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A highly efficient ergonomic approach for the bonded repair of composite aerostructures utilising a virtual environment.

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Abstract

This work presents an innovative approach to produce standardised procedures for a specific type of damage and subsequent repair of a Carbon Fibre Reinforced Plastic Composite (CFRP) aerostructure, along with an analysis of the process based on ergonomic methodologies and digital tools. A case study is presented to illustrate the approach's unique ability to increase the operator efficiency and reduce the opportunities for injury. The key benefit of this research is the demonstration of the potentialities of using 3D environments to highlight process issues and to provide design suggestions that will reduce the time and cost of the repair.

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Keywords: Manufacturing; Human; Composite

1. Introduction

As the utilization of composites materials continues to increase, to meet the demand for advanced lightweight structures in the aerospace, automotive and rail industries, maintenance and repairability of the assets become key considerations. In some instances part replacement is both difficult and expensive, hence OEM engineers are considering the repairability of structural and secondary composite components during the initial design phase of a structure's development [1]. Furthermore, now that composites are becoming ubiquitous on primary aircraft structures, the quality of the repair, compaction of the repair patch and integrity of the bondline in adhesively bonded repairs become critical, driving a range of new technologies as well as the pursuit of a standardised repair technician certification.

This work addresses this issue by presenting an innovative approach to produce standardised procedures for a specific type of damage and subsequent repair of a Carbon Fibre Reinforced Plastic Composite (CFRP) aerostructure, along with an analysis of the process based on ergonomic methodologies and digital tools. The primary economic drivers for composite repairs are time and labour. Manual repairs are time-consuming and highly dependent on operator skill. The emergence of automated composite repair technologies has the potential of minimizing costs while improving reliability. Nonetheless, while automated scarfing and surface finishing tools are in their nascent phase of utilization within the aerospace industry, the completion of a repair is still subject to considerable manual intervention.

2. Literature Review

2.1. Industry scenario

Aircraft structures and specifically fuselages were chosen for analysis in this study. This is due to the fact that the aeronautical industry represents the highest value of sales for CFRP products globally [2]. Due to the rapid expansion of the utilization of composites in primary aerostructures, the servicing and repair of such structures has yet to mature. As a consequence, for example, there is a shortage of technicians capable of completing a patch repair to a CFRP composite and currently there are no industry wide standardised procedures for repairs. This issue was highlighted by the General Accounting Office (GAO) in America, an influential policy which issued a

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report expressing concerns about the accelerating use of composites in aircraft structures, highlighting repair issues as one a particular challenge [3]. The type of damage in a composite structure may involve a combination of matrix cracking, fibre breakage and delamination [4]. The extent of this damage and the projected reduction in structural integrity will determine the type of repair required. In this paper, the study is focused on a bonded scarf or patch repair. The lack of a standardized approach leads to variations in the methodologies currently adopted by industry [5]. Therefore, there is a need to produce a standardised and economical repair for industries that utilise CFRP composites.

2.2. Sustainable Manufacturing

The consideration of sustainability aspects in all phases of the manufacturing system life cycle is a central task in order to improve the overall factory sustainability, involving both technical and human factors. Ergonomic analysis of a work flow has historically been either neglected entirely or only very basic analysis performed due to the time and complexity of the task required. While this is a technology that has been moving into the automotive industry, currently very few businesses will use it to analyse a workcell. The introduction of 3D software modelling computer programmes such as JACKS, ANNIE-Ergoman and RAMSIS, has demonstrated excellent potential in evaluating workcells in the early design phase [6]. Their utility cannot be underestimated. According to the report "Costs to Britain of workplace fatalities and self-reported injuries and ill health, 2013/14" from the Health and Safety Executive (HSE, 2013/2014) there were 630,000 workplace accidents annually on average between 2012/2013 – 2014/2015 [7]. The cost of accidents to businesses, in time and money, is significant. Therefore, if the environment that operators have to work in can be evaluated to reduce the number of injuries/ occupational risks, the benefits will far outweigh the cost of such analysis.

The aim of this study is to analyse and design an efficient composite repair procedure for a specific problem. To identify a representative repair scheme, a number of industries were considered including marine, industrial, automotive and aeronautical applications. Aeronautical repairs were chosen because they represent the greatest revenues of CFRP global sales, 40% in 2012 [8], as well as the fact that it is an industry that is set to continue doubling in size every 15 years [9]. This procedure can be continually developed for new products entering the aircraft market and adapted for other applications.

The manufacture of aircraft entails a large carbon footprint [10] and in operation, a passenger aircraft will produce approximately 2-3 tonnes of carbon dioxide per person for a flight greater than 8 hours [11]. There is therefore a necessity to adopt an approach to increase the operating efficiency of the aircraft. A reduction in energy required to manufacture an aircraft will further potentially translate to a lower unit cost. One of the ways to do this is by reducing the weight of the aircraft (i.e. using composites) coupled with newer manufacturing techniques to create more efficient manufacturing processes and more complex geometries than can be traditionally manufactured [12]. Indeed, as alluded to earlier, lightweighting will deliver benefits across the whole transportation sector. As a specific example, the cost savings that CFRP will have over time, compared to steel, during the lifecycle of buses and trucks are highlighted in [13].

With this increased reliance on CFRP composites within the airframe of modern airlines, certain issues associated with the use of these materials require particular attention. One of the main issues is the repair of composites and how this can occur in a time and cost effective way at an airport apron/hangar. Authors in [14] highlight five main areas of concern with CFRP composite repair, including: structural safety, bond integrity, damage assessment, material removal and surface preparation. While this is a useful paper for describing the different tools that can be utilised within these five areas it does not go into detail on how to define certain damage and also does not describe what is the best repair for a certain type of damage.

2.3. Damage assessment

In order to fully understand how to repair a CFRP composite, it is necessary to ascertain the level of damage that has occurred in the first instance. CFRP fuselage composites react differently when damaged compared to traditional aluminum fuselage components [4]. The makeup of CFRP composites means that it is likely that if contact has occurred and the force is great enough to damage the material, the actual damage may not be visible, rather it may be within the composite structure, due to the laminar layers that make up CFRP composites. Therefore, there is a need to be able to "see into" the material to ascertain the damage that has been caused. A number of visual damage detection techniques are in common use which are appropriate for large scale surface damage (e.g. burns, holes, major impacts). For internal damage detection, a number of non-destructive tests (NDT) are available [15] such as ultrasonic inspection, thermographic inspection, vibration inspection and the use of PZT transducers for the generation and detection of lamb waves. Time-of- flight ultrasonic inspection techniques allow a detailed picture of the depth, size and location of multi-layered structures however it is more time consuming than thermographic inspection techniques. Therefore, when designing the process for repairing CFRP composites it will be necessary to evaluate the trade-off between the details of assessment of the area of concern compared to time taken to determine this damaged region. This is to ensure the procedure is economically viable. That said, for critical components such as an aircraft fuselage, all available information should be accessible to a repair operator, thereby aiding the decision process and ensuring the integrity of the repair.

Following on from assessing the damage, a clear analysis of the damage incurred needs to be carried out. The extent of damage and its impact on structural integrity, i.e. projected residual strength, will determine the type of repair required. A decision tree is often available to MRO personnel assist in determining the most appropriate repair, an example from BAE Systems is given in [16, 17]. While the principle of having different severities of damage is useful, this report does not define, in a quantitative or qualitative way, what constitutes superficial damage to severe damage. This information should be provided by the aircraft manufacturer in their MRO manuals. For the purposes of this work, the damage that will be analysed will be split into three categories: minor damage (damage up to 25mm in diameter and 0.5mm deep), partial damage (damage up to 25mm in diameter and more than 0.5mm deep) and through-thickness damage as described in [17].

2.4. Bonded repair

Once the problem has been specified the appropriate response can be decided. Occasionally it is not possible to fix the damage within a composite with a patch repair, as was highlighted by the Ethiopian airline whose batteries burnt through the CFRP composite fuselage. In this instance a large section had to be removed and a new piece manufactured and put into its place [3]. In [14] numerous techniques that are currently being utilised in order to achieve the desired result, depending on the size and magnitude of damage, are described.

Composite repair for aircraft is a new field of material engineering and therefore new techniques for repairs are being developed continually, e.g. [18] and [19] report on techniques such as self-curing patches and patches that can be cured using joule heating. While these techniques and others similar to them may become viable at some point in the future, for this study they have been disregarded since they are still in the early stages of development.

It is also important that the operators have the right skill levels in order to tackle the repairs that will be required as is highlighted in [5] and [16]. Authors in [16] describe how the most complex repairs have the most skilled operators working on them and by "working their way" through different repairs the operators build a skills base depending on the level of complexity of repair and skill required. This is a logical way of parting knowledge and could be adopted within the aircraft industry. That is not to say that this type of training is all that should happen, since external tuition may be useful and required from time to time due to the fact there are a lack of skills within the aircraft MRO sector as highlighted in [5]. From having the correct technique to fix the problem to having the operators who can carry it out with the correct skills, a framework that ensures quality of repair and repeatability is the aim to be achieved. Authors in [16] presented the framework used in Formula 1 manufacture to ensure a satisfactory result and therefore a framework similar to this could be utilised to ensure uniformity of repair and follow procedures in line with total quality management (TQM) principles [20].

2.5. Virtual repair

The process of composite repair needs to be verified before it is used on an airplane. This verification may occur in a number of ways: it could be tested in real life, however this can be expensive due to labour rates and the cost of material involved. By applying this technique in the repair process, it does not necessarily result in it being viable physically or economically. The issues that may occur would require human operators to perform the procedures as robotics, while promising [3] are not developed enough to be viable. Therefore, by analysing the repair within a virtual environment and applying ergonomic principles associated with workcell design, problems can be visualised and solved before they actually occur, saving time and costs. Hence it is important that the ergonomics of the tasks involved in a workcell are analysed and improved in order to ensure repeatability and reliability of the process but also to ensure that operators are capable of working safely. Studies carried out in [21] and [22] have shown the benefits of virtual reality simulation and ergonomic analysis within the work place. However, the quality of the simulation is dependent on the information that is fed into the system about workstation dimensions and geometric features. It is therefore, sometimes difficult to have a completely accurate model.

By applying the correct ergonomic principles during design, life cycle costs can be reduced, as highlighted in [23]. Historically, ergonomic optimisation has been analysed using statistical data in a tedious process therefore making it difficult to practically implement within the workplace. Now that there are numerous commercial software tools available to perform ergonomic studies, the process has sped up, making it more viable for businesses. Some of the main software tools designed have been highlighted in [24]. In the paper the software tools are analysed and it was concluded that all have a good potential in evaluating workcell ergonomics. Therefore, provided the model is set up correctly, there is no reason why it should not be capable of giving valid readings for analysing the ergonomics of an operator completing a composite repair. The method of analysing the ergonomics of a workcell comes from [6]. In the paper, two methods are presented and analysed; the Posture Evaluation Index (PEI) and the Workcell Evaluation Index (WEI). In order to calculate the WEI it is necessary to complete an analysis of the PEI for every operation. Even though there are some assumptions, such as non-excessive working temperature and appropriate rest periods, the methodology provides a valid tool for workcell analysis in order to reduce the number of accidents/incidents and thus increase productivity [25].

3. Methodology

3.1. Stage 1-Standardised repair procedure design

A key aspect of designing a suitable repair is to understand the type of damage that could be inflicted by ground crew on aircraft fuselages and how the repair is to be performed. In [17], the different types of damage that can occur to a CFRP structure were classified in three types. In the types of damage were further categorised and analysed thus helping to define the repair technique for certain forces applied to CFRP aircraft structures. From these two studies it was shown that each type of damage can result in a different repair procedure due to the different severities. Fig. 1 demonstrates the procedure to follow in order to decide how to define the scale of the damage and the actions to be taken.

Three main types of damage can be inflicted upon a CFRP fuselage and the specifications of these types of damage are “Minor Damage”, “Partial Damage” and “Through thickness damage”. By assessing the type of damage it is then possible to make an informed decision on what are the correct actions to take.

The area of focus of this work is on partial damage, this means that the process was designed around this severity of damage as each type of damage requires a different technique. A repair process was designed in order to ensure the fuselage could be fully repaired.

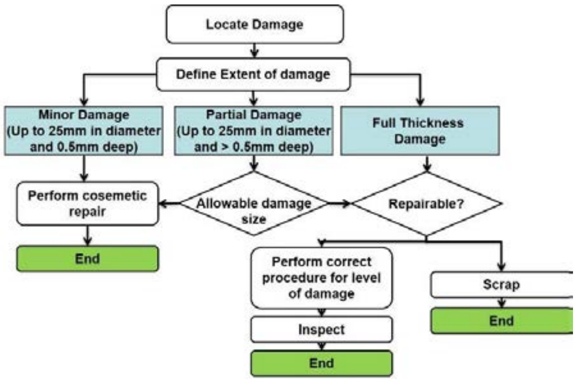


Fig. 1. Process for diagnosing severity of damage [17].

Table 1. Repair method for CFRP Damage.

Macro Operation 1	**Remove damaged CFRP layers to required depth**
OP 1.1	Mark out affected area with tape
OP 1.2	Calculate depth and size of layers to remove
OP 1.3	Removal of damaged material
OP 1.4	Clean surface
Macro Operation 2	**Create new patch**
OP 2.1	Source CFRP sheet compatible with fuselage CFRP material
OP 2.2	Cut out sizes of CFRP depending on depth and sizes of material removed by laser
OP 2.3	Lay non-stick plastic down on work bench
OP 2.4	Lay cut-outs flat on plastic sheet
OP 2.5	Cut CFRP pre-preg
Macro Operation 3	**Insert patch in place and cure**
OP 3.1	Laying pre-preg on fuselage
OP 3.2	Ensure layers are oriented correctly and that all air pockets are removed
OP 3.3	Place no stick plastic sheet over outer layer of repair
OP 3.4	Attach heating elements to fuselage
OP 3.5	Place blanket over heating elements and cover with vacuum bag
OP 3.6	Apply heat to the patch along with vacuum to cure the repair
OP 3.7	After curing remove vacuum, blanket and heating elements
Macro Operation 4	**Finish patch**
OP 4.1	After testing the repair sand down the outside of patch ensure it is smooth
OP 4.2	Clean surface using appropriate methods
OP 4.3	Apply correct paint to repair area
OP 4.4	Allow time for paint to cure

In Table 1 the macro procedures for removing damaged CFRP layers and creating a new patch are described. By breaking down these processes into distinct operations it allows a greater understanding of the procedure as a whole, facilitating the development of an efficient and flexible solution. These procedures were analysed in greater detail in order to understand the sequence of operations involved in the process designs and the equipment necessary to be modelled at a later stage in the study. The procedures for inserting the CFRP patch, curing and also the finishing of the repair are also described in Table 1.

3.2. Stage 2 – Work cell ergonomic evaluation design

In order to evaluate the ergonomics of the workcell, the design process was carried out in accordance with the macro processes described in Table 1. Following the sequence of operations, tools and materials were specified which allowed the process to be completed using current techniques from the CFRP industry. These techniques were adapted to new technologies to improve operator’s health and the accuracy of the repair. Once an initial idea of the processes and tools required to complete the procedure were known, the work space tools and a digital mock-up of the fuselage were designed using 3D software packages such as SolidWorks and Inventor. From there the individual models were imported into a digital environment. A virtual workcell was created in order to simulate the tasks as described in table 1.

By utilising this workcell design the critical postures of the operator were identified. The critical postures were decided by the frequency that the operator would use a certain posture and the importance to the task. Once the initial postures were defined, the sequence of operation was simulated. This aided with producing realistic times for the operator to walk around the production area.

By simulating the operations in a virtual environment, the workers’ postures were evaluated using the Posture Evaluation Index (PEI), developed and illustrated in [6]. The PEI integrates the results of the Low Back Compression Analysis (LBA) [26], the Ovako Working Posture Analysis (OWAS) [27], and the Rapid Upper Limb Assessment Analysis (RULA) [28], in a synthetic non-dimensional index able to evaluate the “quality” of a posture:

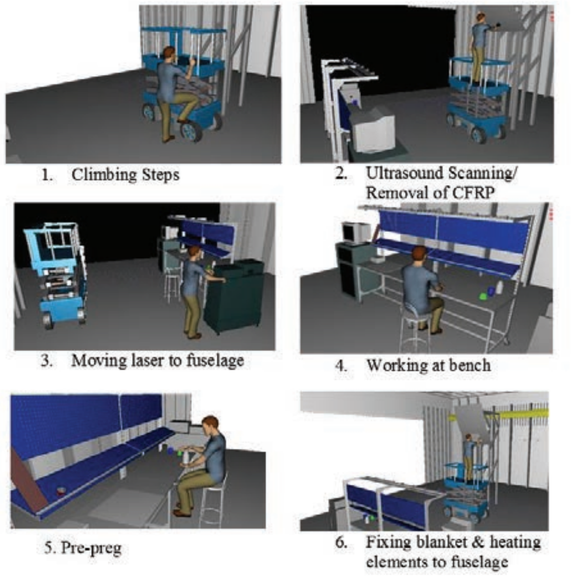
$$PEI = \frac{\mathrm{LBA}}{3400} + \frac{\mathrm{OWAS}}{3} + \frac{\mathrm{RULA}}{5} \tag{1}$$

The first phase was to consider the possible alternatives of movement to ensure that the operator was able to move around safely and efficiently within the workcell; this generally implied analysis of the alternative routes, postures and speeds of execution. This was followed by the use of digital human modelling software for reachability and accessibility analysis of critical postures. The procedure was designed to verify that within the designed layouts, every movement required was feasible and thus all critical positions and areas could be reached by an operator. A collision detection tool was used to verify these parameters.

Seven critical postures, which the operator would assume while performing the repair procedures, were identified.

The seven operations associated with the critical postures identified are as follows:

1. Placing steps next to fuselage
2. Climbing steps
3. Ultrasound scanning/removal of CFRP
4. Moving laser to fuselage
5. Working at the bench
6. CFRP Pre-preg
7. Fixing blanket & heating elements to fuselage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4. Working at bench
5. Pre-preg
6. Fixing blanket & heating elements to fuselage

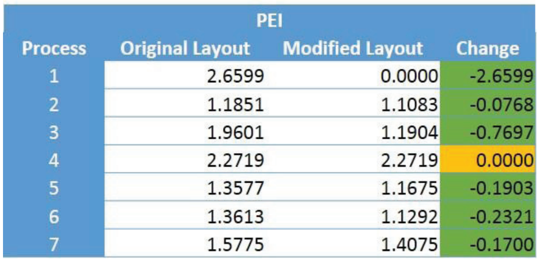
Fig. 2 Revised workcell configurations: sequence of operations reduced to six.

After the results for the PEI were calculated for the seven critical configurations, the PEI of each configuration was analysed against the benchmark, PEI < 3 [6].

This allowed for the review of the procedures and equipment initially used to obtain these values. In order to improve PEI of certain postures reducing to acceptable levels, the layout of tools were modified, the operator postures were changed in sitting position rather than standing and also a scissor lift was utilised instead of stairs. In order to validate the changes applied to the critical configurations, the PEI analysis was performed again using the new postures and configuration of equipment along with the new timings of the workcell. In order to adequately improve the results, the repair procedure was optimised until the PEI was acceptable whilst still allowing a satisfactory repair. Fig.2 shows the final configuration of the workcell.

3.3. Stage 3 – Work cell optimization results

Fig.3 shows the improvements made to the workcell. Firstly, the initial task was completely removed since it is now carried out by moving a motorised scissor lift into the area.



	PEI		
Process	Original Layout	Modified Layout	Change
1	2.6599	0.0000	-2.6599
2	1.1851	1.1083	-0.0768
3	1.9601	1.1904	-0.7697
4	2.2719	2.2719	0.0000
5	1.3577	1.1675	-0.1903
6	1.3613	1.1292	-0.2321
7	1.5775	1.4075	-0.1700

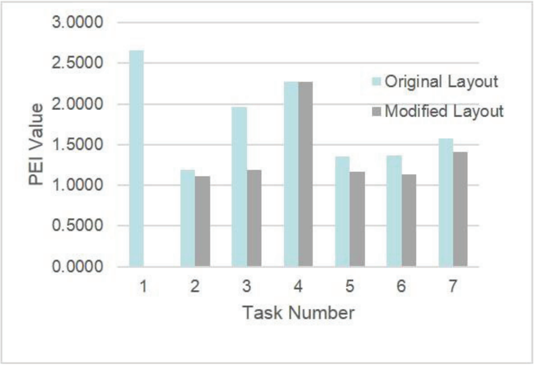


Fig. 3. Comparison of PEI results.

The PEI value reduced by an average of 23% for the remaining tasks

By allowing the operator to sit down while working at the bench, the forces on the low back reduced dramatically and support to the arms of the operator were added. This resulted in an improvement of the PEI for task 5 and 6.

Finally task 7 was improved also due to the use of a scissor lift which allowed the operator to work at a higher level and closer to the work piece therefore resulting in an improved ergonomic grip and stance.

4. Conclusions

In this study a methodology for the repair of a carbon fibre composite fuselage was developed. This methodology should enable the repair procedure to be standardised across different aircraft manufactures and may have relevance in other industries. The initial ergonomic analysis of the critical postures showed that there were areas for improvement which lead to a change in the workspace design and modification of the procedure in order to improve the ergonomics of the workcell.

The method for completing a repair on a CFRP fuselage is crucial for aircraft manufacturers, maintenance contractors and operators. This is due to the fact that currently there are no standard work procedures in order to repair a CFRP fuselage, however each manufacturer has their own repair method. This issue, coupled with the fact that there is a shortage of skilled CFRP repair technicians means that by having a standardised repair process that can be applied across various aircraft types, will ensure a reliable and repeatable repair process that can be followed across most, or all, MRO centres equipped for composite repair work. As the aircraft industry expands into developing economies it is likely that repair operators may not have the correct skill set to perform a repair. Therefore, having a standardised procedure will aid with training and development of operators capable of performing the repairs. In addition, by implementing a standardised procedure it will be expected that the MRO of aircraft will be improved and become more economical, flexible and efficient.

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