

PUBLISHABLE SYNTHESIS REPORT

Contract n°: *BRPR-CT98-0796*

Project n°: *BE-97 4099*

Title: “*COMPOSITE REPAIR OF METALLIC
STRUCTURE FOR AGEING
COMMERCIAL AIRCRAFT*”

Project coordinator: *HELLENIC AEROSPACE
INDUSTRY S.A.*

Partners: *IAI, OGMA, ALENIA, Cytec,
GMI*

As. Contractors: *NTUA, DUT*

Project Period: **from** *01/02/1999*
to *31/7/2002*

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SUMMARY

The Aviation Industry has long recognized that the world fleet of aircraft faces specific aging problems such as fatigue and corrosion requiring particular attention. Metallic aircraft components are susceptible to the development of in service cracks by the various processes of fatigue or stress corrosion. These defects are generally developed from sites of local stress concentration, such as fastener holes or other abrupt configuration changes. Conventional methods of repair for metallic aircraft structures usually include the use of bolted or riveted metallic reinforcement. While these procedures may be effective in the short term, they frequently introduce additional stress concentrations leading to further cracking and creating areas that are difficult or impossible to be inspected. Further on, the conventional repairs introduce cutting of damaged areas, which is not indicated in aging cases, due to the reduction of strength. Bonded repair technology is considered today as a reliable alternate to mechanically fastened repairs.

The bonded repairs have achieved significant cost savings. Some benefit is derived from the reduced application time and the longer fatigue life of the repairs, compared to mechanically fastened repairs. Although today, the bonded repairs considered more efficient than the mechanically fastened, each repair is faced as tailored made for each case.

However for the industrial engineering and maintenance production line, there is a lack of appropriate technical manual -standards and specifications- to control the implementation of the repair as integrated method, from the design phase, up to application and quality assurance.

This project was aiming at the development of:

- (i) An engineering repair manual and standards, which will provide engineering guides and methods for bonded repairs from the design phase up to final validation and quality assurance
- (ii) Design criteria
- (iii) Material Systems data base (composite and adhesives) used in bonded repairs (patching)
- (iv) Two innovative Equipment for surface preparation and curing bonded repairs, tested and evaluated within the project.

A database for the most prone to damage structures of aircraft was developed and candidate locations using structural data were investigated in order to determine the economic and technical feasibility of repairs by composite patching. For this purpose repairability criteria were developed as well as an economical model in order to be used both as standard method for the feasibility analysis in the initial phase of the engineering study for each repair case. User-friendly calculation methodology developed for estimating the effect of the repair as well as the loads in the composite material patch and the metallic parent metal. Different composite material systems (carbon and boron), in combination with specific structural adhesives were investigated for the bonding performance and series of experimental cycles for curing and surface preparation were applied. The necessary technological infrastructure (repair equipment, NDE capabilities) has been developed and extensive validation tests performed for the evaluation of new technology and methodologies.

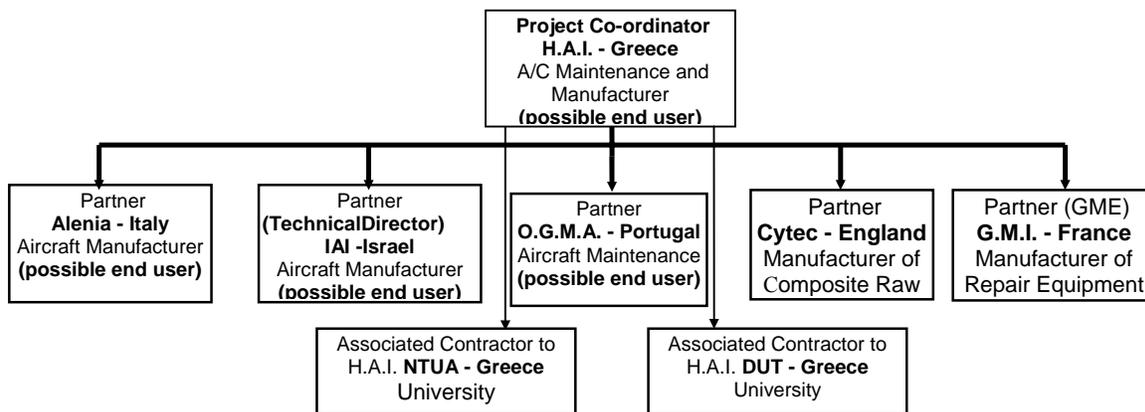
The COMPRES project resulted in a great number of innovative and beneficial results for the composite material repair field. The following is a summary of some of the major achievements of the project in list form:

- Composite Material Repair Manual with standardized methodology
- Extensive comparison and suggestions regarding repair analytical methodology
- Simplified Rose Model Approach to analytical repair problem
- Numerous innovative analytical approaches including 3D p-version finite elements
- Comprehensive approach to deal with the thermal mismatch residual stress problem:
 - *Low temperature cure cycle*
 - *Induction heating for field repair*
 - *Analytical approach to understand the problem*
 - Extensive use of co-cured patches
- Surface Preparation Study for quality bonding
- Effect of Corrosion inhibiting primer on surface preparation quality
- Expanding composite material data base
- Statistical Data reduction of damaged structure
- Repair of thick cross section structure
- Non-linear adhesive effects
- Comparison of co-cured vs pre-cured repairs
- NDE round robin study
- Equipment development
 - *GILDA: Phosphoric acid closed system*
 - *Induction Heating*
 - *Including thermocouple in the susceptor*
 - *Design for uniform temperature distribution*
- Parametric repair design for actual structure
- Definition of repair design criteria
- Development of new composite patch repair analysis techniques
- Development of composite patch repair analysis software employing FE method
- Application of simplified techniques for the quicker analysis of repairs
- Definition of guidelines for the stress and fatigue analysis of composite patch repairs
- Material Selection and Design Allowable Data Generation of Composite and Adhesive.

KEYWORDS:

Repair, Composite Material, NDE, Surface Treatment, Induction Heating, Adhesive, Composite, Cure, Induction, Primer.

THE CONSORTIUM



The consortium combined the necessary expertise and facilities. There are aircraft manufacturers with diverse experience in different aircraft including the ATR regional transport, the ASTRA business jet, subcontract manufacturing work on the Airbus, structural conversions of Boeing 747's, military aircraft, unmanned airborne vehicles, etc. The consortium included aircraft companies with vast experience in maintenance techniques, which is essential to this project. Other smaller companies which include composite material repair equipment expertise, as well composite prepreg and adhesive specialists add to the multidisciplinary nature of the consortium to help tackle our specific technical objectives. Among the consortium of this project included partners with analytical and testing capabilities and experience. The theoretical and technical expertise of the universities supplement the consortium and helped create a well rounded and versatile team. The consortium was enhanced by the participation of Qinetiq (former DERA) as subcontractor. All the partners have extensive experience in multi-national projects.

PARTNERS PROFILE

HELLENIC AEROSPACE INDUSTRY (HAI)- Coordinator

HELLENIC AEROSPACE INDUSTRY (HAI) established in 1975 is an aeronautical company, which specialises in the following line of business and products:

Maintenance, Overhaul and Modification of Aircraft, Helicopters, Engines, Accessories, components and Avionics

Assembly and Manufacturing of Airframe and engine parts, major assemblies, master tools, complete electronics and telecommunication products and systems.

All the aforementioned operations are fully supported by Quality Assurance and Control, Marketing, Training, Engineering and Research & Development. The Engineering R&D activity within H.A.I. includes the scientific areas of Engines, Electronics, Aerospace, Advanced Materials & Processes. The Engine facilities house 18 production shops in an area of 170,800 sq. ft., which offer repair, overhaul, modification and testing for more than 20 different types of turboprop, turbojet, turboshaft, turboprop and reciprocating engines.

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IAI - ISRAEL AIRCRAFT INDUSTRIES-Technical Manager

Israel Aircraft Industries is Israel's main aerospace corporation. It is a public company with about 14,000 employees, and over 2 billion EUROS of annual sales. A few of the many projects currently in progress at IAI are: design, integration and manufacturing of a family of business jet, conversion of Boeing 747 from passenger to cargo configuration, jet engine nacelles, military aircraft upgrade programs, development and manufacturing of unmanned airborne vehicles (UAV's) for military and civil applications, etc.

The innovation process is one of the cornerstones of Israel Aircraft Industries. The IAI Engineering Division is involved in over 70 innovative R&D projects encompassing a wide range of subjects. IAI is also a partner in 33 5th Framework EU R&D programs including two large Growth Technology Platforms TANGO and AWIATOR

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ALENIA AERONAUTICA S.P.A.

Alenia Aeronautica S.p.A., a company of Finmeccanica S.p.A is dedicated to a full range of activities, from design and production to modification and product support for both military and civil aircraft.

In the military aircraft field the company designs and manufactures, directly or through international collaborations, combat and transport aircraft such as the Eurofighter/Typhoon,, the AMX tactical aircraft, the tri-national Tornado multi-role combat aircraft, the C-27J Spartan tactical transport airlifter jointly developed with Lockheed Martin, the ATR42MP Surveyon, a maritime patrol version of the ATR42 commuter aircraft. The company has long been co-operating with Boeing and is also involved in the new A380 programme. Employing a staff of more than 9,300 people, it reached 2001 revenues of 1,328 million Euro, 80% of which from the export and with a Research & Development expenditure of more than 160 million Euro.

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OGMA, INDUSTRIA AERONAUTICA DE PORTUGAL, S.A.

OGMA, Indústria Aeronáutica de Portugal, S.A., is devoted to providing overhaul, repair and retrofit of aircraft, engines, accessories, avionics and ground equipment, and also has the capability of manufacturing and assembling components and structures for national and foreign organisations, both civil and military.

OGMA is an Official Lockheed Hercules Service Center for the performance of the C-130 heavy maintenance. Other examples of aircraft and engines for which OGMA is an authorised service centre include the Lockheed P-3, Embraer 135 and 145, Eurocopter, Allison AE2100, AE3007 and AE1107.

OGMA is involved in the manufacturing and assembly of different types of aircraft's like Pilatus PC XII, Dornier DO 328 and Dornier DO 728.

OGMA is involved in other expert fields like: Research, development, test and production of aeronautical materials, Fabrication of several Composite materials with special emphasis on Kevlar and carbon fibers, R&D of advanced composites for aeronautical applications with the goal of developing new techniques for detection and repair of composite structures and R&D in software and hardware applications used in the development of different types of automated test equipment.

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CYTEC ENGINEERED MATERIALS

Cytec Engineered Materials is a division of Cytec Industries Inc. a global speciality chemicals and materials company with \$4 billion world wide sales. The company's focused growth is based on applying technology to create solutions in partnership with our customers. Cytec serves major markets for water and wastewater treatment, mineral processing, paper recycling, automotive and industrial coatings, plastics, adhesives, aerospace adhesives and composites, and chemical intermediates.

The Cytec Engineered Materials division has ten sites world wide, serving the space, aerospace, automotive, marine, and industrial markets.

Cytec Engineered Materials has been a partner within a number of UK & EU funded projects such as ABHTA, AMCAPS II and TANGO.

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G.M.I.

GMI develops control equipment and instrumentation with special application in the field of advanced materials. Investigation is conducted specially in the field of composite structure maintenance to design innovative tooling and equipment. Topics covered are: damage analysis, drying, bonding, machining, thermal control, advanced sensors. In more than ten years GMI has established co-operation with major aircraft manufacturers. Agreements exist with Airbus, ATR, Dassault, Aerospatiale, Bombardier.

Developed Capabilities

- innovative equipment design (electronic, software, mechanics, pneumatic)
- sensor investigation and design: resin viscosity, surface sensors for pressure, temperature, humidity, thermal transfer,...
- Composite production equipment control

- Composite repair processes
- Engineering workshop, training

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QinetiQ

In July 2001 the British Government's Defence Evaluation and Research Agency (DERA) was split into two organisations, DSTL and QinetiQ. DSTL remains part of the Ministry of Defence and continues to handle the most sensitive areas of research. QinetiQ comprises the greater part of DERA and has over 8000 staff; it is currently a wholly government owned plc and competes on the world stage to deliver innovations to a wide range of customers.

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ASSOCIATED CONTRACTORS:

National Technical University of Athens (NTUA). Section of Mechanics in the Department of Engineering Science

The National Technical University (NTUA) is the oldest and most prestigious educational institution of Greece in the field of technology, and has contributed unceasingly to the country's scientific, technical and economic development since its foundation in 1836. The personnel of the nine Faculties include more than 700 people as academic staff, 140 scientific assistants and 260 administrative and technical staff. The total number of NTUA employees is about 1350. Scientific research in NTUA is funded by both the public and private sectors, as well as by European Union sources through numerous European projects.

NTUA participated in this project with scientific staff from the Faculty of Applied Sciences/Section of Mechanics. The researchers were specialized in the finite element method, composite materials and fracture mechanics. Research on FE modelling of composites used in the construction of aeroplanes has been pursued within the section, in collaboration with the greek aircraft industry.

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Democritus University of Thrace (DUT)

The laboratory of Applied Mechanics of the Democritus University of Thrace has a long experience and is fully equipped for execution of R&D projects.

Among its facilities are all the necessary equipment for full verification mechanical testing including a fully computerised fatigue loading MTS machine for uniaxial and triaxial loading, an automatic polariscope for evaluation of stresses, a furnace adjustable to the MTS machine for performing high temperature experiments, equipment for measuring residual stresses, lasers, etc.

DUT specialises in stress analysis, fracture and fatigue testing, crack growth analysis, testing of composites, and finite element analysis.

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TECHNICAL ACHIEVEMENTS:

The following achievements obtained during the project:

- **Statistical Breakdown of Damage Prone Areas**
An extensive investigation was made to determine the characteristic metallic structures of ageing aircraft, prone to damage. These cases were categorized in an attempt to provide the potential damages which can be repaired by composite patching
- **Summary ranking table of the 11 analytical repair approaches**
Evaluation of 11 analytical methods for repair approaches was made and a summary ranking table was established according to the accuracy of results given by each specific method and approach.
- **Thermal mismatch analysis**
The real magnitude of the residual stresses problem due to the difference of thermal coefficients was addressed and analysed
- **Development of new composite patch repair analysis techniques**
New techniques were developed for the quick and reliable analysis of composite patch repairs
- **Parametric Analysis and Repair of Real Structure**
Three real structures were chosen to be repaired by the developed methodology
- **Material selection – low energy cure.**
 - Reduced residual stresses in metallic repair through selection of sub-100°C cure adhesive & composite.
 - Induction curable materials identified (iron particles/nickel coated carbon fabric/magnetic stainless steel) within project.
- **Material screening- composite/adhesive/primer/in-situ cure.**
 - Material data generated by partners according to specific processing conditions required for low energy cure – co-bonding of composite and adhesive below 100°C initial cure.
 - Low energy cure mechanical data compared with standard pre-cure cycle.
 - Trials of induction cure materials.
- **Allowables data generation**
 - Allowables data generated on down-selected materials – carbon-epoxy & boron-epoxy composite.
- **Material specifications**
 - Generation of specifications for carbon-epoxy, boron-epoxy, adhesive & primer materials. Data base for all evaluated material systems was established
- **GILDA**
A new equipment for surface preparation process was developed by GMI
- **Induction Heating**
An innovative induction heating equipment and an introduced innovative curing process for the application of composite patching were developed by GMI
- **Surface preparation methods comparison & Effect of Corrosion Inhibiting primer**
Surface preparation methods for efficient bond durability were investigated and introduced
- **Thick section patch repair**
Theoretical and experimental studies were investigated for the application of composite patches on thick structural sections
- **NDT round robin**

An assessment of the most innovative NDT methods was carried out in order to conclude the reliability of each one when applied for the detection of specific damages

ANALYTICAL APPROACH OF THE TECHNICAL ACHIEVEMENTS

In order to fully realise the benefits of adhesively bonded composite patches over mechanically fastened joining techniques for repair of metallic aircraft structures, the following results must be offered :

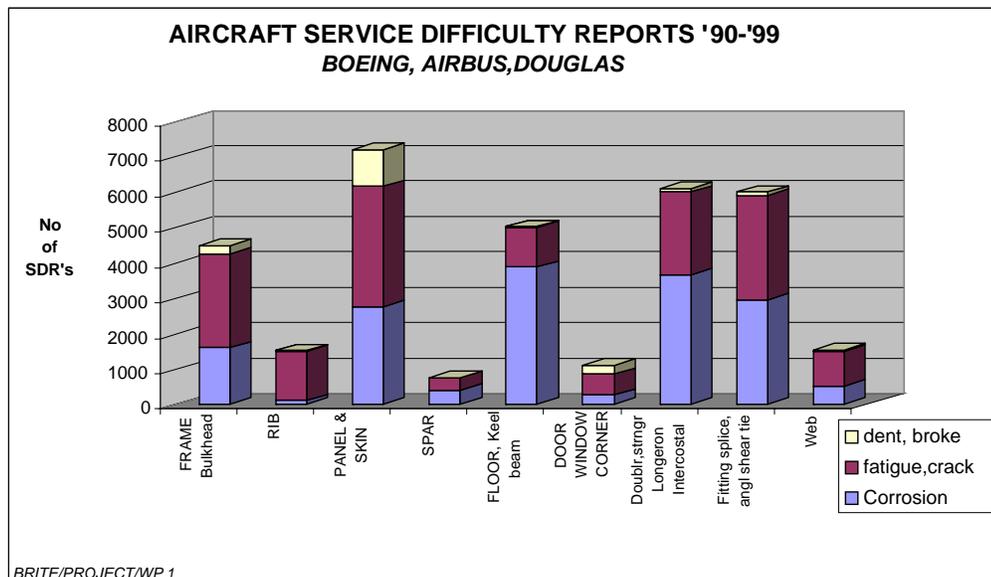
- (a) Reduced cost of repair, and better overall aircraft life-cycle costs.
- (b) Shorter repair time, which directly impacts on airline profitability.
- (c) Improved repair durability, through lower fatigue crack growth and reduced corrosion risk.

Two important potential knockdown factors exist when developing a high performance repair process.

1. The minimisation of residual stresses generated through CTE mismatch between metallic base structure and secondary bonded or co-cured composite & adhesive at elevated temperature.
2. Effect of high (>130°C) temperature on the aluminium microstructure which could alter the mechanical properties of the aircraft structure.

1. Statistical Breakdown of Damage Prone Areas

One of the primary objectives of the *COMPRES* project is to prepare a manual for standardized composite material repairs for *characteristic metallic structures* of ageing commercial aircraft. An integral task in this project is to determine what “characteristic” structures will be presented in the manual. Thus a statistical study was performed to help



determine the areas of the aircraft most prone to damage. The figure below presents a part of the results of this study.

2. Summary ranking table of the 11 analytical repair approaches

Throughout the COMPRES project, multiple analytical approaches were used or developed to assess the bonded composite repair case. Some resulted in more accurate results, while others may have been less accurate but much easier to model. In a very useful summary table NTUA ranked the methods with respect to:

- Accuracy
- Modeling effort
- Applicability
- Computer resources necessary

This information will give the user of the manual a reasonable guideline of which method is most appropriate for a specific purpose and for given constraints.

SUMMARY OF ADVANTAGES AND DISADVANTAGES OF STRESS ANALYSIS METHODS FOR THE DESIGN OF COMPOSITE PATCH REPAIRS					
No	Brief Description	Accuracy	Modeling Effort	Applicability	Computer Resources
1.	Rose Equations	C	A	C	A
2.	3D FEA using h-version elements	A	B	A	C
3.	3D FEA using p-version elements	A	B	A	C
4.	Mixed 3D-2D FEA	B	B	B	B
5.	2D FEA using co-planar shell elements with equivalent stiffens	C	A	C	A
6.	2D FEA using co-planar laminate elements	B	A	B	B
7.	2D FEA using shell elements at different planes connected with constraint equations	B	C	C	B
8.	2D FEA using shell elements at different planes connected with spring elements	B	C	C	B
9.	2D FEA using three layers of special Mindlin elements connected with constraint equations	B	C	B	B
10.	Mixed Finite Elements – Boundary Elements Analysis	A	C	A	C
11.	Modified Rose Equations	B	C	B	B
	Accuracy	Modeling Effort	Applicability	Computer Resources	
	A: Excellent	A: Minor	A: All cases	A: Minor	
	B: Good	B: Average	B: Most cases	B: Average	
	C: Poor	C: Large	C: Simple cases only	C: Large	

3. Thermal mismatch analysis

There exists a significant difference between the thermal expansion coefficients of the composite material patch and the metallic structure. This “thermal mismatch” induces serious residual stresses. Upon heating the area during the curing of the adhesive and patch, the metal expands more than the composite repair. Upon subsequent cooling, the metal wants to contract, and the composite patch constrains the desired contraction, inducing detrimental tensile residual stresses in the metal. Although this phenomenon has been known for a long time, little progress had been made to properly analyze the effect and to solve the problem. In COMPRES, extending the state-of-the art by seriously tackling this important phenomenon, became one of the major emphases of the project.

Three aspects of the problem were addressed:

- Analytical methodology to better understand the magnitude of the residual stresses
- Developing a lower cure cycle to diminish the effect by having a smaller temperature range
- Developing innovative induction heating curing method which allows more local heating of the adhesive and patch without significant heating of the surrounding metallic parent structure

4. Development of New Composite Patch Repair Analysis Techniques

New techniques have been developed for the quicker analysis of composite patch repairs and their accuracy has been verified against standard methods, like 3D FEA. Among these techniques have been the following:

- Simplified Rose Equations
- Combined boundary element/finite element method
- Application of standard 2D laminate elements to represent the repair layout.

5. Parametric Analysis and Repair of Real Structure

In the COMPRES manual a parametric analysis and repair are presented for the following structures:

- Cracked stiffened skin
- Corrosion in a wing skin
- Cracked frame

Static, fatigue and damage tolerance analysis were carried out in order to help determine the appropriate repair for a wide range of cases which included different thickness of the damage area, various stress level, and a range of operating temperatures.

For each repair concept, the patch type, material, lay-up, drawing, repair procedure, NDT and surface treatment are detailed in the manual.

6. Repair design criteria

Criteria to be used for the design of a composite patch repair or composite patch reinforcement of a metallic structure have been defined. These criteria, as presented in the following table, are supported by extensive analytical and numerical work that has been performed including restrictions in the areas where calculation of stresses was found to be difficult and / or inadequate. Moreover, some tips are listed after the criteria as initial design guidelines for the engineers that design a composite patch repair.

	Cracked substrate (repair)	Uncracked substrate (reinforcement)	Comments
Metallic Substrate	Stress Int. Factor AFTER $< (1/\lambda)^{1/m}$ Stress Int. Factor BEFORE $K_{\text{patched}} < (1/\lambda)^{1/m} K_{\text{unpatched}}$	Max. Von Mises stresses AFTER $<$ Max. Von Mises stresses BEFORE $\sigma_{\text{Von Mises patched}} <$ $\sigma_{\text{Von Mises unpatched}}$	Max. Von Mises stresses refer to the point requiring reinforcement.
	Max. Von Mises stresses at the edges of the patch AFTER $< \frac{3}{4}$ Max. strength of the material $\sigma_{\text{Edges patched}} < \frac{3}{4} \sigma_{\text{strength}}$		
Adhesive	Shear strain AFTER $<$ max. elastic permissible shear strain $\gamma^A < \gamma^A_{\text{max elastic}}$		For cracked plate this criterion applies to a region outside $r < 0.2a$, where $2a$ =crack size.
Composite Patch	Tensile stress X axis AFTER $<$ Tensile Strength X axis $(\sigma^P_X < \sigma^P_{X \text{ max}})$		$X=0^\circ$ =Load direction
	Verification of non-failure using an interactive criterion (e.g. Tsai-Hill)		

7. MATERIALS ACHIEVEMENTS

Establishment of a low energy ($<100^\circ\text{C}$) vacuum-only repair cycle, and corresponding mechanical data generation.

Material selection of boron-epoxy (br/ep), carbon (graphite)-epoxy (gr/ep), and adhesive materials based on existing Cytec products that fulfilled the criteria of cure cycle restriction and service temperature performance.

The chosen composite systems were CYCOM® 753, an epoxy that was developed for low temperature (60°C) cure marine applications, and CYCOM® 950-1, which is a toughened 125°C -cure epoxy that develops a 150°C dry Tg. Textron 5521 F/4 was the 120°C cure UD boron-epoxy material studied in the project.

The adhesives selected for cure and performance compatibility with the 753-prepreg system were FM® 73 & FM® 94. Both these toughened epoxies are capable of cure down to 80°C . All these materials are capable of being processed under vacuum only conditions.

A corrosion inhibiting structural bonding primer, BR® 127 was proposed for application to protect the aluminium.

Cytec Engineered Materials supplied a number of materials for induction curing process development by GMI in Task 2.5 over the course of the project.

A screening test programme that was established by the task partners developed data on the two composite systems CYCOM® 753 & CYCOM® 950-1 on 193-g/m^2 plain weave carbon fabric. The data was both physical-chemical, and mechanical, enabling both the resin and composite system properties to be established. DSC analysis was used to determine degree of cure from a variety of cure cycles. DMA established Tg level developed from these cure cycles.

For CYCOM® 753 a two step cure was found to give the highest cure level & Tg.

The mechanical test results indicated that while CYCOM® 950-1 had higher dry ILS performance than CYCOM® 753, there was no difference in wet performance due to the lower water absorption of CYCOM® 753. Given the benefit of low temperature cure capability preferred composite system for down selection and qualification was CYCOM® 753.

FM® 73 and FM® 94 screening data were generated for a number of cure cycles, including alternative low energy cycles using two-step cures.

Summary data tables for boron-epoxy and carbon-epoxy composite allowables were generated based on ratified results from each partners work share.

Statistical reduction according to MIL-HDBK-17 was applied to the partner generated test values to obtain the Design Allowables.

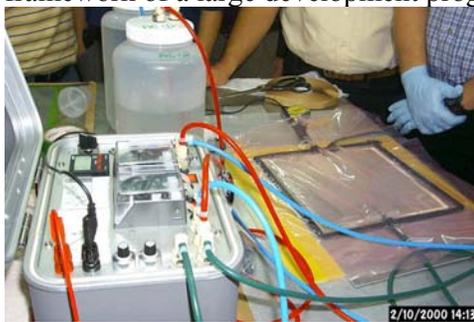
8. GILDA

GMI developed the GILDA. The GILDA is a closed cycle phosphoric acid instrument, with a number of modifications compared to the conventional Phosphoric acid anodise close cycle systems:

The major difference is the use of two peristaltic pumps for fluid transfer, one for insertion o fluid into the process bag and one for it's removal, instead of vacuum pressure. This allows one to flood the bag with acid (or water) by activating the first pump only. The fluid flow rate is also better controlled in this manner. The recommended technique for surface treatment is the use of a double-bag lay-up, during which the inner bag contains the acid, and the outer bag is used for the application of vacuum pressure onto the inner bag.

The GILDA also allows for better adjustment of the voltage and current applied to the treated specimen during the anodize process, and is a smaller instrument than the PACS model.

Another, obvious advantage, is the fact that this instrument is being developed with close cooperation between the manufacturer, GMI, and potential users, COMPRES partners, having experience with this and other types of field surface treatment, and all this in the framework of a large development program.



GILDA instrument and process bag.

Satisfactory results were obtained by IAI and Alenia using a GILDA equipment.

The bag configuration and processing parameters were optimised. Parameters optimisations has been validated by mechanical tests on specimens bonded after treatment.

9. Induction Heating Equipment

Induction Heating Technology is an innovative approach in repair of metallic structures by bonding.

It constitutes an ideal candidate of technology for supplying the energy needed for curing the adhesive and thermosetting resins used in the fabrication of the reinforcement patches. Induction is a non contact process which is an advantage to heat geometrically complex surfaces.

The alternative solution which we would qualify of traditional way is to use heating flexible mats to transfer the heat to the material by conduction. As we will see, the induction process will avoid the design and manufacture of conformable patching element to complexed geometrical profiles by the use of an Induction Coil to be installed at a certain distance of the reference area.

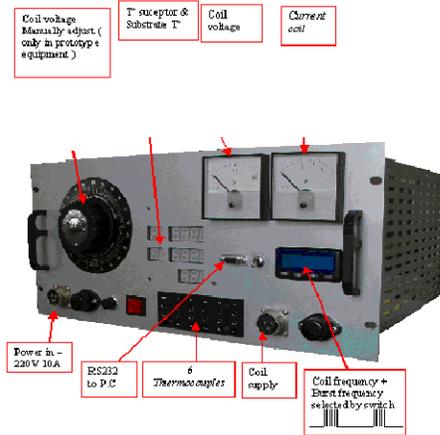
In general, an induction system is constituted of following elements as:

- A Power Generator,
- An Induction Coil
- A Susceptor,

INDUCTION HEATING EQUIPMENT
COIL POWER SUPPLY WITH MICROPROCESSOR CONTROL



Prototype MU01 of Induction Power System for Induction Heating Bonding



Power Controller MU 01 Prototype

OTHER RELATED PROCESS HANDLING

A direct application of the system related to the bonding process can be:

Curing Of A Primer:

In this case, use is made of a ferro-magnetic grid mounted at a certain distance from the aluminium surface (the cure is thus performed without contamination and with allowance to the solvents to evaporate) This grid will induce currents in the aluminium substrate and this heat generation will require specific control parameters to be tuned by the operator because this time we will need to heat the aluminium

Heating by Inducto-Conduction:

We will call this class of application under this name to mean: transferring heat by conduction, this heat being generated by induction on the transferring element. This mode will be required when heat cannot be transferred through an embedded susceptor and the implementation will be a direct application of the possibility offered by our system to adapt the control parameters in a broad range

10. Surface preparation methods comparison

The surface preparation method should be efficient, practical, non-dangerous, environmental friendly, cost effective and safe under field conditions. In the development of practical repair application the surface preparation method is usually predetermined by laboratory validation tests.

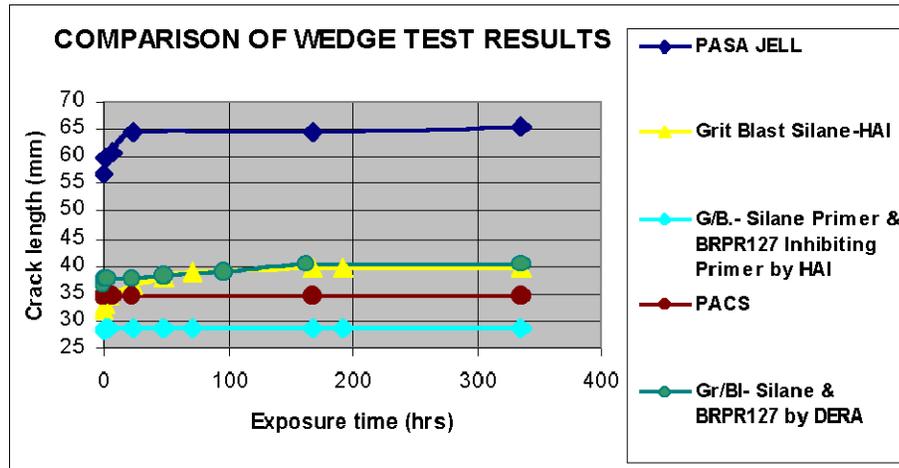
The following methods were considered candidates for the selection of the surface preparation method to be applied:

- Grit Blast Silane and BR 127 inhibiting Primer
- Phosphoric Acid Anodize (PACS or GILDA)
- Pasa Jell 105

The use of BR127 primer, with careful control of coating thickness, is recommended for critical applications where corrosive environments may be encountered. However, for other repairs, particularly those where airworthiness can be assured by a fail-safe approach, the use of BR127 may not be necessary. This recommendation is supported by the good environmental durability and good in-service performance reported for repairs involving grit blast-silane treatment without primer. Furthermore, significant time and effort is required for primer application and cure, and there is a risk that performance may be affected adversely if primer application is not controlled adequately and the coating is too thick.

Boeing wedge tests have proved to be a most effective means of evaluating the quality of the repair and the appropriateness of the adhesive/surface treatment, for the particular service environment. Hence prior to proceeding with the application Boeing wedge tests should be performed.

Indicative results of Boeing Wedge Test are presented below after, performed on specimens surface treated with Grit Blast Silane (with and without primer), Phosphoric Acid Anodize (PAA and PACS) and Pasa Jell 105.



The crack growth is recorded and the quality of surface treatment and bonding is evaluated according to the following Table.

Boeing wedge test ratings

1 hr crack growth	Rating
0. to 2.5 mm	Very good
2.8 to 6.2	Good
6.3 to above	Marginal to un-acceptable

An investigation aiming at the comparison of the proposed methods was made, based both on the bond strength results and other parameters as presented in the following tables . The selection of the surface preparation method should be based on the estimation of the availability of instrumentation, environmental conditions, limitations due to the area of repairs, industry or field application as well as the cases where the repair should be performed directly on aircraft or on a disassembled component.

To all the above mentioned cases the additional parameters of cost, Simplicity and Safety should be added.

Surface preparation methods. Comparison of all the parameters

Method	Mechanical Properties			Other Characteristic Parameters		
	Single Lap Shear Strength	Peel Strength	Wedge test results Crack length propagation	Simplicity	Cost	Environmental impact
Phosphoric acid anodize (PACS) *	A	A	A	B	B	A
Pasa Jell	A	A	B	B	B	B
Grit Blast/Silane and Primer	A	A	A	A	A	A
GILDA*	A	A	Under further investigation	A	Not yet specified	A

NOTE: *For hard corrosive environmental conditions the electrolytic based surface preparation methods secure durable bonding .

- A: Excellent (Lap shear strength: higher than 30 MPa, Peel strength: Higher than 8 N/mm and Wedge test: less than 2.5 mm for the first 1 hour of exposure)
- B: Good (Lap shear strength: 25-30 Mpa, Peell strength: 6-8 N/mm, Wedge test: 2.6-6.2 mm for the first 1 hour of exposure)
- C: Satisfactory (Lap shear strength: 20-25 MPa, Peel strength: 3.5-6 N/mm, Wedge test: 6.3 mm for the first 1 hour of exposure)

11. Effect of corrosion inhibiting primer

Boeing wedge tests were carried out to determine the effect of a corrosion inhibiting primer (BR1217) on the environmental durability of adhesive bonded aluminium alloy (2024-T351) specimens. Application of a single coat of BR127 primer after grit blast-silane treatment resulted in significant improvements in wedge test performance when specimens bonded with three different adhesives were exposed to 50oC/95%RH for up to 336 hours. When two coats of primer were used, the improvements in wedge test performance were much less pronounced. In general, similar trends were observed during additional exposure of specimens to neutral salt spray. Examination of uncracked portions of primed and unprimed specimens did not reveal any evidence of ingress of corrosion in the vicinity of bondlines, even after exposure to salt spray for 1344 hours.

Based on the results of this study, the use of BR127 primer, with careful control of coating thickness, is recommended for critical applications where corrosive environments may be encountered. However, for other repairs, particularly those where airworthiness can be assured by a fail-safe approach, the use of BR127 may not be necessary. It should be noted that significant time and effort is required for primer application and cure, and there is a risk that performance may be affected adversely if primer application is not controlled adequately and the coating is too thick.

12. Thick section patch repair

Theoretical and experimental studies were undertaken to investigate various aspects of bonded patch repair of thick sections. The main conclusions of this research are:

1. Constant amplitude fatigue testing demonstrated that effective retardation of crack growth was achieved when 20 ply woven carbon/epoxy patches (manufactured from Cycom 753-42%-3KHS-P-199-1520 prepreg) were bonded to both sides of 12mm thick aluminium alloy test pieces containing central through-thickness cracks. For both R=0.1 and R=-1 loading, patches applied by co-cure of adhesive and prepreg were as effective as bonded precured patches in retarding the growth of fatigue cracks. As expected, 10 ply patches were less effective than 20 ply patches. For specimens repaired with 10 or 20 ply precured patches, small increases in fatigue crack growth rate were observed when the test temperature was increased from 24°C to 70°C and from 70°C to 82°C.
2. A 3D BE/FE model for analysing bonded patch repairs has been developed to enable the effect of nonlinear adhesive stress-strain behaviour to be taken into account. In general, slightly slower rates of fatigue crack growth were predicted if linear rather than nonlinear adhesive behaviour was assumed. Fatigue crack growth rates predicted from a simple 1D model were significantly different from those predicted by the 3D model. In general, fatigue crack growth rates predicted by the nonlinear 3D model were in excellent agreement with corresponding experimental data for patched specimens. The relatively small increases in fatigue crack growth rate observed for patched specimens when the test temperature was increased from 24°C to 70°C or 82°C were explained in terms of the opposing effects of reduced residual stresses and increased adhesive strain as test temperature increased. The nonlinear 3D model predicted that a reduction in cure temperature from 120°C to 95°C would result in only very small reductions in fatigue crack growth rate, due to reduced residual stresses.

13. NDE Round Robin

The achievement is concerned with the assessment of the capability of advanced inspection methods (NDE) to verify the structural integrity of the "Co-Bonding" Metal Substructure-Composite Patches.

The NDE methods :

- **Ultrasound**
- **Thermography**
- **Eddy Current**
- **Shearography**

were assessed using dedicated "Calibration Specimens" manufactured according to the "On-Aircraft" repair requirements and containing typical defects such as delaminations, disbonding, metal cracks.

The "Carbon" and "Boron" Reference Standards have been tested by the partners performing a "Round Robin" testing.

A Ranking of the detection capability of the applied methods versus type of defects is available.

"Thin" Composite Patches

	Delaminations		Disbonding		Metal Cracks	
	<i>Carbon</i>	<i>Boron</i>	<i>Carbon</i>	<i>Boron</i>	<i>Carbon</i>	<i>Boron</i>
Thermography	A	A	A	A	NA	NA
Ultrasonics	A	A	A	A	NA	NA
Eddy Current	NA	NA	NA	NA	A	A

Shearography	A*	A*	A*	A*	NA	NA
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"Thick" Composite Patches

	Delaminations		Disbonding		Metal Cracks	
	<i>Carbon</i>	<i>Boron</i>	<i>Carbon</i>	<i>Boron</i>	<i>Carbon</i>	<i>Boron</i>
Thermography	NO	A	NO	A	NA	NA
Ultrasonics	A	A	A	A	NA	NA
Eddy Current	NA	NA	NA	NA	A	A
Shearography	A*	NO	A*	NO	NA	NA

A = Applicable

NA =Non Applicable

NO = No Capability of Detection

A* = Capability to detect Corner Patch Defects (Dia > 5.0 mm)

EXPLOITATION AND FOLLOW-UP ACTIONS

The main products of the COMPRES program are the following:

- **Engineering manual** entitled “bonded composite repair technical manual” which can be used for design, analysis, fabrication, application, quality inspection and validation of all related bonded repairs in conjunction with commercially available equipment
- **Innovative processing equipment.** These equipment have been developed to be used alternatively to commercially available equipment providing the following advantages:
 - Better bonding quality, increased strength and durability, reduction of cost and time, elimination of metal deformation effects, elimination of thermal mismatch phenomena

In order to apply the developed method on “civil type aircraft” certification of JAA is required. To this target an airworthiness document for bonded repairs has already been prepared and will be officially presented to JAA according to proposed schedule. This schedule includes all the necessary steps proceeding the application for certification.

The following plan represents all the scheduled steps that will be followed within next years:

ANTICIPATED EXPLOITATION PLAN							
	1st yr	2nd yr	3rd yr	4th yr	5th yr	6th yr	7th yr
Project duration							
Publications (papers, conferences)							
Technology Implementation phase: Prototype Repairs							
Application on real structures HAI - ALENIA- IAI - OGMA							
Validation							
Approval by the Acceptance authorities JAA Certification							
Publication of the results							
Market survey							
Feasibility study							

REFERENCES

1. “Bonded Composite Repairs for Ageing Commercial Aircraft- A Multi-National Research Effort” by Arnold Nathan, Herman Leibovich and Dr Slava Krylov. 20th ICAF Symposium, 15 July 1999, Washington USA.
2. Z.P. Marioli-Riga, G.J. Tsamasphyros, G.N. Kanderakis, Development of a Method for A/C Emergency Repairs by Composite Patches, S.A. Paipetis, E.E. Gdoutos, (Xanthi1997), Vol II 143-156.
3. G.J. Tsamasphyros, G.N. Kanderakis, Z.P. Marioli-Riga, Three-dimensional Finite Elements Analysis of Debonding and Thermal Effects Near the Crack-Tip of a Metal Structure Repaired by a Composite Patch, 5th National Congress on Mechanics, University of Thessaly, Greece, June 1999.
4. Z.P. Marioli-Riga, G.J. Tsamasphyros, G.N. Kanderakis, Non Destructive Evaluation of the Crack Propagation under a Composite Patch Repair Using the Eddy Current Method, The International Society for Optical Engineering (Newport Beach, CA, USA, 5- 9 March 2000).
5. N.P. Furnarakis, G.J. Tsamasphyros, G.N. Kanderakis Z.P. Marioli-Riga, Three - Dimensional Finite Elements Analysis of Composite Patches with Structurally Integrated Fibre Optic Sensing The International Society for Optical Engineering (Newport Beach, CA, USA, 5- 9 March 2000).
6. G. Goulios , Z.Marioli-Riga, Composite Repair of metallic structures for ageing commercial aircraft (COMPRES) Conference Aerodays 2001 Hambourg.
7. G.Goulios , Z.Marioli-Riga ,Composite Patch Repairs for Commercial Aircraft , Air & Space Europe Vol 3, No ¾ -2001.Aircraft technologies & structures
8. «Comparison between Analytical and Numerical Methods for the Analysis of an Isotropic Structure Repaired by a Bonded Composite Patch», G. Tsamasphyros, G. Kanderakis, D. Rapti, D. Karalekas, E. Gdoutos.
9. Design of Emergency Aircraft Repairs Using Composite Patches, Z. P. Marioli-Riga, G.J. Tsamasphyros, G.N. Kanderakis, Mechanics of Composite Materials and Structures, 8:1-6,2001.
10. Poole, P., Brown, K., Lock, D., Stone, M., Sutton, G. and Young, A. “Effect of environmental exposure on bonded patch repair of cracked aluminium structures”, Proceedings of 2000 USAF ASIP Conference, San Antonio, 2000.
11. Poole, P. DERA/MSS/MSTR4/RF002540 : “Effect of primer on bond durability” DERA/MSS/MSTR4/LR004193 Contract No: COMPRES MSS Room G069, Building A7, DERA Farnborough Hampshire GU14 0LX. 21 December 2000
12. Material Selection & Design Allowable Data Generation
13. Poole, Armstrong. Brown, Pape and Young, “Bonded Composite Patch Repair of Thick Sections – Effect of Adhesive/Prepreg Co-cure and Service Temperature”, QINETIQ/FST/SMC.CRO13784, Issue 2, June 2002

COLLABORATION SOUGHT

Further improvement of the project main product is required before the exploitation phase starting. For this period, industrial partners will collaborate with their customers in order to apply prototype repairs and assess further improvement.