THIRTEENTH EUROPEAN ROTORCRAFT FORUM

11.2

Paper No. 26

EH101: LIGHTNING PROTECTION OF COMPOSITE MATERIALS: RESULTS OF PRELIMINARY TESTS ON CFC PANELS

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September 8-11, 1987
ARLES, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

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ABSTRACT

In the development of the EH101 helicopter a complete lightning protection policy has been foreseen. As far as direct effects of lightning are concerned a set of tests on CFC panels with various kind of protection systems have been performed at CESI on behalf of Agusta. The aim of these tests was to compare the performances of the various kinds of protection layers when applied either to solid CFC panels or to honeycomb panels.
Due to the preliminary nature of the tests only the current component A of those foreseen by MIL-1757 has been applied. Furthermore tests were performed on various kinds of joints to verify the behaviour of the jointing system.
In this paper, after a general survey on lightning effects, the results of some of the above mentioned tests will be presented.

1 INTRODUCTION

The EH101 rotorcraft has been designed with a large amount of advanced composite materials (CFC) used in critical structural parts. These materials are particularly exposed to the effects of the lightning. In fact, advanced composite materials are likely to be struck by the lightning as the metallic alloy, but, having a resistivity three orders of magnitude larger /1/, present a reduced current carrying capability and a reduced shielding effectiveness.
As a consequence of the low current carrying capability, structural damages, like resin pyrolisis, delamination and puncture of skins are to be expected from a lightning attachment to unprotected CFC: these effects are commonly referred to as direct effects of lightning current.

As a consequence of the low shielding effectiveness the lightning current can induce voltages on cables and equipments, resulting in permanent damages to electric and electronic apparata, or in temporary upset of on board computers: these second effects of the lightning are generally referred to as indirect effects.
Protection against the above mentioned effects can be achieved by means of

- laying on the outermost play of the laminate a metallic or metallized coating (particularly effective against direct effects but also effective in reduction of indirect effects);

- designing the paths of cables in such a way to minimize the impact of lightning magnetic field

- using filters and overvoltage protection devices to reduce the effects of lightning induced transients on electric apparata.

Structural joints between CFC parts or between CFC and alloy parts are other sources of direct and indirect effects caused by the lightning. In fact a structural joint involving CFC give rise to a high lumped resistance that can cause eccessive heating, sparks which can lead, in worst cases, to debonding of the joint; as far as indirect effects are concerned, a joint causes an increase of the voltage, resistively coupled with signal and feeder cables. In this case it is the design of the joint that plays a major role in limiting direct and indirect effects of the lightning.

From the above considerations it derives that the problem of reduction in lightning flight hazard must be considered deeply also during the design phase; a suitable test activity is then particularly useful to verify the behaviour of the adopted protective solutions.
In the case of EH101 project, a complete lightning protection policy has been implemented, to define the best protection system and to indicate the various test activities to be carried out for the assessment of the behaviour of the various adopted solutions /2/.

This paper refers to two of the research activities foreseen in the above mentioned lightning protection policy. Namely, this research, concerning direct effects of lightning, has been performed on several CFC panels with the following aims:

-1st. activity: analysis of the lightning current impact on CFC panels protected with conductive coating;
-2nd. activity: analysis of the behaviour of jointed panels when conducting the lightning current.

In the following the tests carried out are described and some of the relevant results presented.

2 CURRENT WAVEFORM AND TEST SET UP

The test carried out are called lightning physical damage tests. They consist in applying a current pulse, simulating the lightning current, to the sample. When the effects of the arc impact on the laminate are to be studied, the lightning arc attached to the aircraft must be simulated; in the case of structural joints analysis, only current conduction is simulated. The sample must withstand the thermal and electrodynamic stresses without large damages.
In principle the testing current must represent the current of a severe lightning stroke.
The current waveshape suggested by the Standards /3,4/ is shown in fig. 1.
This current consists of four components, namely:

-A component: simulating the first lightning return stroke;
-B component: simulating the intermediate phase of lightning
-C component: simulating the continuing current phase of lightning
-D component: simulating a restrike

The Standards accept for the A component a damped oscillating wave, the other components must be unidirectional.

When the values of peak current, transferred charge, duration and action integral (i^2dt), adopted by the Standards and listed in fig. 1 are used, an event is simulated having a probability to be exceeded in criticity of about 0.5% for a negative polarity lightning and 5% for a positive polarity one /5,6/. The relatively high probability to have a positive lightning more severe than that simulated in the tests must be corrected at the light of the low probability to have positive lightnings, which are about 10% of the total number of lightnings /5,6/.

Particular attention must be paid to the parameter called action integral. The action integral is the energy dissipated per unit resistence and plays the major role in determinig the threshold of damage in composite materials, because the damage of CFC laminate is mainly connected to the thermal stress /7/.

For this reason and taking into account the research task, it has been decided to apply to the test panels only a waveshape having the same time dependency as the A component with four levels of peak current and action integral, namely:

-level 1: I_p=50 kA$\pm$20% $i^2dt=0.12X10^6$ $A^2s\pm40\%$
-level 2: I_p=100 kA$\pm$20% $i^2dt=0.48X10^6$ $A^2s\pm40\%$
-level 3: I_p=150 kA$\pm$20% $i^2dt=1.1X10^6$ $A^2s\pm40\%$
-level 4: I_p=200 kA$\pm$10% $i^2dt=1.9X10^6$ $A^2s\pm20\%$

The test circuit adopted to generate the described current wave is shown in fig. 2. Each test panel was fixed on a support as shown in fig. 3a, 3b. Fig 3a shows the panel test fixture during the arc impact tests: in this case the current, generated by the capacitor bank, was fed to the test panels through an arc about 1 cm long. Fig. 3b shows the panels fixture during testing of structural joints: in this case the current was fed to the sample with a conductor connected to the upper blocking bar; the current flow was perpendicular to the jointing line. In each case the lower blocking bar was connected to the return circuit through the measuring shunt. A typical oscillogram recorded during the tests in shown in fig. 4.

3 ANALYSIS OF THE LIGHTNING CURRENT IMPACT ON CFC LAMINATE PROTECTED WITH CONDUCTIVE COATINGS

3.1 PROTECTION COATINGS SELECTED AND ADOPTED TEST SAMPLES

Three protection coatings have been selected, namely:

-flame sprayed aluminum coating 150 um thick
-aluminized fabric (Thorstrand TEF 7)
-nickel coated fabric

The flame sprayed aluminum has been applied after polimerization of the laminate. The aluminized and nickel coated fabrics have been cocured with the laminate.
The test samples prepared for this test activity were of two types

-sandwich panels made with CFC laminate-Nomex honeycomb-CFC laminate
-solid CFC laminates with different layups

The layups of the various groups of test samples and relevant dimensions are given in Table I.
About half of the panels were unpainted and half were treated with primer and normal aircraft paint, to permit a comparison between behaviour of painted and unpainted protected surfaces .

3.2 TEST RESULTS

As an example, the test results referring to sandwich panels are shown in fig. 5.
In the figure the extension of the damage to the protection layers, to the external laminate (the laminate to which the arc has been applied), to the honeycomb and to the internal laminate are shown for the various protection layer and current levels . The extension of damages is expressed as dimension of an equivalent circular damaged surface having an area equal to the actual one.

From the figure it can be deduced what follows:

-for the unpainted panels all the adopted protection layers assure the absence of puncture of the laminate. Furthermore only in the case of nickel coated fabric a delamination has been detected in external laminate, but its extension does not exceed 80 cm^2, in the worst case.

The damage to protection layers, never exceeding an area of 320 cm^2, consists in burning of the flame sprayed aluminum layer, burning of the resin layer which cover the aluminized fabric, or strap of the nickel fabric.

-for the painted samples a dramatic decrease in protective effectiveness is shown. Infact, the area of damage to the protection layers is reduced or unchanged but the deepness of the damage is largely increased by the presence of the paint. In particular panels protected with flame sprayed aluminum are not punctured up to the third test current level, but a delamination involving two or three layers and having an area of about 320 cm^2 has been recorded. At the highest current level the puncture has been recorded of both internal and external laminates, with a damage to the honeycomb extending for an area of about 300 cm^2. Fig. 6 shows the effects of a 200 kA pulse: puncture of the sample, delamination and tufting of the laminates, burning of the honeycomb.

Panels protected with aluminized fabric are punctured at the second test level. Fig. 7 shows the effects of a 105 kA pulse.

External laminate of the panels protected with nickel coated fabrics is punctured at the first current level. At the second current level the panel is completely punctured. The further increase of the test current causes only an increase in the area of the damage to the honeycomb. Fig. 8a, 8b show the effect of a 53 kA and of a 186 kA pulse.

Results concerning the solid CFC laminates confirm this trend.

Some particular aspects about the solid CFC laminate test results must be noted.

In the case of unpainted samples protected with flame sprayed aluminum a delamination involving the first layer and having an area of about 3-4 cm^2 has been recorded.

In some cases it has been noted that, after the test, the last layer of the laminate is cut in one or two points without any sign of burning. This damage may be caused by the flexural stress due to jet forces of the arc and hence depends on the flexural stiffness of the sample and is thus influenced by the test fixture.
Tests carried out on unprotected unidirectional laminates resulted in puncture of the samples at the first current level. In this case, due to the unidirectionality of the lamination, the puncture consists in a slit oriented in the direction of the lamination. In this case the figure of equivalend damage diameter does not hold, and the criticity of the damage largely depends on the structural role of the part in the rotorcraft.

4 ANALYSIS OF THE BEHAVIOUR OF JOINTED PANELS WHEN CONDUCTING THE LIGHTNING CURRENT

4.1 TESTED JOINTS AND SAMPLES

Three types of joints have been considered, namely

-rivetted joint between CFC laminate and aluminium sheet: the joint is clamped by 10 Ø=4 mm blind rivets made of stainless steel.
-rivetted joint between CFC laminate and aluminium sheet: the joint is clamped by 10 Ø=4 mm blind rivets made of titanium.
-glued joints beetween two CFC laminates.

The jointed parts are overlapped for 30 mm. In Table II the layups of the panels and their dimensions are presented.
The rivetted panels are protected either with aluminized fabric or nickel coated fabric.
The panels with glued joint are protected with aluminized fabric; the joint is also covered with flame sprayed aluminum for a length of 60 mm or 80 mm or 100 mm as indicated in fig. 9.
The metallized fabrics have been cocured with the laminate, the flame sprayed aluminum has been applied after polimerization.
Also in this case half of the samples were painted and half of the samples were unpainted.

4.2 TEST RESULTS

In these tests the second and fourth test current levels have been applied to the samples. In the case of rivetted joints these levels correspond to a current density of 10 kA$\pm$20% and 20 kA$\pm$10% per number of rivets and to an action integral density of 4.8×10^3 $A^2s\pm40\%$ and 19.2×10^3 $A^2s\pm20\%$ per square number of rivets. In the case of glued joints these levels correspond to a current density of 1.1 kA/cm$^2\pm$20% and 2.2 kA/cm$^2\pm$10% and to an action integral density of 60 $A^2/cm^4\pm40\%$ and 240 A^2/cm^4 $\pm20\%$; the above defined densities are referred to the area and square area of overlapping.
From the tests results it can be deduced that:

-For the rivetted joints the maximum damage to the laminate consists in a local delamination of the first layer in a very narrow zone around each head of the rivets with local tufting. This damages is larger in case of painted panels. The typical damage to the protection layer consists in cut of the fabric between the rivets, this damage is larger in the case of nickel coated protection layer. In fig. 10 an example of damage to this type of joint is given.
-For the glued joints the flame spraying aluminum is partially removed by the second test level current and totally removed by the fourth test level current. At the fourth test level a light damage to the protection layer has been recorded. No difference in damage types and extension can be correlated to the dimension of the flame sprayed zone.
-In all the tested joints the fourth level of test current causes sparks at the joint. In glued panels, in some cases, these sparks cause a local burning to the last layer of the laminate.
-In all the cases no signs of reduction in the structural strength of the joint has been recorded.

Some checks have been made by applying an arc directly to the rivets. The results of these checks indicate that the rivets can resist to the stresses associated to the arc impact up to the fourth test level.

5 FUTURE TESTS

Tests like those described must be considered a part of a large experimental activity. The research carried out is a starting point; completion of the research needs:

-testing of other protection layers like metallic meshes, or semiconductive paints;
-testing of various samples with the complete current waveshape suggested by the Standards. This implies the use of particular generation circuits;
-testing of full-scale samples of part of rotorcraft

At the light of this needs Agusta and CESI are planning other research activities in this field, not necessarily devoted to EH101 project. In particular other tests will be carried out, according to Standards, in CESI laboratories with the generation circuit shown in fig. 11, on other protective coatings and part of rotorcrafts.

6 CONCLUSIONS

Physical damage tests have been carried out to verify the behaviour of different protection layers and different jointing technologies. The results indicate that:

-To protect unpainted laminate against the effects of the lightning arc all the tested protection systems can be considered satisfactory, unfortunately only painted surfaces are in use in aircraft manufactoring. In this last case puncture of the laminates are to be expected, at least with the tested protections, in case of a severe lightning strike.

Flame sprayed aluminum seems to perform better than metallized fabrics at least when the first lightning strike is simulated. This performance may be explained with the higher strength of metallized cloth with respect to flame sprayed aluminum, that gives rise to narrower damage areas, consequently the lightning energy is concentrated in a narrower zone.

-The tested jointing technologies perform satisfactorly when conducting the first return strike current, as far as absence of reduction in mechanical strength is concerned. The presence of sparks at the joint must be considered if flame ignition hazard or noise to electronic equipment must be avoided.

The tests have pointed out other particular aspects, namely:

-expecially when testing unidirectional laminates the criticity of recorded damages must be considered at the light of the utilization of the material in a given strucural part of the aircraft;

-test fixture influences to some extent the damage due to its influence on the flexural strength. This fact means that the same laminates can have different behaviours depending on its location in a complexe structural part.

Future tests foreseen on other protection layers and complete parts of rotorcrafts will give information on the behaviour of protection and joints, when applied to complexe structural assembly and when tested with the complete waveshape foreseen by the Standards.

At the end of the complete lightning test activity all the information required to define a lightning protection system will be available.

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TABLE I

ARC IMPACT TESTS: LAYUP AND DIMENSIONS OF PANELS

Panel types	Protection	Layups	Material	Dimensions [mm]
Sandwich: CFC-Honeycomb-CFC	Flame sprayed aluminum	L0	Flame sprayed aluminum	750X750
		L1 [-45/+45]	GR/EP 199-45-001	
		P2 0	GR/EP 199-45-001	
		P3 0	GR/EP 199-45-001	
		P4 0	GR/EP 199-45-001	
		P5 0	GR/EP 199-45-001	
		Honeycomb	Nomex	750X750X10
		P1 0	GR/EP 199-45-001	750X750
		L2 [-45/+45]	GR/EP 199-45-001	
Sandwich: CFC-Honeycomb-CFC	TEF 7	L0	TEF 7-F155	750X750
		L1 [+45/-45]	GR/EP 199-45-001	
		P2 0	GR/EP 199-45-001	
		P3 0	GR/EP 199-45-001	
		P4 0	GR/EP 199-45-001	
		P5 0	GR/EP 199-45-001	
		Honeycomb	Nomex	750X750X10
		P1 0	GR/EP 199-45-001	750X750
		L2 [-45/+45]	GR/EP 199-45-001	
Sandwich: CFC-Honeycomb-CFC	Nickel coated fabric	L0	Nickel coated fabric	750X750
		L1 [+45/-45]	GR/EP 199-45-001	
		P2 0	GR/EP 199-45-001	
		P3 0	GR/EP 199-45-001	
		P4 0	GR/EP 199-45-001	
		P5 0	GR/EP 199-45-001	
		Honeycomb	Nomex	750X750X10
		P1 0	GR/EP 199-45-001	750X750
		L2 [-45/+45]	GR/EP 199-45-001	
Solid CFC laminate	Not protected	P1÷P10 0	GR/EP 199-45-001	300X570
Solid CFC laminate	Flame sprayed aluminum	L0	Flame sprayed aluminum	300X570
		L1 [-45/+45]	GR/EP 199-45-001	
		L2 [-45/+45]	KV/EP 199-46-001	
		P3 0	GR/EP 199-45-001	
		P4 90	GR/EP 199-45-001	
		P5 0	GR/EP 199-45-001	
		L6 [-45/+45]	KV/EP 199-46-001	
		L7 [-45/+45	GR/EP 199-45-001	
Solid CF C laminate	TEF 7	L0	TEF 7-F155	300X570
		L1 [-45/+45]	GR/EP 199-45-001	
		L2 [-45/+45]	KV/EP 199-46-001	
		P3 0	GR/EP 199-45-001	
		P4 90	GR/EP 199-45-001	
		P5 0	GR/EP 199-45-001	
		L6 [-45/+45]	KV/EP 199-46-001	
		L7 [-45/+45]	GR/EP 199-45-001	
Solid CFC laminate	Nickel coated fabric	L0	Nickel coated fabric	300X570
		L1 [-45/+45]	GR/EP 199-45-001	
		L2 [-45/+45]	KV/EP 199-46-001	
		P3 0	GR/EP 199-45-001	
		P4 90	GR/EP 199-45-001	
		P5 0	GR/EP 199-45-001	
		L6 [-45/+45]	KV/EP 199-46-001	
		L7 [-45/+45]	GR/EP 199-45-001	

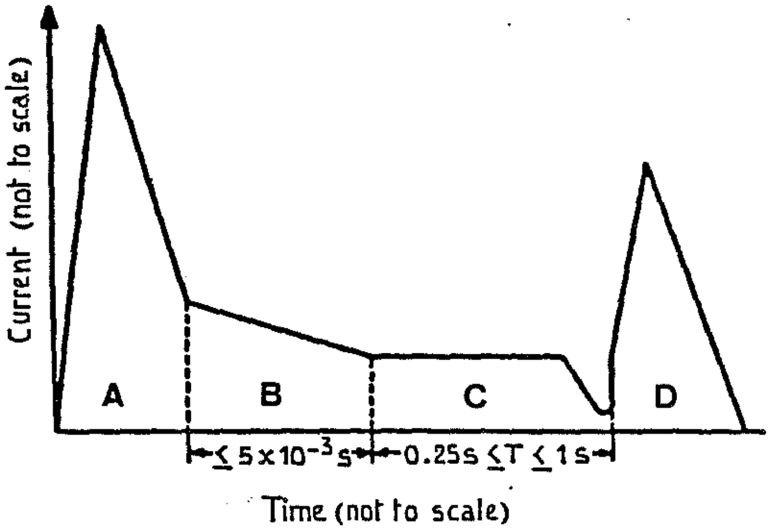
The 0° lamination direction is parallel to the direction of flow of the test current

TABLE II

JOINT ANALYSIS TESTS: LAYUP, JOINTING TECHNOLOGY AND DIMENSIONS OF THE LAMINATES

Joint technology	Jointed materials	Laminate layup	Material	Protection	Dimensions
10 titanium blind rivets	CFC/aluminium	L0 L1 [-45/+45] L2 [-45/+45] P3 0 P4 90 P5 0 L6 [-45/+45] L7 [-45+45]	Nickel coated fabric GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001 GR/EP 199-45-001 GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001	Nickel coated fabric	300X750
10 stainless steel blind rivets	CFC/aluminium	L0 L1 [-45/+45] L2 [-45/+45] P3 0 P4 90 P5 0 L6 [-45/+45] L7 [-45+45]	Nickel coated fabric GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001 GR/EP 199-45-001 GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001	Nickel coated fabric	300X750
10 stainless steel blind rivets	CFC/aluminium	L0 L1 [-45/+45] L2 [-45/+45] P3 0 P4 90 P5 0 L6 [-45/+45] L7 [-45+45]	TEF 7 GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001 GR/EP 199-45-001 GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001	TEF 7	300X750
Glued joint	CFC/CFC	L0 L1 [-45/+45] L2 [-45/+45] P3 0 P4 90 P5 0 L6 [-45/+45] L7 [-45+45]	TEF 7 GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001 GR/EP 199-45-001 GR/EP 199-45-001 KV/EP 199-46-001 GR/EP 199-45-001	TEF 7 + flame sprayed aluminum on joints extending for 60, 80, 100 mm	300X750

The 0° lamination direction is parallel to the direction of flow of the test current



CURRENT COMPONENT A
(Initial Stroke)
Peak Amplitude = 200 kA+10%
Action Integral = $2 \times 10^6 A^2$ s $\pm$ 20%
Time Duration $\leq$ 500 s

CURRENT COMPONENT B
(Intermediate Current)
Maximum Charge Transfer = 10 Coulombs
Average Amplitude = 2 kA $\pm$ 10%

CURRENT COMPONENT C
(Continuing Current)
Charge Transfer = 200 Coulombs $\pm$ 20%
Amplitude = 200 ÷ 800 A

CURRENT COMPONENT D
(Restrike)
Peak Amplitude = 100 kA+10%
Action Integral = $0.25 \times 10^6 A^2$ s $\pm$ 20%
Time Duration $\leq$ 500 s

Fig. 1. Physical damage tests. Current waveshape recommended by the Standards.

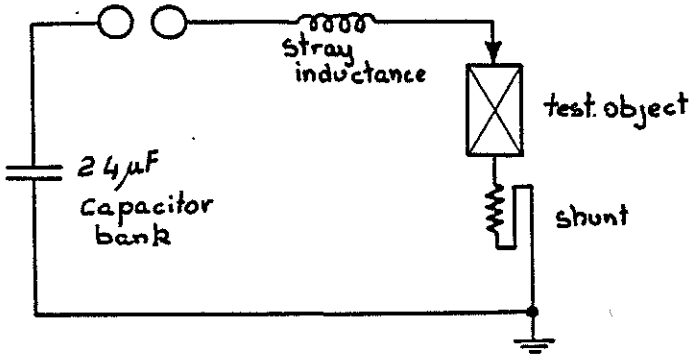


Fig. 2. Test circuit adopted for the tests on laminate CFC panels.

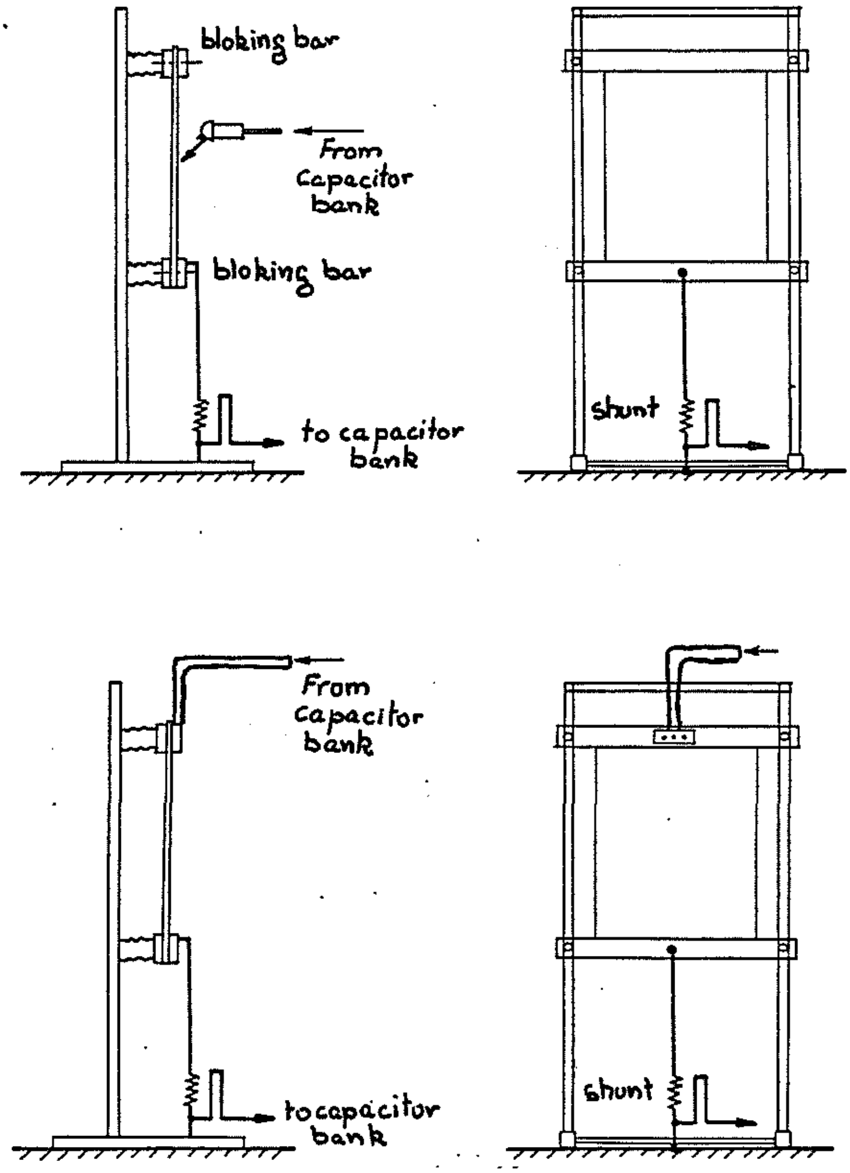


Fig. 3. Test fixture used in laminate CFC tests

a) test fixture used in arc impact tests

b) test fixture used in jointed panel tests

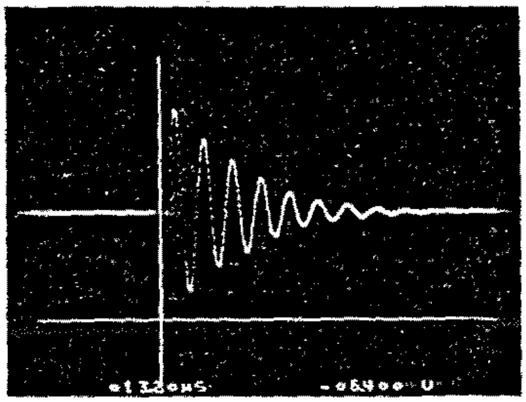
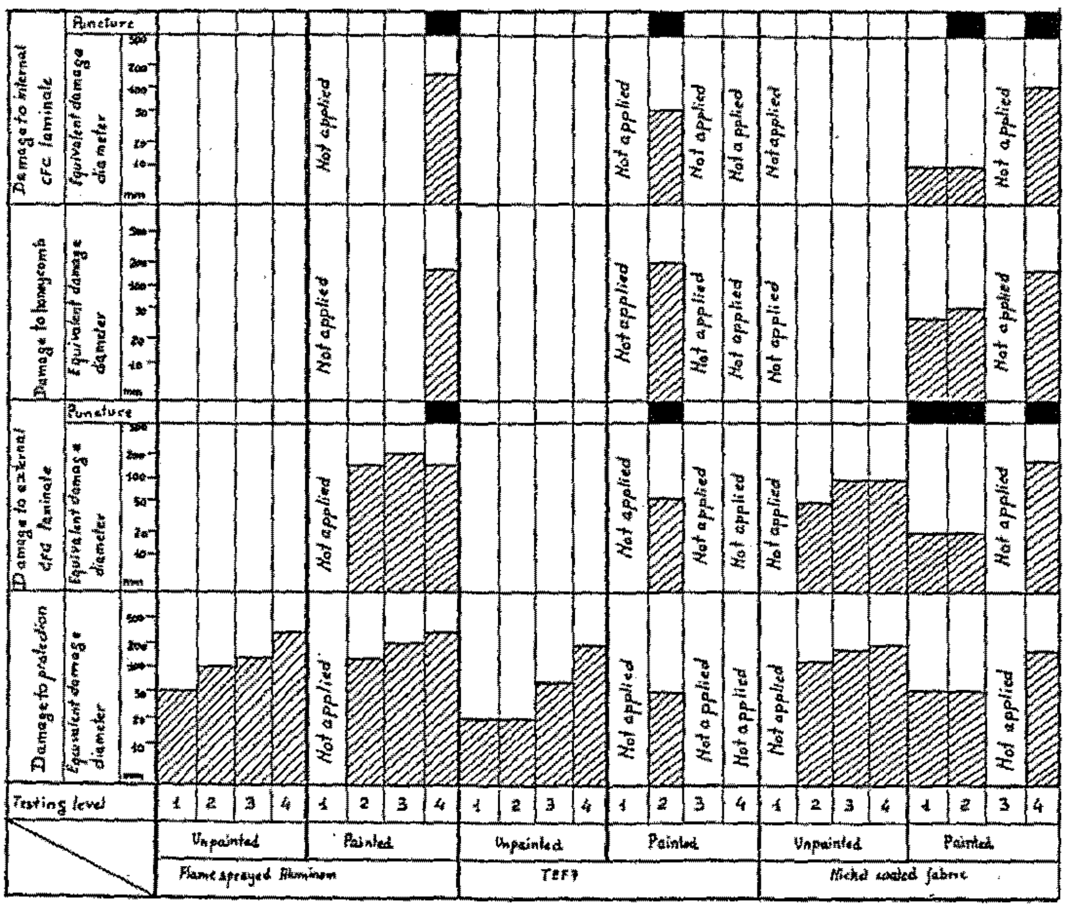


Fig. 4. Typical current oscillogram recorded during physical damage tests.



Testing levels	Parameters I_p [kA]	$\int i^2 dt$ [$10^6 A^2 s$]
1	50±20%	0.12±40%
2	100±20%	0.48±40%
3	150±20%	1.4±40%
4	200±40%	1.52±20%

Fig. 5. Results of arc impact tests on sandwich laminates.
Equivalent damage diameter: diameter of a circulare damage having the same area of the actual damage.

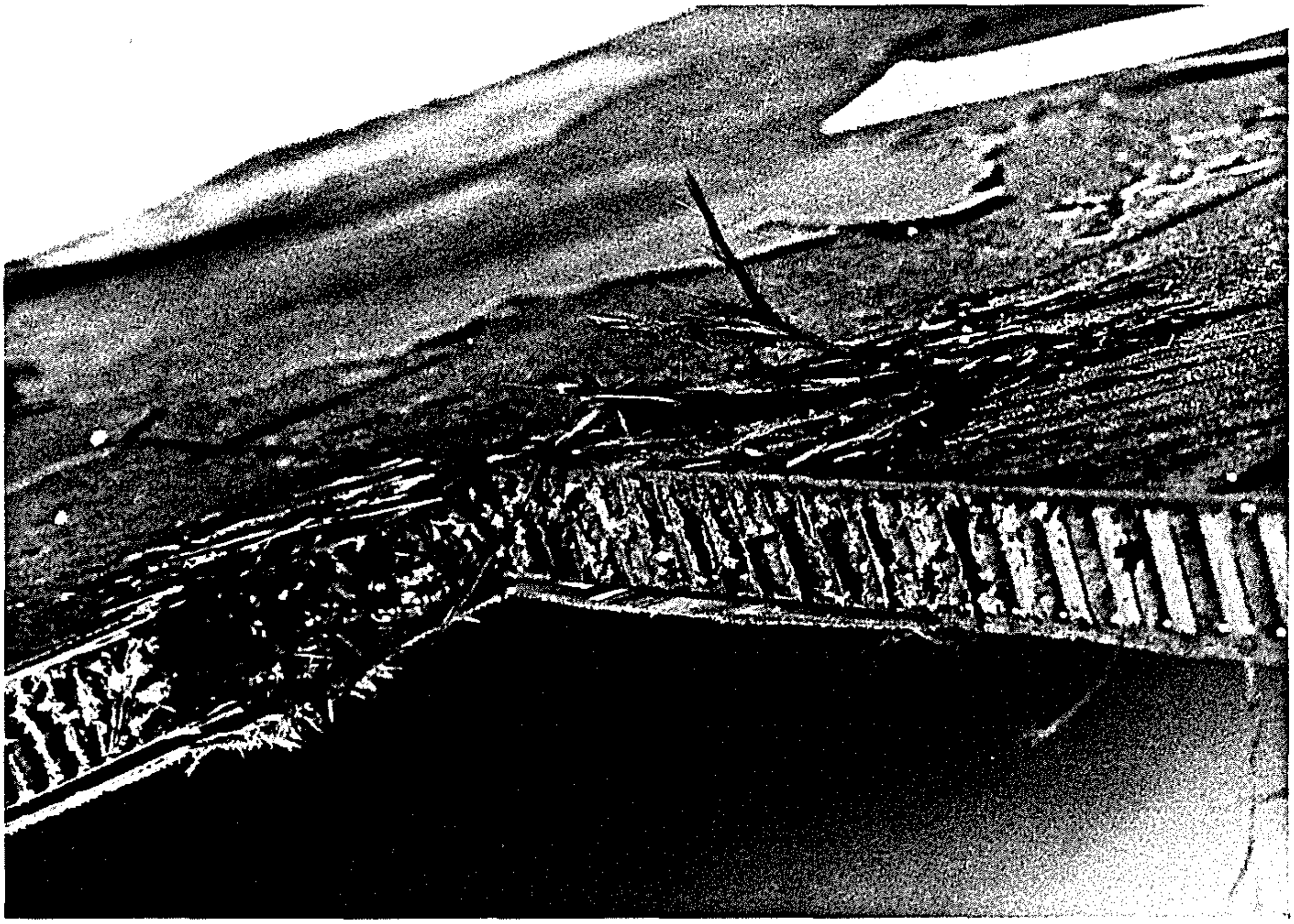


Fig. 6. Arc impact tests. Damage caused by a 200 kA strike to a painted sandwich panel protected with flame sprayed aluminum.

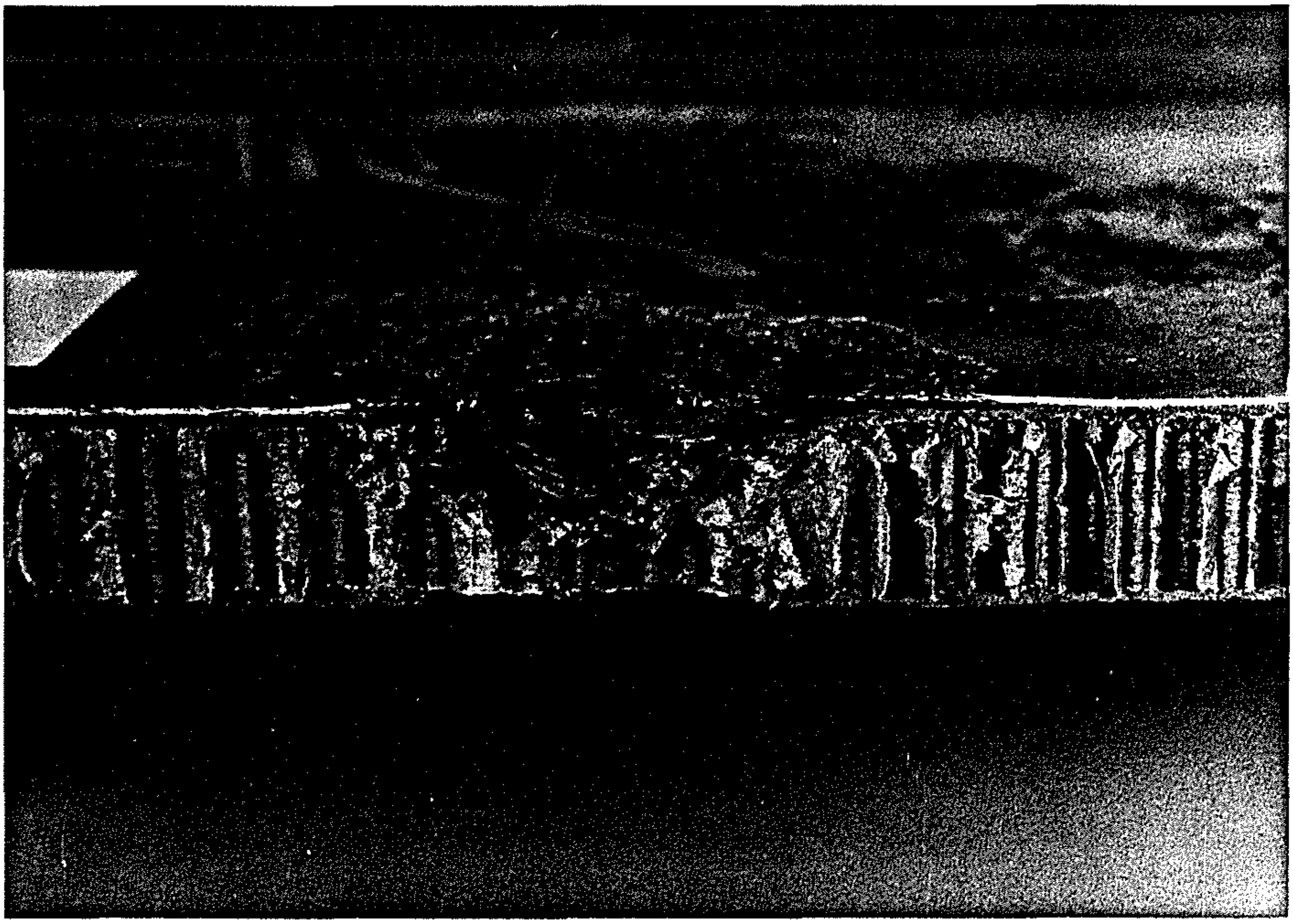


Fig. 7. Arc impact tests. Damage caused by a 105 kA strike to a painted sandwich panel protected with TEF 7.

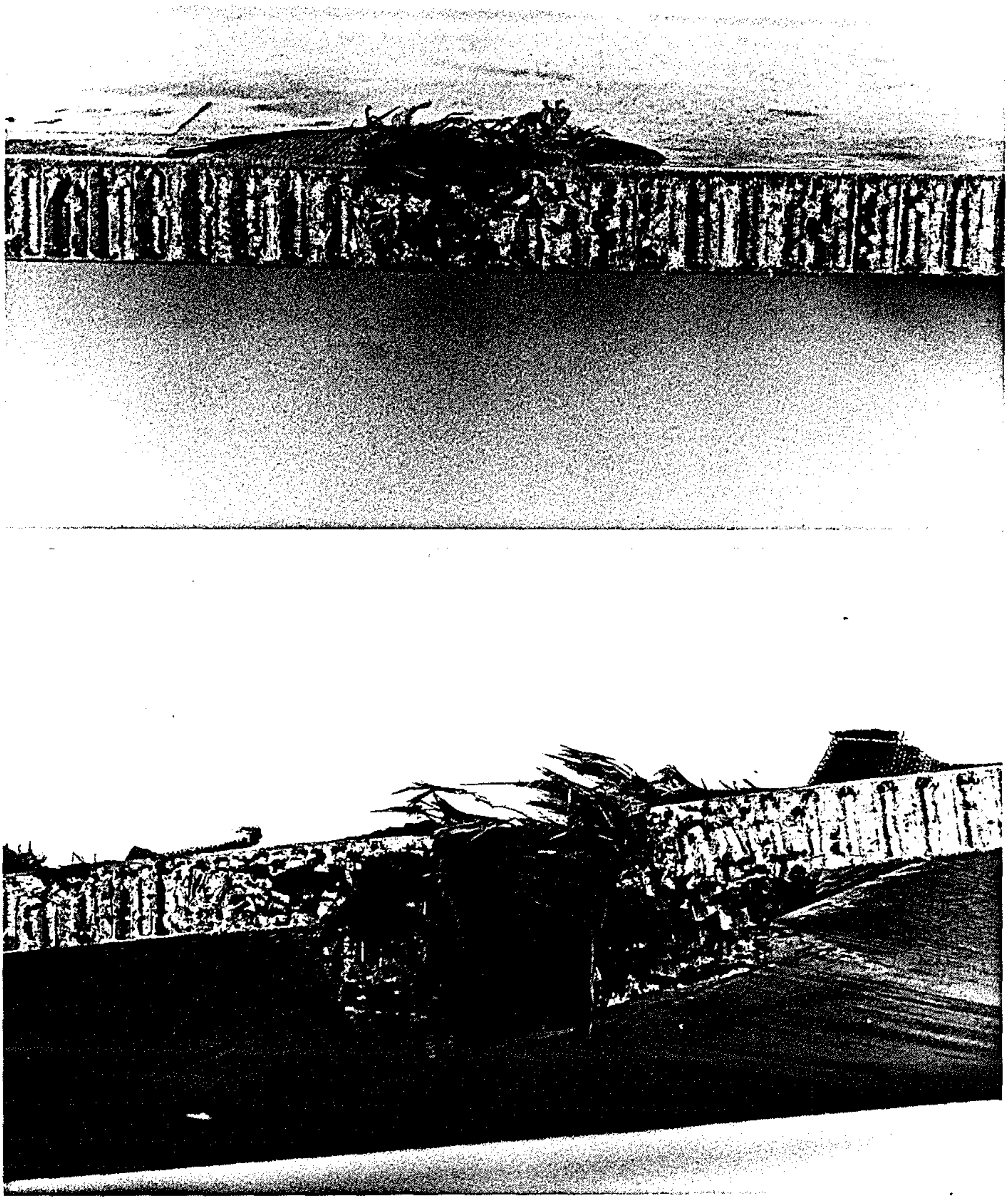


Fig. 8. Arc impact tests. Damage caused by a 53 kA (a) and by a 186 kA (b) strike to a painted sandwich panel protected with nickel coated fabric.

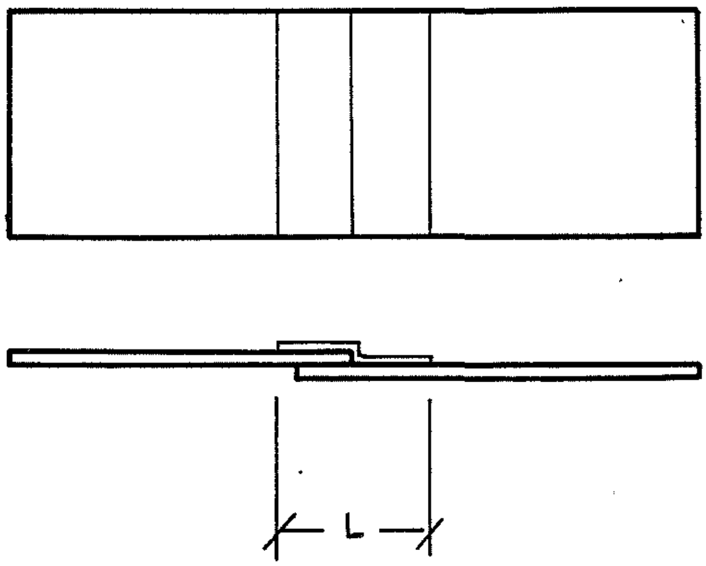


Fig. 9. Detail of the flame sprayed aluminum on the joint of the glued panels.
L=extension of the flame sprayed zone: L=60, 80, 100 mm.

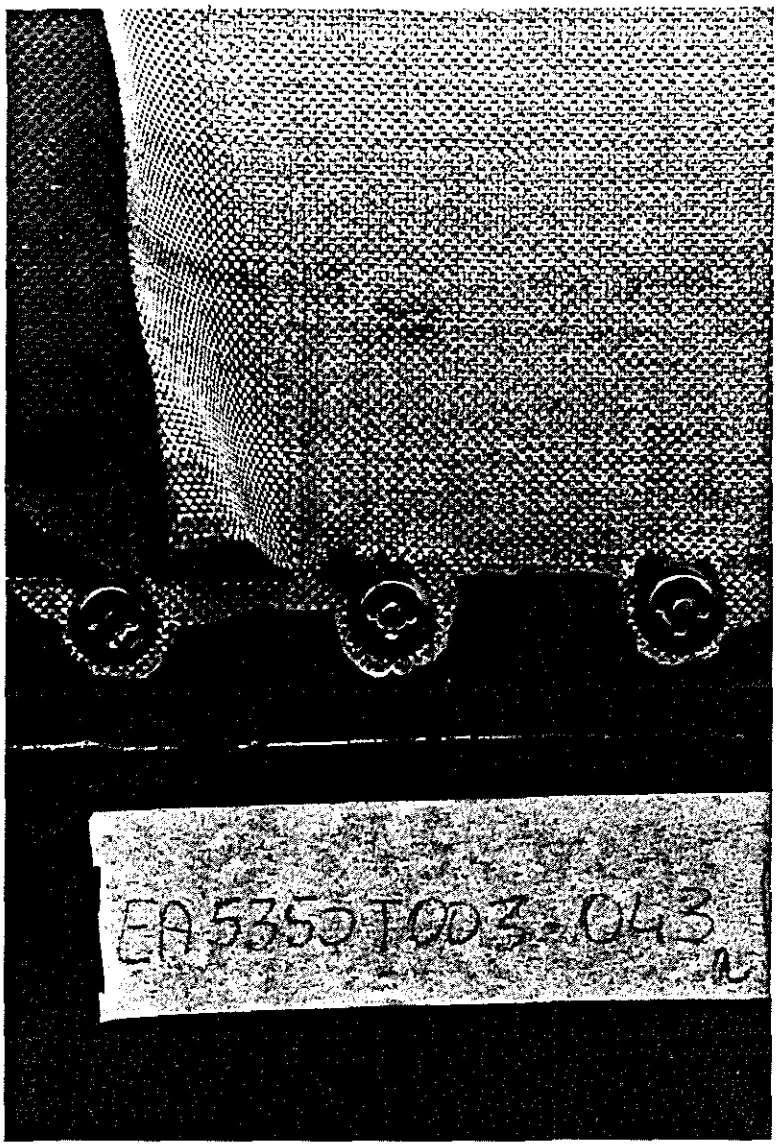


Fig.10. Joint analysis tests. Damage caused by the conduction of a 200 kA strike to a painted jointed panel protected with nickel coated fabric and jointed to a aluminium sheet with ten titanium blind rivets. The paint has been removed by the current.

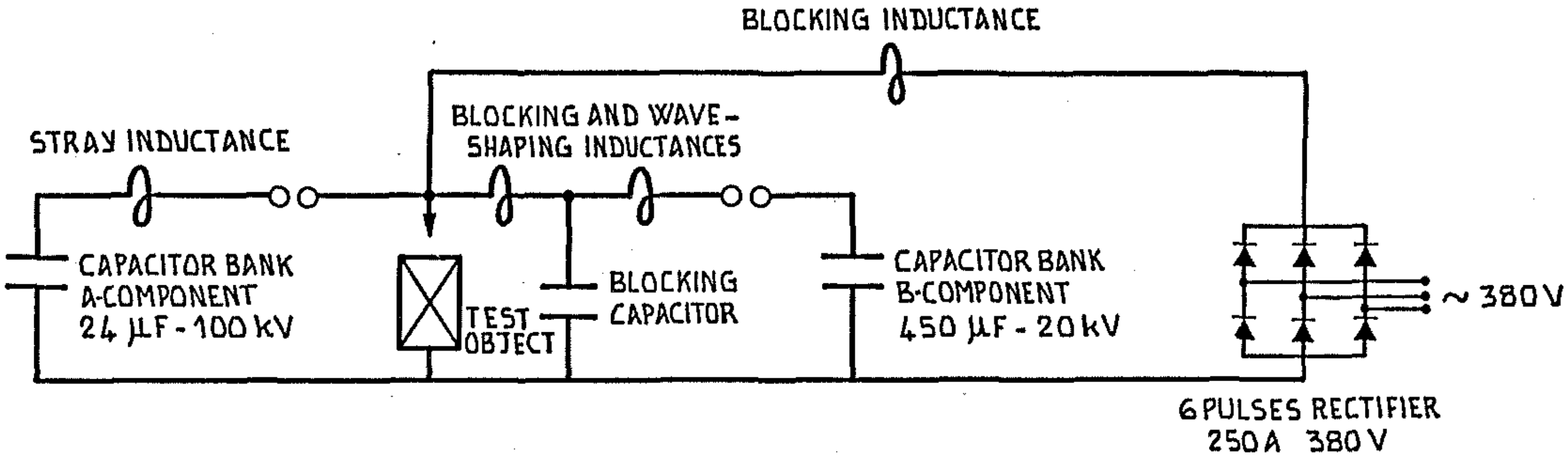


Fig.11. CESI test facility adopted for generation of the current waveshape suggested by the Standards.