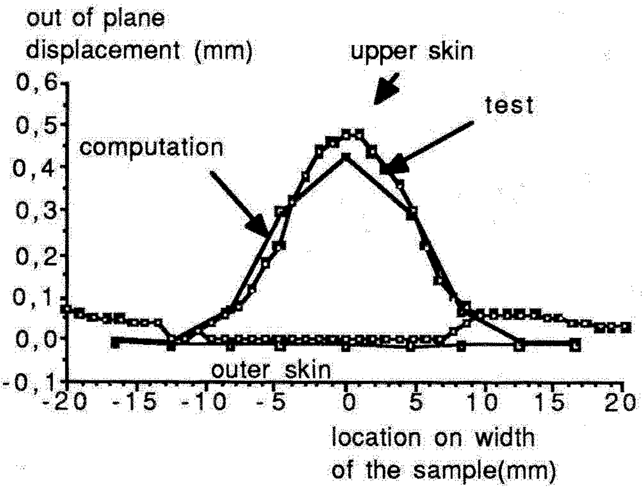


fig 12: Experimental and computed shape of the blister

Conclusions

The objective of this study was to set up a methodology and to provide data allowing a better knowledge of the local buckling phenomena around an embedded delamination.

One carbon-epoxy material and two quasi-isotropic 32 plies were studied:

- $[(0/-45/90/45)_4]_{sym}$
- $[(0/45/0/-45/90/45/90/-45/0/45/90/-45/0/-45/90/45)]_{sym}$.

Four different shapes of defect (circle, square, elliptic oriented 0°, elliptic 90°) and two "in thickness" locations (under 4 and 8 plies) were considered.

Geometrically linear Finite Element computations of buckling load showed a good agreement with experiments: there is no local buckling for defects under 8 plies.

Buckling loads were determined for defects located under 4 plies and the effect of several parameters was studied (stacking sequence, thickness of a ply...).

Geometrically nonlinear Finite Element computations of the shape of blister had been achieved. Comparison with experiments showed a good agreement

In particular this study points out that for realistic delamination size ($S=350\ mm^2$), a surface delamination seems more damageous than an "in thickness" defect because local buckling appears before overall buckling.

Further work is needed to study the post-buckling behaviour of the delamination in order to define a methodology to predict the possible propagation of the delamination.

References

1. Shivakumar, Whitcomb, "Buckling of a Sub-laminate in a Quasi-Isotropic Composite Laminate", J. of Composite Materials, 19, (1985)

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