COMPOSITE STRUCTURES REPAIR

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ABSTRACT

This paper concerns itself with the repair of composite materials on modern aircraft with particular emphasis on repair techniques and equipment for field use. The high strength to weight ratio of composites make them ideal to meet the demand for increasing the performance of military aircraft. However, with the increasing use of composite materials, a need has been created for unique repair methods. To meet the need to simultaneously apply pressure and a uniform temperature to the patch, a composite repair console and integral vacuum/heater blanket was developed by Grumman.

I. INTRODUCTION

Composite structures are made of a number of fiber and epoxy resin matrix laminates. These laminates can number from two to greater than 50 and are generally bonded to a sub-structure such as aluminum or non-metallic honeycomb. The laminates are manufactured in the form of rolls of epoxy pre-impregnated sheet. The sheets are layed up with alternating matrix directions and heat cured under pressure to form the final skin.

The high strength to weight ratio of composite materials offers advantages for aircraft applications, which include reductions in weight and fuel conservation. In addition, these structures can readily be manufactured to conform to complex shapes. However, these materials are highly susceptible to impact damage and the extent of the damage is difficult to determine visually. This has introduced the need for improved inspection and unique repair techniques.

The composites presently being used on military and commercial aircraft include boron/epoxy, graphite/epoxy, fiberglass/epoxy and kevlar/epoxy. Because of the higher price of boron/epoxy composites compared to the current generation of graphite/epoxy composites, the trend is toward minimal use of boron/epoxy. The costs comparison is about $200/lb for boron/epoxy pre-impregnated materials to tens of dollars per pound for graphite/epoxy prepregs. Aerospace materials manufacturers are developing a variety of new or improved reinforcement fibers for use in the next generation of composite materials.(1) These include large diameter boron fibers, boron fibers on carbon filaments, boron fibers coated with boron carbide, silicone carbide fibers, aromatic polyamide fibers, high modulus carbon fibers and aluminum oxide fibers. Table 1 presents a list of applications of composite structures on some of todays aircraft.

Table 1 Typical Applications of Composite Structures

AIRCRAFT	COMPOSITE APPLICATION	
F-14	BORON	HORIZONTAL STABILIZER
	FIBERGLASS	RADOME AND VENTRAL FINS
F-15	BORON	HORIZONTAL AND VERTICAL STABILIZERS
F-18	GRAPHITE	WINGS, HORIZONTAL AND VERTICAL STABILIZERS AND ACCESS DOORS
AV8B	GRAPHITE	WINGS, HORIZONTAL STABILIZER, OVERWING FAIRING, FORWARD FUSELAGE AND CONTROL SURFACES
VIGGEN	GRAPHITE	VERTICAL STABILIZER
LAMPS HELICOPTER	KEVLAR	GEAR BOX, TRANSMISSION PYLON, DRIVE SHAFT AND NOSE COVER
	GRAPHITE	ROTOR BLADE TRAILING EDGE
L-1011	KEVLAR	INTERIOR AND SECONDARY STRUCTURE EXTERIOR PARTS
SPACE SHUTTLE	GRAPHITE	WING SUBSTRUCTURE
757 AND 767	GRAPHITE	NOSE GEAR DOORS, ENGINE NACELLES AND CONTROL SURFACES
	KEVLAR	LOWER WING PANELS
	KEVLAR/GRAPHITE	MAIN LANDING GEAR DOORS AND OVERWING FAIRING

II. DAMAGE ASSESSMENT

The use of composite materials on aircraft has introduced additional requirements for inspection and quality assurance.

Damage to composite materials can be external or internal. External damage includes scratches, dents, edge crushing, punctures, gouges and skin cracks. Internal damage is quite typically in the form of delaminations, crushed core, voids, or corrosion due to ingested moisture.(2)

In most cases, external mechanically caused damage is evident from visual inspection. However, it is often desirable to define the damage area more closely to determine the repair size and procedure required. Non-destructive inspection techniques are effective in detecting internal damage and the extent of external damage.

Table 2 presents a summary of the non-destructive inspection techniques commonly used in the field. It should be noted that the allowable repairs for field operations are quite limited. This will be discussed further in Section III. We must also be aware that post patch non-destructive inspection is required to insure that the patch is free of voids. We have found that approximately 30% of the patches applied to F-14 stabilizers contain voids and must be partially or fully redone. Voids are not a design problem and are not unique to titanium/adhesive patches. They are a characteristic of adhesive bonds.

III. REPAIR TECHNIQUES

Repairs to composite materials are intended to restore the strength of the part to at least 100% of its original strength. Because of this and the fact that these materials are frequently used on highly

Table 2 Nondestructive Inspection Techniques

METHODS	APPLICATION	ADVANTAGE	DISADVANTAGE
VISUAL INSPECTION	DETECTION OF SURFACE DEFECTS OR STRUCTURAL DAMAGE IN ALL MATERIALS	SIMPLE TO USE IN AREAS WHERE OTHER METHODS ARE IMPRACTICAL; OPTICAL AIDS ENHANCE THIS METHOD	RELIABILITY DEPENDS UPON ABILITY AND EXPERIENCE OF INSPECTOR. ACCESSIBILITY IS REQUIRED FOR DIRECT VISIBILITY OR BORESCOPE.
ULTRASONIC INSPECTION	DETECTION OF SURFACE AND SUBSURFACE DEFECTS, CRACKS, LACK OF BOND, LAMINAR FLAWS, AND THICKNESS GAGING IN MOST METALS, BY PULSE ECHO TECHNIQUES	FAST, DEPENDABLE, HIGHLY SENSITIVE AND ACCURATE, EASY TO OPERATE; RESULTS IMMEDIATELY KNOWN; PORTABLE	TRAINED INSPECTOR IS REQUIRED. CRACK PLANE ORIENTATION MUST BE KNOWN TO SELECT WAVE MODE TO BE USED. TEST STANDARDS ARE REQUIRED TO ESTABLISH INSTRUMENT SENSITIVITY.
RADIOGRAPHIC INSPECTION	DETECTION OF INTERNAL DEFECTS SUCH AS CRACKS, CORROSION, INCLUSION, AND THICKNESS VARIATIONS	ELIMINATES MANY DISASSEMBLY REQUIREMENTS, HIGH SENSITIVITY, PROVIDES PERMANENT RECORD ON FILM	METHOD PRESENTS RADIATION HAZARD AND REQUIRES TRAINED INSPECTOR. FILM-PROCESSING EQUIPMENT IS REQUIRED. CRACK PLANE MUST BE NEARLY PARALLEL TO X-RAY BEAM, TO BE DETECTED. NOT VERY SENSITIVE TO TIGHT FATIGUE CRACKS. ELECTRICAL SOURCE IS REQUIRED. SPECIAL EQUIPMENT IS REQUIRED, TO POSITION X-RAY TUBE AND FILM.
THERMAL TECHNIQUES (TURCO BOND CHECK)	DETECTION OF SURFACE AND SUBSURFACE DEFECTS SUCH AS DELAMINATIONS, VOIDS, CRACKS, AND LACK OF BOND	SIMPLE IN PRINCIPLE; EASY, PORTABLE, FAST, SENSITIVE METHOD; AND RESULTS EASY TO INTERPRET	TRAINED INSPECTOR AND ELECTRICAL SOURCE ARE REQUIRED. UNIFORM HEAT IS REQUIRED. PART MUST BE CLEANED BEFORE AND AFTER INSPECTION.
ACOUSTIC IMPACT INSPECTION (TAP TEST)	DETECTION OF SUBSURFACE DEFECTS SUCH AS DELAMINATIONS AND VOIDS	SIMPLE TO USE; FAST, PORTABLE	RELIABILITY DEPENDS UPON ABILITY AND EXPERIENCE OF INSPECTOR.

stressed sections of the aircraft, the allowable size of field repairs is often limited.

Patches can be applied in the form of surface, stepped, or scarf. (See Fig 1). Stepped and scarf patches have the advantage of providing a smoother surface than surface patches. However, because of the difficulty in machining the aircraft part for these patches, surface patches are most commonly used. The repair material itself may consist of a number of epoxy preimpregnated layers of the parent material, or alternate layers of adhesive and metallic sheet stock. Table 3 and Figures 2 and 3 present the data required to determine the size and number of layers required for each zone on the F-14 stabilizer. As can be seen in Figure 2, the F-14 Boron Epoxy Stabilizer patches are surface type and consist of 1 layer of adhesive, 2 layers of preimpregnated fiberglass and a number of alternating layers of adhesive and titanium. The number of layers required was determined by stress analysis and testing to restore the strength of the part to 100% of the original. The adhesives used in these patches require a uniform temperature of 350°F and a pressure of 10 psi minimum for proper curing.

Frequently when repairing a composite surface, there is also a need to repair damaged core material. This is done by cutting out the damaged core and replacing it using a potting compound, or if the damage is small using just a potting compound.

IV. REPAIR MATERIALS

Tables 4 and 5 list the materials required for repair of the F-14 Boron Epoxy Stabilizer and their storage requirements. In addition to the patch materials, there are a number of cloth layers required for separation, breathing, and bleeding of the adhesive resins. Figure 4 shows a typical boron epoxy patch layup.

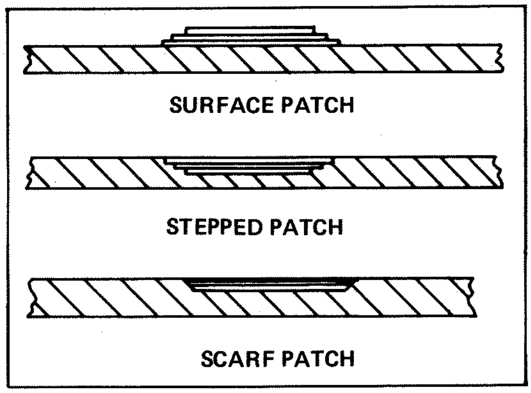

Fig. 1 Patch Types

The limitation of shelf life and the requirement for refrigerated storage for these comsumables presents a serious problem to shipboard repair shops. To help alleviate this problem, Grumman supplies a consumable kit, which provides enough material to effect one maximum size patch or a few smaller patches.

A concept that is presently under investigation is to provide precured patches that would then be applied with one layer of adhesive. This type of patch would greatly reduce repair time and eliminate the problem of voids in patches by allowing inspection of patches prior to application. The disadvantage of precured patches is reduced flexibility.

Table 3 Titanium and Fiberglass Layer Sizes[3]

REPAIR ZONE	TITANIUM LAYER DIAMETER (INCHES)									FIBERGLASS LAYER DIAMETER	
	2.0	2.8	3.6	4.4	5.2	6.0	6.8	7.6	8.4	D_{F1} (INCHES)	D_{F2} (INCHES)
1	*	*								3.6	4.4
2		*	*	*						5.2	6.0
3		*	*	*	*					6.0	6.8
4		*	*	*	*	*				6.8	7.6
5		*	*	*	*	*	*			7.6	8.4
6		*	*	*						5.2	6.0
7				*	*	*	*			7.6	8.4
8				*	*	*	*	*		8.4	9.2
9		*	*	*	*	*	*	*		8.4	9.2
10		*	*	*	*	*	*	*	*	9.2	10.0

NOTE

ASTERISKS (*) INDICATE SIZES OF TITANIUM LAYERS NEEDED TO FABRICATE REPAIR PATCH FOR EACH REPAIR ZONE.

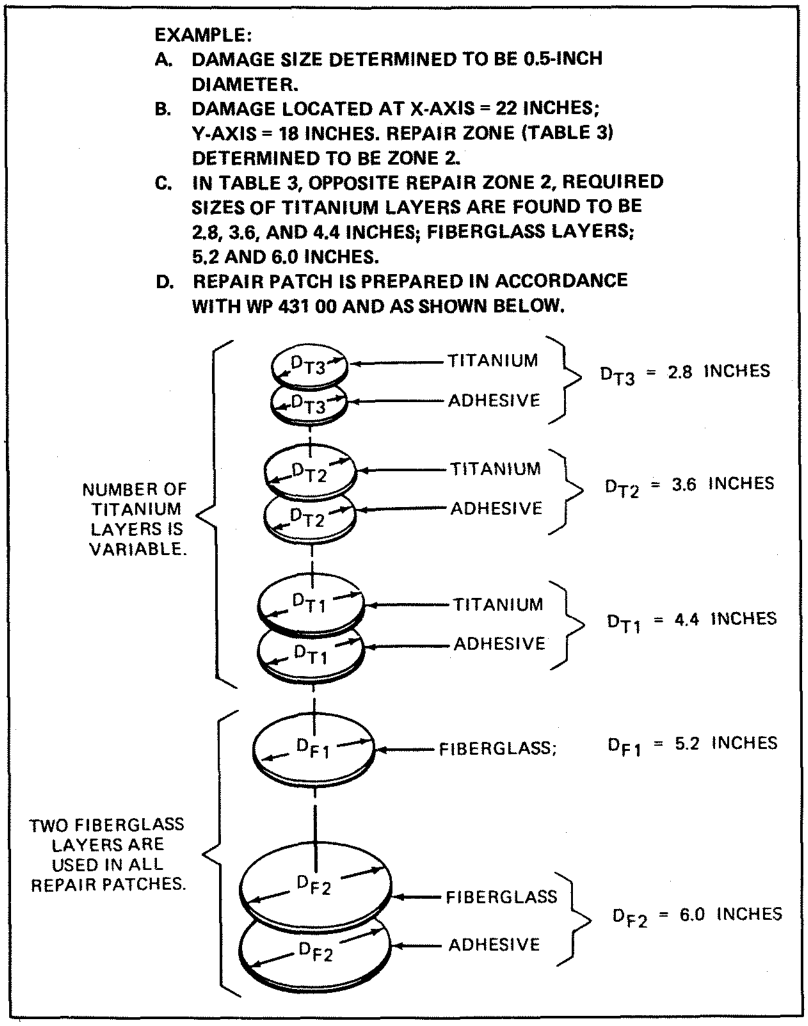

Fig. 2 Typical Repair Patch Development (3)

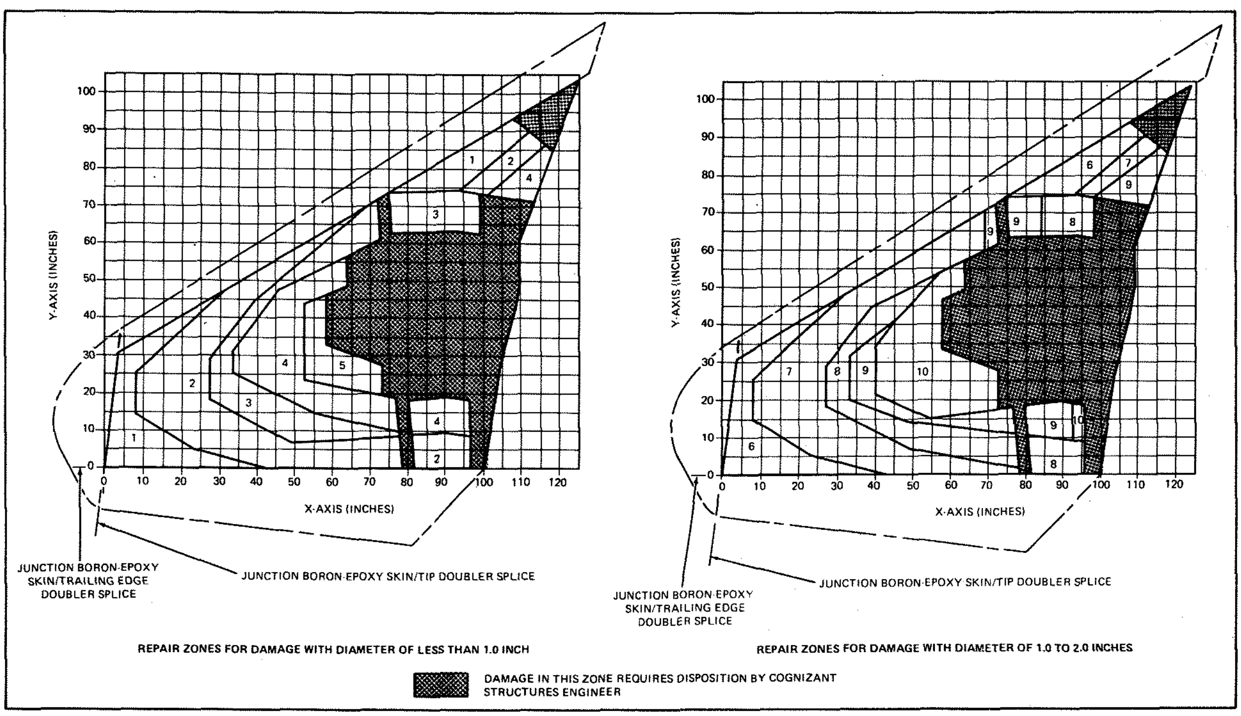

Fig. 3 Boron-Epoxy Structure Repair Zones (3)

Table 4 Materials Required for F-14 Boron Stabilizer Repair[4]

	NOMENCLATURE/MANUFACTURER	SHELF LIFE	STORE BELOW
1.	EC2333 PRIMER (MINNESOTA MINING & MFG. CO.) 3 M CORP MIN	6 MOS	40°F
2.	METLBOND 329-1A ADHESIVE NARMCO MATERIALS INC. DIV. OF CELANESE CORP. CA	6 MOS	0°F
	OR		
	RELIABOND 398 ADHESIVE CIBA-GEIGY COMPOSITE MATERIAL DIV. CA	6 MOS	0°F
3.	RELIABOND 350 CONDUCTIVE FILM ADHESIVE (RELIABOND MFG. CO.)	6 MOS	0°F
4.	EPOCAST 1310/9223 POTTING COMPOUND FURANE PRODUCTS DIV. M & T CHEMICALS INC. LA, CA	1 YEAR	AMB
5.	EA956 A/B LIQUID EPOXY ADHESIVE (HYSOL DIV. DEXTER CORP.) PITTSBURG, CA	1 YEAR	40°F
6.	EPIBOND 87803 A/B ADHESIVE FURANE PRODUCTS DIV. M & T CHEMICALS INC. LA, CA	1 YEAR	AMB
7.	EA934 A/B EPOXY PASTE ADHESIVE (HYSOL DIV. DEXTER CORP.) PITTSBURG, CA	1 YEAR	40°F
	OR		
	AEROBOND 2143 A/B EPOXY PASTE ADHESIVE (HYDOL DIV. DEXTER CORP.) PITTSBURG, CA	1 YEAR	40°F
8.	7576/665/2054 FIBERGLASS EPOXY NARMCO MATL'S INC. DIV. OF CELANESE CORP., CA	6 MOS	40°F
9.	PASA-JELL 107 TITANIUM PRE-TREAT (SEMCO DIV. PRODUCTS RESEARCH & CHEMICAL CORP.) LA, CA	NONE	AMB
10.	PASA-JELL 105 ALUMINUM PRE-TREAT (SEMCO DIV. PRODUCTS RESEARCH & CHEMICAL CORP.) LA, CA	NONE	AMB
11.	TITANIUM FOIL (0.008 IN. THICK) TIMET DIV. OF TITANIUM METAL CORP OF AMERICA TORONTO, OH	NONE APPLY-REPAIR PATCH	N/A
12.	ALUMINUM FOIL (2 IN. WIDE, 0.004 IN. THICK)	NONE APPLY REPAIR LIGHTENING STRIPS	N/A
13.	BLEEDER-RELEASE CLOTH COATED, 23 PB (CHEMICAL FABRICS CORP.), VT	NONE CURING	N/A
14.	RELEASE CLOTH, COATED P/N 100-3-108 (CHEMICALS FABRIC CORP.), VT	NONE CURING	N/A
15.	CLOTH, GLASS FINISHED, 7781 VOLAN A, A1100 TYPE 11 CLASS 2 (BURLINGTON GLASS FABRICS CO.), NJ	NONE	N/A

Table 5 Materials Required for F-14 Fiberglass Radome Repair(4)

NOMENCLATURE/MANUFACTURER	SHELF LIFE	STORE BELOW
1. EPOCAST 1310/9223 POTTING COMPOUND FURANE PRODUCTS DIV. OF M & T CHEMICALS INC. LA, CA	1 YEAR	AMB
2. EA956 A/B LIQUID EPOXY ADHESIVE (HYSOL DIV. DEXTER CORP.) PITTSUBRG, CA	1 YEAR	40°F
3. AF130 UNFILLED EPOXY FILM ADHESIVE (MINNESOTA MINING & MFG. CO.) 3M MN	6 MOS	0°F
4. USP E720E FIBERGLASS EPOXY PREPREG (US PROLAM INC., CT) OR	6 MOS	0°F
F161-505 FIBERGLASS EPOXY PREPREG (HEXCEL CORP.) CA	6 MOS	0°F
5. 7781 FIBERGLASS CLOTH A1100 OR VOLAN "A" FINISH	NONE	N/A
6. HRP NON-METALLIC HONEYCOMB CORE (HEXCEL CORP.) 3/16 IN. GF 12-5.5 CA	NONE	N/A

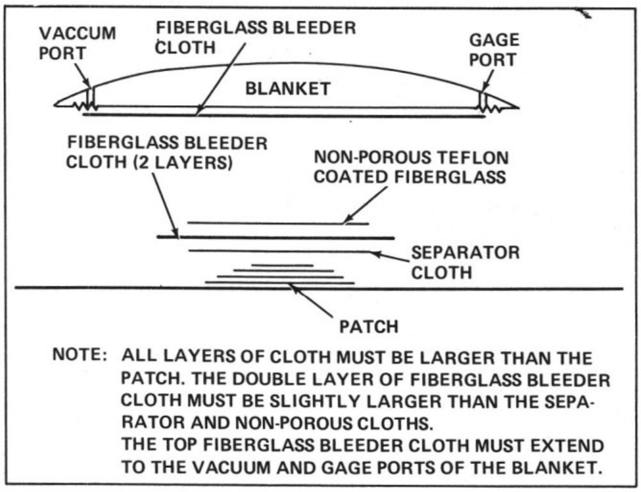

Fig. 4 Typical Patch Layup

V. EQUIPMENT FOR FIELD USE

To meet the need for new shipboard maintenance techniques and equipment on the F-14, a Composite Repair Kit was developed by Grumman. This kit is designed to simultaneously provide heat (350°) and pressure (10 psi minimum) in the application of repair patches to the F-14's Boron/Epoxy Stabilizer.

During the evolution of the F-14 kit, we found it necessary to develop a blanket with three zones of varying watt density to compensate for the greater heat loss at the outer area of the patch. To balance the heater element, we instrumented a boron/epoxy panel and purchased a heater with three separately controlled zones. Each zone was controlled with a variac to provide an even 350°F temperature across the entire 12 inch diameter heater surface. Based on the variac readings, a heater element was manufactured for us with three zones of varying watt density (approx. 5 watts/sq. in. inner zone, 7 1/2 watts/sq. in. middle zone, and 10 watts/sq. in. outer zone).

These zones in the etched foil heater element were then wired to one 115 volt input line, which is controlled by a single temperature probe in the center of the blanket.

Although this blanket works quite well, its use is restricted because it is balanced for the thermal properties of boron/epoxy skin on an aluminum honeycomb structure.

The additional experience and knowledge we gained from the development and use of this kit led us to the need for a versatile Composite Repair Set that can perform well on a variety of composite materials and sub-structures. The equipment we developed meets many of the needs of present and future composite repairs. It is a small unit for use on a variety of materials including boron/epoxy, fiberglass, kevlar and aluminum. (See Figure 5). The basic function of the kit is to apply heat and pressure to meet the repair patch conditions.

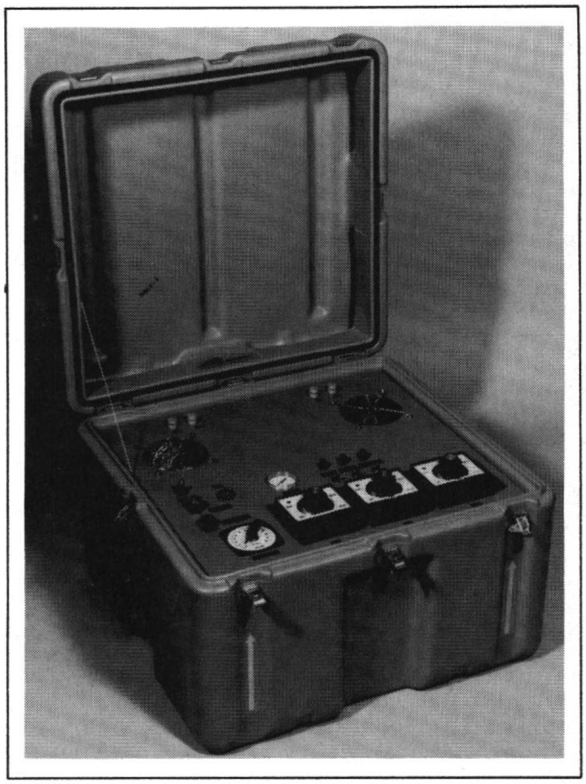

Fig. 5 Composite Repair Console

Included in the console is a vacuum pump, fan, gage, temperature controllers, a timer and related components to provide vacuum and temperature control to the blanket. (See Figure 6.)

The vacuum pump, which has a capacity of 0.5 CFM at 20 inches of mercury vacuum and an ultimate pressure of 26 inches of mercury vacuum, is connected to the blanket with a vacuum hose. The connection on the blanket carries the vacuum path to a series of concentric grooves in the bottom of the blanket, which allows the bottom of the blanket to be evacuated, thus applying atmospheric pressure to the top of the blanket and patch.

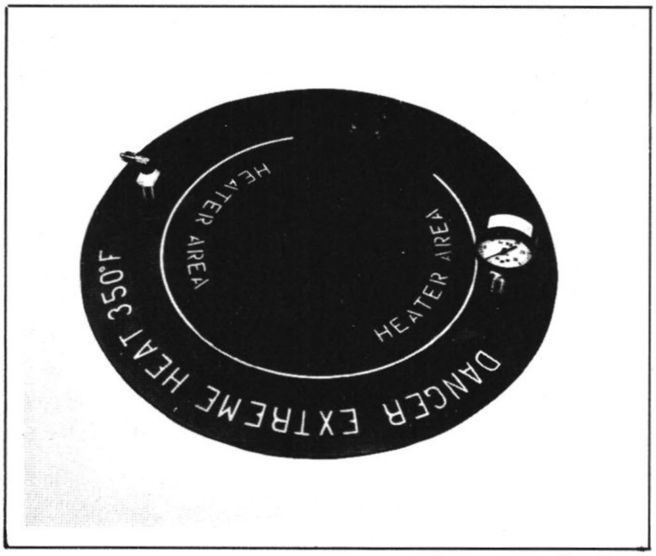

Fig. 6 Composite Repair Blanket

Table 6 Composite Repair Set Characteristics

VACUUM PUMP	0.5 CFM @ 20 IN. HG VACUUM ULTIMATE VACUUM 26 IN. HG
TEMPERATURE CONTROLLERS	50°F-450°F WITH AUTOMATIC RATE OF RISE 2°F/MIN TO 8°F/MIN RECORDER OUTPUT AVAILABLE
TIMER CIRCUIT	AUTOMATICALLY CONTROLS TOTAL CURE CYCLE
MAX HEATER CAPACITY	1500 WATTS/CONTROLLER
BLANKET	INTEGRAL VACUUM/HEATER TEMPERATURE RANGE 50°F-350°F WATTAGE 1000 TOTAL TEMPERATURE DISTRIBUTION ±20°F

Since the required watt density of sections of the blanket is different for materials and substructures with different thermal properties, this second generation Repair Set contains three temperature controllers with each heater zone having its own probe and input control circuit. This permits even heating on surfaces with different thermal conductivities. The initial second generation blanket was kept the same size and shape as the F-14 blanket so that the existing mold could be utilized. This provides for a 12 inch diameter heater area. Integral vacuum and temperature control techniques can be utilized on blankets of other shapes and sizes. Table 6 shows the characteristics of the Composite Repair Console and Blanket. The Console can also be used as a vacuum source and temperature control for strip heaters utilizing bagging techniques. This is extremely important for complex shapes, which require the additional flexibility of strip heaters.

In order to eliminate the need for an operator to manually adjust the temperature every 5 to 10 minutes while following the desired rate of rise curve, we have developed a temperature controller with an adjustable rate of rise circuit. With this circuit, rate of rise from 2°F/minute to 8°F/minute are provided. Coupled with the rate of rise feature, we are providing a total cycle timer. This allows the operator to set a total on time based on the time to reach cure temperature and the required cure time. Output signals for a strip chart recorder are provided for verification of the cure cycle.

Both the automatic rate of rise feature and the total cycle timer provide for a more controlled cure cycle and reduce the need for constant monitoring of the unit while curing a patch. This set satisfies many of the needs for a versatile, easy to use field type Composite Repair Set.

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