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Damage Tolerance Characteristics of Composite Sandwich Structures

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SUMMARY

Current damage tolerance requirements impose strict constraints on the design of composite aircraft structures, since the various forms of defects taken into consideration must show 'no-growth' characteristics in the environmental and loading conditions expected in the operative life.

A research activity was carried out by Agusta, in collaboration with the University of Pisa, with the purpose of assessing the damage tolerance characteristics of typical composite sandwich structures used by the helicopter industry. A particular effort was dedicated to the study of delamination growth under compression loading, a basic step for understanding the damage tolerance behaviour of composite structures. The results of the numerical analysis carried out show that G, the Strain Energy Release Rate, is a suitable parameter for describing the behaviour of the delamination, but it is essential to consider its partition according to the fundamental modes.

1. - INTRODUCTION

Sandwich structures have been in the past, and are still at present, widely used in most aircraft and helicopter design, due to their inherently high specific strength and stiffness. This structural configuration is particularly efficient in the range of low load intensities, [1], and the interest for its application has grown since advanced composite materials have become commonly used for the thin skins. A milestone contribution to the understanding of sandwich design was given by Plantema, [2]. Further development has taken place in recent years, particularly as far as manufacturing technology and the delicate problem of fittings is concerned; it is worthwhile mentioning the recent review of design problems carried out by Zenkert, [3].

A sandwich composite structure may show many different failure modes for the skin and the core, which must be taken into account in the design phase: intralaminar and interlaminar matrix failures, fibre failures, global buckling, face wrinkling, shear crimping and core fracture. The problem becomes even more complex, if possible, when a prescribed load capability in the presence of manufacturing defects or impact damage must also be assured, as required by current Airworthiness Regulations, [4]. Usually, compliance with such Requirements is accomplished through the development of the so-called building block approach or pyramid of tests, [5-6]: a very large test program is devised and carried out, with hundreds of tests at coupon level (to produce a consistent data base and to define material allowables, also keeping environmental conditions into account), dozens of tests at element level (to verify the analysis methodology used for the strength evaluation of the different structural elements and to assess the variability of composite materials properties), and, finally, a reduced number of tests at subcomponent or component level. These kinds of tests are carried out not only to verify load paths and design methodologies, as well as static and fatigue strength and stiffness, but also to substantiate the acceptability of the maximum manufacturing discrepancies and the no-growth of the Barely Visible Impact Damage (BVID), whose relevant energy levels are determined in a specific preliminary activity.

The conclusion is that, due to the lack of reliable theoretical tools, the industries are more or less forced, for the design of primary composite structures, to use rather conservative strain allowables, obtained by means of the abovedescribed extensive test campaigns, a very expensive and time-consuming procedure.

The present paper summarizes the main results obtained by Agusta and the Department of Aerospace Engineering of the University of Pisa in a collaboration carried out within the framework of a wide research program, funded by the European Community. The main purpose of the research program was to obtain experimental data about the residual strength and residual fatigue life of damaged (impact and delamination) composite components. Such data is useful not only to assess the damage tolerance behaviour of selected configurations of practical interest, but also to verify the potentialities and capabilities of available analytical tools. Indeed, the results obtained are quite interesting, since they show that the very stringent no-growth requirement of current Airworthiness Regulations [4] can be, in certain circumstances, relaxed.

2. - DESCRIPTION OF THE RESEARCH PROGRAM

The purpose of this research was to increase the understanding of the damage tolerance behaviour of composite sandwich structures, which are inherently very susceptible to impact damage, [7], using experiments and analytical studies,

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with the long term objective of developing reliable analysis methodologies.

Agusta has a wide experience in the field of the certification of composite structures; as an example, the Tail Unit of the EH-101 helicopter is made of a composite skeleton covered by sandwich panels, which were the object of a wide test activity during the certification process. The civil version of this helicopter was certified as a Safe Life structure, including BVID discrepancies, according to FAA AC 20-107A. The approach followed by Agusta in the certification process, described in [8-9], is in accordance with the building block approach or the pyramid of tests, but there was considerable interest in the assessment of damage tolerance capability, both on the part of Agusta/Westland and on that of the Airworthiness Authorities. It seemed therefore reasonable to carry out the major part of the tests of the present research using some specimen configurations which were developed by Agusta within the EH-101 Safe Life certification program, so that the test results could also be evaluated by means of a comparison with other meaningful data.

For this purpose, three different specimen configurations were used, all of them with the same core material but with differences in core thickness and in the lay-up of the skins. For the sake of brevity, in the present paper the panel configurations will be called A, B and C. All the specimens were manufactured by Agusta, using only one batch of material: the honeycomb core was made of Nomex, Euro-Composites ECA 3.2-48 (1/8"-3.0), while the material used for the skins was unidirectional carbon/epoxy Cyanamid 985-GT6-135 or fabric 985-GF3-5H-1000. Fig. 1 shows a drawing of a typical panel. The specimens are representative of parts of the real structure of the EH-101 Tail Unit, and they all have the peculiarity of having different thicknesses and lay-ups for the two skins, i.e. the complete panel is neither symmetrical nor balanced; table I summarizes the different lay-ups for the three configurations (outer and inner refer to the helicopter Tail Unit).

In the present research, attention has been focused on the evaluation of the effect of impact damage and on the assessment of delamination growth, under static and fatigue load conditions. Two types of damage were considered:

(i) impact damage, using different energy levels and impactor diameters, in order to assess the fatigue behaviour in the presence of BVID and Clearly Visible Impact Damage (CVID);

(ii) artificial delamination, introduced during manufacturing by means of a teflon insert at a given interface between the plies (only panels of type A and C).

The impact energy to be utilized was assessed by means of an analysis/evaluation of the frequency and severity of the possible hazards to which the structure was expected to be exposed, both in the production phase and in the operative life.

Impact damage was inflicted on the panels by means of the drop weight procedure. The energy level capable of producing BVID was assessed by means of appropriate susceptibility tests; both painted and unpainted panels were used for this purpose, in order to take into account the worst case of accidental damage during the manufacturing process and in service. BVID was assumed to be the impact damage visible from a distance of 1 meter. All the impacts were inflicted at the centre of each panel, on the thicker skin, since this is the outer skin of the real structure and therefore it is more likely to be accidentally impacted in service. The panel was supported at the edges for closer simulation of the in-service condition.

For a more complete information, some Clearly Visible Impact Damage (CVID) was also introduced; two types of CVID were studied: one obtained by using the same hemispherical impactor but increasing the BVID energy by 50%, the other using a pyramidal impactor, simulating a tool box, with the same BVID energy but obviously introducing CVID.

The second type of defect examined, the teflon insert, has two purposes: first, it is a rough and very simplified modelling of the damage introduced by impact; second, the evaluation of residual strength capability in the presence of delamination is particularly important in order to assess the tolerance of manufacturing defects, since many such defects (porosity, foreign object inclusion, ..) can be considered to be equivalent to a simple delamination.

In conclusion, the experimental activity comprised the following types of tests, classified according to the type of defect:

(a) static and fatigue tests (Constant Amplitude, Compression-Compression, R=5) on impact damaged specimens, using different energy levels and impactor geometry;

(b) static and fatigue tests (as before) on panels with an artificial delamination in the form of a teflon strip, as wide as the whole panel width;

(c) static and fatigue tests (as before) on panels with a circular teflon insert, in the centre of the specimen.

Moreover, tests on Double Cantilever Beam (DCB) and End Notch Flexure (ENF) standard specimens were carried out to assess the threshold and critical values of G, the Strain Energy Release Rate, for modes I and II.

Tab. II shows the different types of panels and defects included in the whole test program. The tests on type C specimens, with teflon inserts, were carried out at Pisa, while all the other tests were performed by Agusta.

3.- EXPERIMENTAL METHODOLOGY

3.1 Test apparatus

Servo-hydraulic actuators were used, of a load capacity of +/- 150 KN, and a stroke of +/- 15 mm. Since the panels were not symmetrical, particular attention had to be paid to the anti-buckling guides, as compression was unavoidably accompanied by bending. Experimental and also numerical analyses were carried out at the Department of Aerospace Engineering of Pisa in order to assess the possible influence of the geometry of the anti-buckling guides on the strain distribution in the panel: two different solutions were studied, one which provided support on the panel edges along a surface (L-shaped guides) and another which used two cylinders, each one constraining a single line of the specimen. The differences were negligible and all the tests done by Agusta were carried out with the L-shaped guides, while in all those carried out at Pisa University the cylindrical guides were used.

3.2 Non Destructive Inspection

After manufacturing, all the sandwich panels were inspected by means of a through-transmission UltraSonic technique in order to assess their integrity and compliance with standard Agusta production quality. After that impact damage was introduced, the extension of damaged area was assessed by means of U.S. inspection; an attenuation greater than 6 dB was assumed as a criterion for identification of damage.

3.3 Test procedure

All the tests were carried out in load control, considered to be representative of the operative conditions. A number of static test specimens were fitted with a particularly high number of strain gauges, in order to provide detailed information about strain distribution. For all the other specimens, two couples of strain gauges, bonded back-to-back, were used: the first couple was positioned in the axial, vertical centreline, at a distance from the top equal to a quarter of the panel height (sufficiently far from the defect), and the other couple was bonded on the horizontal centreline, at a distance from the lateral free edge equal to a quarter of the panel width. The strain measured on the thick skin (the outer one) in this location was conventionally used to assess the stiffness of each panel and to define the fatigue loading. In the case of the teflon strip defect, the other strain gauge location was obviously used.

During the tests on delamination growth, carried out in Pisa on type C panels, the specimens were inspected in situ by means of U.S., using a contact probe and a gel as a couplant. Such an inspection was carried out by means of the pulse-echo technique, setting the instrument in such a way as to reveal the echo of the U.S. wave in its path back to the front skin, passing through the lateral walls of the Nomex cells; therefore, a fairly jagged delamination front was sometimes observed.

In the static tests, the specimen was loaded in steps, and after each step an U.S. inspection took place for the evaluation of delamination growth.

The delamination growth was measured, in the fatigue tests carried out in Pisa, at a prescribed number of cycles, while in all the tests carried out by Agusta, global damage was evaluated by continuously measuring the residual stiffness, by means of a LVDT, fixed to bonded brackets on the thick side.

In some cases, the end shortening and the maximum out-of-plane displacement under a given applied load were also measured, in order to obtain useful information for the calibration of the numerical models.

4. - TEST RESULTS

4.1 Fatigue behaviour of damaged specimens

Three different types of panels were used, as described above, to which different types of damage were introduced. The relevant S-N curves, based on about 20 tests each, in RTD conditions, are shown in figs. 2, where the maximum cyclic strain applied is divided by a reference strain value derived in compression static tests on integer specimens. For all the types of specimen, about 10 further specimens were tested in RTW (84% R.H.), after ageing up to saturation at 70° C and 84% R.H., in order to confirm the curve shape and to derive the knockdown factor due to humidity alone.

Fig. 2a concerns type A specimens, all tested by Agusta, and shows a relatively flat curve. For further investigation, specimens with a teflon disk insert (30 mm diam.) in the thick skin were also tested. The static strength of the BVID specimens and that of the teflon insert panels are quite similar, while the CVID specimens show a reduction both in the static strength, as could be expected, and in the fatigue strength. The results of the RTW tests, not reported, show a negligible environmental effect.

Fig. 2b shows the results of type B specimens, again all tested by Agusta; this time, with a greater thickness of the impacted skin, the CVID fatigue results are in the scatter band of the BVID specimens, while the reduction of the static strength is still considerable. In this case, too, the effect of the environmental conditioning (not reported) is quite small.

It is particularly interesting to observe the type C panel results, shown in fig. 2c, since they refer to a wider set of defects. As far as impact damage is concerned, the severity of the damage proved to have a large influence on static strength, giving evidence of the well-known notch sensitivity of composite materials. As far as the fatigue strength is concerned, even if few CVID results are available, the same observation made for the B specimens can be confirmed; it should be kept in mind that A specimens had the thinnest skin, about half of B and C configurations. The second type of defect, the teflon insert, allows us also to assess the effect of a weak bonding at the interface between skin and core, which proves to be the most detrimental from the fatigue point of view, while static strength is not affected to the same extent.

The fatigue results of impact damaged specimens fall in the middle of the two types of artificially delaminated panels; the average measurement of the damaged area for BVID panels was about 1200 mm^2, that is about twice the area of the 30 mm diam. disk, but also about five times less than the strip defect area.

In figs. 2 the test results, relevant to BVID panels, are fitted by a four parameter non-linear curve shape of the type:

$$S = S_l + A * (N+C)^{-B}$$

where S_l is the endurance limit (conventionally assumed to be at 10^9 cycles), N is the number of fatigue cycles and A, B, and C are parameters determined by fitting the test data.

4.2 Observations about delamination growth

In the static and fatigue tests carried out in Pisa on type C panels, information was also collected concerning delamination growth. The teflon insert was placed between the fifth and the sixth ply from the outside of the thick skin, thereby obtaining an outer sub-laminate $[0_2, +45, -45, +45]_T$ and leaving an inner sub-laminate $[0_3]_T$ in contact with the core.

An example of the evolution of the strip defect in a static test is shown in fig. 3, where the different positions of the delamination front over the panel width are shown for different loads. Similarly, a stable subcritical growth is also observed for the teflon disk specimens, which was much smaller in dimension and with a pronounced tendency towards preferential directions, i.e. a non homothetic growth. An example is shown in fig. 4. In both cases, out-of-plane displacement of the delaminated plies and panel end shortening were measured, in order to obtain useful data to calibrate the numerical models.

In fatigue tests, delamination grows to a much larger extent than in static tests, and the trend concerning the shape that emerged from the static tests finds a much clearer confirmation. Typical examples of the delamination growth at different number of cycles are shown in fig. 5 for the teflon strip specimens and in fig. 6 for the teflon disk specimen: in the last case, there is clearly an evolution towards a stable configuration of the delamination, a sort of butterfly shape.

Another interesting observation concerns the considerable influence of the occurrence of buckling on fatigue delamination growth: when buckling does not occur, the growth is negligible. At the very beginning of the series of tests on circular insert panels, a large scatter was observed in terms of applied strain versus life, with short lives associated with occurrence of buckling and long lives with no buckling occurrence, with a faint correlation with the applied cyclic strain level. Similar experimental observations were found in the literature [10-12] and attributed to a sort of vacuum effect, due to the autoclave procedure: in other words, the two sublaminates tried to separate but were restrained from doing so by the presence of a pressure differential, a vacuum, which was a function of the manufacturing quality (the presence of porosity reduces this effect). The problem was solved by drilling a small hole, 0.3 mm in diameter, in the outer sublaminate, in the centre of the teflon disk: the subsequent test results became quite consistent and correlated with strain level.

5. - ANALYSIS OF DELAMINATION GROWTH

If the delamination growth data from the teflon strip specimens are analysed in terms of growth rate vs. delamination length, a relatively "strange" result is obtained: the rate decreases with the dimension of the delamination, over most of the range examined. Fig. 7 shows a collection of such data, for the teflon strip specimen: the trend is quite clear. This behaviour is in contrast with the common experience, since usually, with the sole exception of a few specially designed specimens, under a constant load range applied, an increase in the crack (or defect) dimension is associated with a corresponding increase in the driving force and consequently also in the growth rate.

If the data concerning the circular insert are analysed, a similar, but more complex, situation is observed; as an example, fig. 8 shows what happens on the preferential directions of growth, shown in fig. 6.

These experimental results are quite useful, since they provide the opportunity to evaluate also from a quantitative point of view the models that have been proposed in the literature for the prediction of delamination growth; recent excellent reviews can be found in [13-14].

The use of the Strain Energy Release Rate, G, as the parameter capable of describing interlaminar fracture behaviour in composites, is receiving growing credit by the scientific community. In the present research a Finite Element analysis was carried out, using MSC/NASTRAN, to evaluate the capability of the approach. The problem is quite complex, due to the geometrical non-linearity, associated with the occurrence of buckling, and therefore requires long computing times. In the initial phases of the research, a complete model of the panel was used, adequately refined to obtain the required accuracy in the area of the delaminated plies. The load was introduced by means of a constant displacement on the loaded ends. No initial geometrical imperfection was introduced in the model. Sandwich skins and honeycomb were modelled by solid elements, which have produced better results, i.e. closer to the test results, in comparison with the use of shell elements for the skins. But the limits due to the very high number of degrees of freedom (d.o.f.) required have forced us to abandon the model of the complete panel, and to use a "superelement" (or global-local) approach, i.e. the use of a sub-model of the central region, described with a high number of d.o.f. (one element per layer). A preliminary analysis is carried out on a relatively coarse mesh of the complete structure, for the purpose of evaluating the displacements at the boundary nodes of the superelement; then a second analysis is carried out on the sub-model alone, under such displacements, which were applied in incremental steps. This approach has many advantages:

(a) a more refined mesh is used only for the area involved in the delamination, which requires a detailed description;

(b) the "shear locking" effect, i.e. a fictitious super-shear-stiffness, is reduced.

It must be borne in mind that it is very important to obtain an accurate description of the displacement field, since the evaluation of the contributions to G deriving from the different modes (opening, in-plane shear, out-of-plane shear) is greatly dependent on the out-of-plane displacement of the buckled sublaminate; in particular, the contribution of mode I, which is particularly important for delamination growth, is very sensitive to such a quantity. With the "superelement" approach it is possible to obtain out-of-plane displacement of the buckled sublaminate comparable with the test results.

Once the displacement and strain fields are evaluated, G is computed on the delamination front according to the virtual crack extension technique, [15], which proceeds according to the following steps. From the FEM analysis, by means of an integration routine on the stresses, the nodal forces are evaluated along the delamination boundary. The Multi Point Constraint element of NASTRAN is used for modelling the boundary; the nodes of these elements are then relaxed, thus simulating a growth of Δa. The FEM analysis is then repeated on this configuration, and again the nodal forces and displacements are computed. In this way, with an appropriate release of the various MPC rows along the delamination front, it is possible to evaluate G for any propagation shape. Since the forces along the front before the release are available, together with the nodal displacements after the release, the contributions to G according to the different fundamental modes can be easily evaluated along the delamination front. An 'ad hoc' program has been written in C++ language for carrying out automatically, and in an easy and reliable way, the numerical computations for mode I, II and III contributions. In order to simulate the delamination growth, it was considered appropriate to release the nodes along the crack front all together, because otherwise, when relaxing the nodes one by one, the values of the forces and displacements obtained were so small as to be of the order of numerical errors. Fig. 9a shows the distribution of G_I and G_{II} values in the 2-D specimen, for an applied load corresponding to an experimentally observed arrest of delamination growth. The contribution of G_{III} will not be shown, since it proved to be very small and negligible in comparison with those of the other two modes. If the analysis is repeated for different delamination lengths, a rather rapid decrease in mode I component is observed, while the mode II component increases. This effect explains why the delamination growth rate decreases, since a different mode partition of the total G occurs: the opening mode contribution, which is decreasing, is fundamental for the growth, since it is characterized by a lower resistance, i.e. a smaller threshold value, in comparison with the contribution of mode II. Fig. 9b shows how the points, that describe the overall severity of the solicitation on the delamination front, change their position in the G_I - G_{II} plane, moving towards the stable area as the delamination length increases.

In the case of the circular insert specimen, fig. 10 shows the distribution of G_I along the circular delamination front, obtained from the results of the analysis; it is qualitatively consistent with the directions of maximum growth.

These results confirm that the total value of the Strain Energy Release Rate alone is not a particularly meaningful parameter, but that it is very important to consider its contributions according to mode I and II; similar conclusions can be found in [16] and [17]. An important consequence is that a given delamination, subjected to fatigue loading, may evolve to a final dimension and shape that is a stable configuration; in other words, the applied load produces, along the delamination front, couples of contributions mode I/mode II to G that are globally below the mixed mode threshold for propagation. If this happens, composite structures can show interesting damage tolerance characteristics, at least when the defect is a simple delamination. Further research is therefore required, particularly to assess the delamination behaviour in realistic mixed mode conditions, both for what concerns the growth under fatigue loading and the fracture under static load conditions. There is an increasing interest in developing Mixed Mode test specimens and procedures, in order to fully characterize the resistance of a material to interlaminar fracture, considering also interaction between the two fundamental modes. In this respect, the Mixed Mode Bending test, developed by NASA [18-19], is the one that receives most credit, among others, by the composite community. The same authors have also proposed an interactive failure criterion for mixed-mode delamination, [20].

Within the framework of the present research, Agusta carried out Fracture Mechanics tests on DCB and ENF coupons, assessing the critical and threshold G values (for a stress ratio of 0.1) for pure mode I and pure mode II conditions: figs. 11 show the results. It is interesting to compare these values with the results of a very complex numerical analysis, carried out to evaluate the G distribution along the delamination contour of a "butterfly" stable delamination. Such results are shown in fig. 12, where it is observed that the contributions show preferential directions, where they are larger, i.e. the preferred directions of growth. But it is interesting to note that the numerically assessed peaks are just lower than the threshold values reported in figs. 11, particularly for mode I; slight differences in the R ratio (0.1 in the coupon tests and 5, symmetric to 0.2, in the sandwich panels) in this context can be neglected.

The results shown are quite interesting: the numerical approach is complex, non linear, needs to be calibrated with some experimental results, but can offer a powerful tool for evaluating the potential growth of delaminations under compression loading, both of a static and of a fatigue nature.

Another significant observation is related to the test methodology for defining threshold G values; two possibilities exist: to determine the "propagation arrest" or the "no onset of propagation" condition. The latter is usually preferred, since it is closer to the current damage tolerance design requirement, and, besides, testing is simpler and the fibre bridging problem is not meaningful, even if more specimens are required, while the "propagation arrest" procedure requires particular care, in the same way as a load shedding technique does, since the previous load history may influence the result. On the contrary, on the basis of the remarks made above, the "propagation arrest" technique seems to be preferable.

One last remark: in the full scale test of the EH-101 Tail Unit certain artificial delaminations showed a small growth, followed by an arrest. This behaviour was initially attributed to the resolution of the NDI method, but the foregoing considerations provide a more sound explanation.

6. - SUMMARY AND CONCLUSIONS

The results of the present research allow us to draw the following conclusions:

(a) impact damage remains by far the most dangerous type of defect for advanced composite materials; the type of damage associated with an impact is very complex and deleterious, since multiple delaminations are activated, in synergetic action with matrix intralaminar cracking and fibre failure;

(b) however, even if simple delamination is not so crucial for structural integrity, the understanding of the mechanisms that govern its growth, as well as the development of models for its analysis, is a significant step towards the solution of many important problems; just to quote one of the most meaningful, it is possible to give an appropriate answer, on a rational basis, to the definition of the maximum allowable defect that can be tolerated in the manufacturing process. There are important safety and economical concerns behind this question;

(c) the current approach, based on the test pyramid, is very time-consuming and expensive; if progresses in understanding the fracture behaviour of composites can reduce the experimental effort, significant economic advantages can be obtained, without reducing safety levels;

(d) a further effort is required to simplify the analythical effort and also in order to examine other load cases, such as the presence of shear stresses.

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Panel type	Core thick. (mm)	Outer skin	Inner skin
A	12.7	$(0/90)_f$, +45, -45, +45	$(0/90)_f$, -45, +45
B	9.5	0_2, +45, -45, +45, $((-45/+45)_f)_2$	-45, +45, -45, +45
C	12.7	0_5, +45, -45, +45	-45, +45, -45, +45

Table I – Lay-ups of the different panel configurations (f= fabric). The layers are listed from H/C towards the external.

Panel type	Defect
A	BVID, 15 J, impactor 20 mm CVID, 23 J, impactor 20 mm teflon disk, 30 mm diam., in the skin
B	BVID, 25 J, impactor 20 mm CVID, 38 J, impactor 20 mm CVID, 25 J, pyramidal impactor
C	BVID, 15 J, impactor 25 mm CVID, 23 J, impactor 25 mm CVID, 15 J, pyramidal impactor teflon strip, 30 mm wide teflon disk, 30 mm diam., in the skin teflon disk, 30 mm diam., at H/C-skin interface

Table II - Damage introduced in the various types of panel.