ΜΗΧΑΝΙΚΗ.— **Composite Structures in Commercial Aircraft: From Research and Development to Field Experience,** by Corresponding member of the Academy of Athens *James C. Seferis, and Shangying Zeng, Alan G. Miller, Donald S. Krebs and Carlos Blohm*.*

INTRODUCTION

Composite materials are opening a new era in modern aviation. They have been in service in basically every new aircraft developed in the last decade, and will be in large scale usage in the future. This may be attributed to many advantages over traditional load bearing engineering materials including higher performance to weight ratios, increased fatigue life and increased corrosion resistance [1, 2]. The outstanding performance to weight ratio leads to lighter aircraft structures; consequently, additional payloads are possible with possible reduction in operational costs. On the other hand, considerable less corrosion and fatigue problems lead to larger service life times and maintenance intervals, and fewer inspection requirements. Therefore, lower maintenance costs in principle should be obtained. Composite structures are generally constructed by layers of unidirectional fibers or fabric (prepreg) held together by polymer matrices through prepregging and autoclave curing processes as schematically shown in Figure 1. Prepregging and autoclaving are in principle low cost operations, and together with the high parts integration compensate for the relatively high raw material costs, and thus may lead to a lower part costs [1].

However, the advantages mentioned above can only be fully exploited as long as there are no failures or damages to the composite structures during their life-time performance. In practice, although corrosion and fatigue have been practically eliminated with the use of composite structures, more expensive repairs have been realized in dealing with larger damages due to Foreign Object Damage (FOD), lightning striking, etc[1]. A recent survey of al-

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most 1500 aircraft on damage to composite elevators on Boeing 737, 757, and 767 aircraft revealed only 40 problem reports, as schematically summarized in Figure 2, with the specific type of damage reported shown in Figure 3 [3].

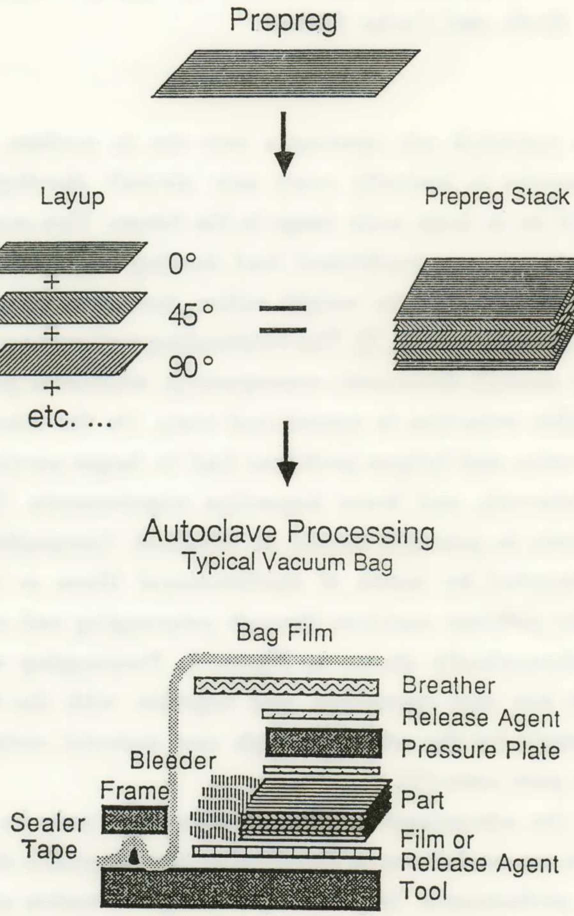

Figure 1. Laminated Structures Made of Prepreg via Vacuum Bag/Autoclave Techniques.

For the airplane operators, the key issues are safety, economics and robustness of repairs. Due to extremely high spare part prices, they are forced to perform composite structural repairs whenever it is possible to avoid scrapping the expensive parts [1]. Unfortunately, the economic benefit realized by the airplane manufacturers from improvements with composites may present the airplane operators with difficult repair options. The repair of composite structures may need to follow a totally different approach than the traditional

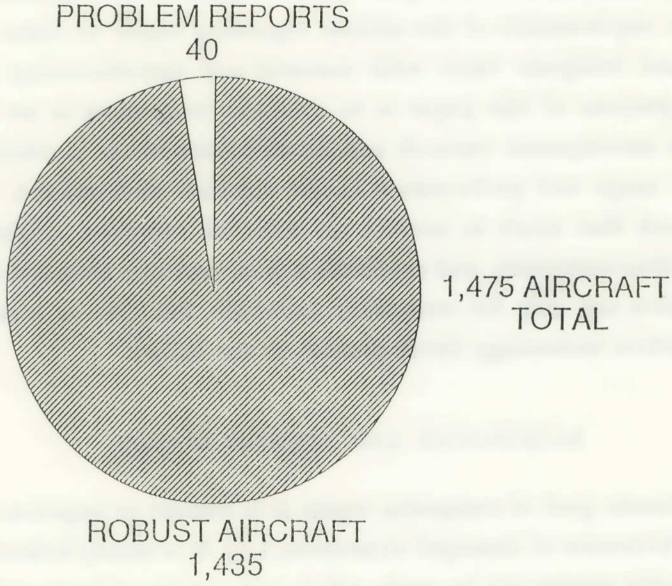

Figure 2. Survey Results of Composite Elevator Damage on Boeing B-737, 757, and 767 Aircraft.

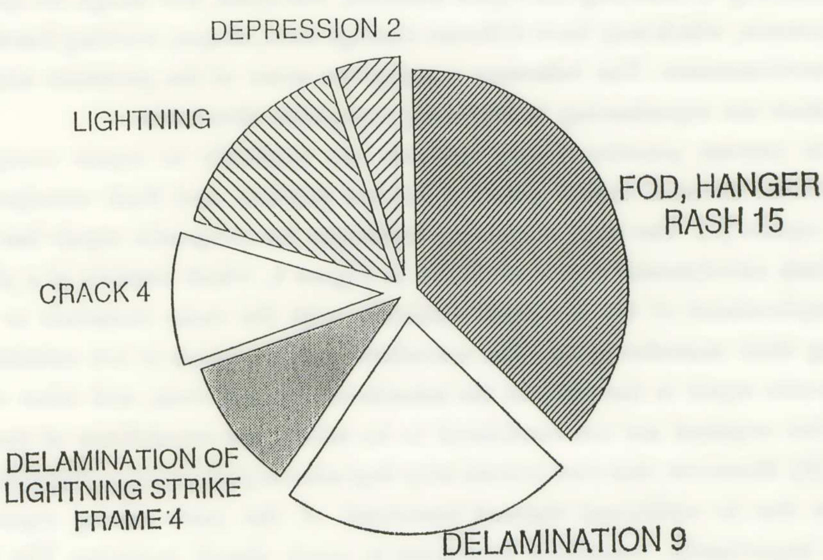

Figure 3. Type of Damage Reported on Damaged Composite Elevators as Shown in Figure 2.

production philosophy of the original parts. Therefore, it is necessary to understand the requirements of the airlines regarding repair to these composite structures and integrate them with material and manufacturing processing issues. The purpose of this paper is to examine composites in an integrated manner that encompasses research and development issues in relating manufacturing to usage and performance in the airplane environment. Finally, a team approach that needs to involve the material suppliers, airplane manufacturers, airline customers, and academia is proposed as a means of developing this integration not only for composite materials, but also as a requirement for cost effective technology developments in the future.

BACKGROUND AND CURRENT STATUS

The ultimate goal of composite repair is to restore or improve the integrity and performance of damaged structures [1,4]. It is widely believed that reliable composite repairs can be made which will restore at least of 80% of the parent laminate static strength and will retain this strength for at least one design life-time [5]. Thus, any damage less than 15 percent is considered repairable [6]. However, in order to repair composite structures, the airlines run into the difficulty of selecting the repair methods, materials, and design for specific components, which may have different damage sizes, shapes, working functions, and environments. The following summarizes some of the problems airplane operators are experiencing in repairing composite structures.

In current practice, three methods are available to repair composite structures: external bolted patches, bonded patches, and flush aerodynamic plug repairs [7]. The most promising technique for composite repair has been the flush aerodynamic repair as shown in Figure 4, which consists of a ply by ply replacement of the damaged materials with the same materials as used during their manufacturing. The autoclave curing process is not suitable for composite repair in the field, as the autoclaves, freezer, oven, and other major facilities required are not considered to be within the capabilities of the airlines [8]. Moreover, this cure process may degrade the performance of undamaged region due to additional thermal treatment of the parts during repair [6]. Most importantly, composite structures in usage absorb moisture. The presence of moisture can cause delamination within the composite structure during the high temperature repair process, especially for honeycomb sand-

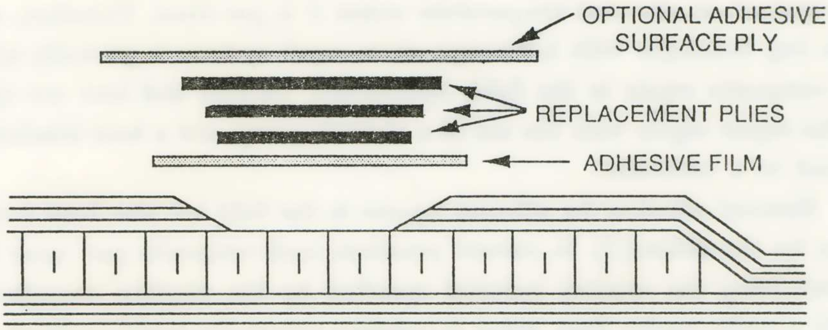

Figure 4. Flush Aerodynamic Scarf Repair for Composite Structures.

wich structures. Figure 5 plots the honeycomb internal pressure during cure, generated from classic steam tables and experimental adhesive flatwise tensile strengths as a function of temperature. The intersection of the two curves indicates the initial point of bond failure between the honeycomb core and the laminate skin. Obviously, the honeycomb sandwich structure should not

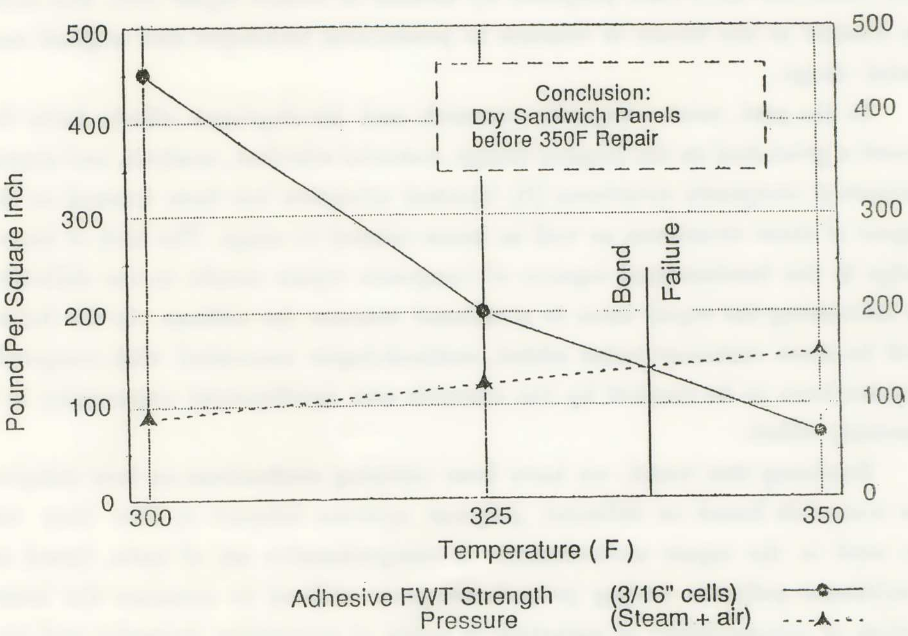

Figure 5. Calculated Honeycomb Panel Internal Pressure due to Water and Measured Adhesive Flatwise Tensile Strength as a Function of Temperature.

be repaired at elevated temperature unless it is pre-dried. Therefore, a vacuum bag technique with low temperature repair systems is generally selected for composite repair in the field. Specifically, vacuum and heat are applied to the repair region with the aid of a vacuum pump and a heat blanket connected to a controller.

Material selection for efficient repairs in the field has also been a critical issue for the airlines[2]. In current practices, each composite part must be repaired using the original material specified by the airplane manufacturer. With a multi-vendor fleet, which is common among the world's airlines, there is a need for airlines to have as many as 65 different materials available for repairs [2]. For thermoset based composites, each material has a limited shelf life (6-12 months) and must be stored in a freezer. Waste can be high due to the difficulty in obtaining small amounts of materials from the manufacturers in a timely manner. Repair kits are available, but are only effective if the part to be repaired is in a depot or the aircraft is on a maintenance cycle. Besides, the high cure temperature and long cure time are also not acceptable for the airlines. Long shelf life, low temperature cure, and short cure time of the repair materials have been proposed by airlines to reduce repair cost, and must be studied in the future in relation to production technique and original material usage.

In the past, most composite research and development efforts have focused a great deal on the original design, material selection, analysis, and manufacture of composite structures [8]. Limited attention has been focused on the repair of these structures as well as issues related to usage. The lack of knowledge in the fundamental aspects of composite repair results in the difficulty in addressing the repair issue in a rational manner for airlines. As the future will be more customer value added, methodologies associated with composite repairs have to be created by the research and development community in a teaming effort.

Realizing this trend, we have been carrying evaluations on how composite materials based on different polymer systems interact so that they can be used in the repair environment. A comprehensive set of tests, based on traditional polymer testing procedures, were utilized to examine the interaction or compatibility of materials in terms of processing, property and molecular structure. Specifically, attention has been focused on the interaction between adhesives and prepreg materials typically found in repair processes, and how different combinations of materials will exhibit «composite» proper ties. For instance, the glass transition temperature has been considered as the most important variable (property) that is associated with material interaction. By generating the correlation between glass transition temperatures and compositions, a positive or negative deviation from the rule of mixture can be observed, as shown in Figure 6. As the degree of this deviation is associated with the degree of interaction or compatibility between dissimilar materials, it can be used for both quantitative and qualitative evaluation of resin compatibility. Thus, a valuable tool for determining which material systems are compatible can be developed, and used for specific composite repair applications.

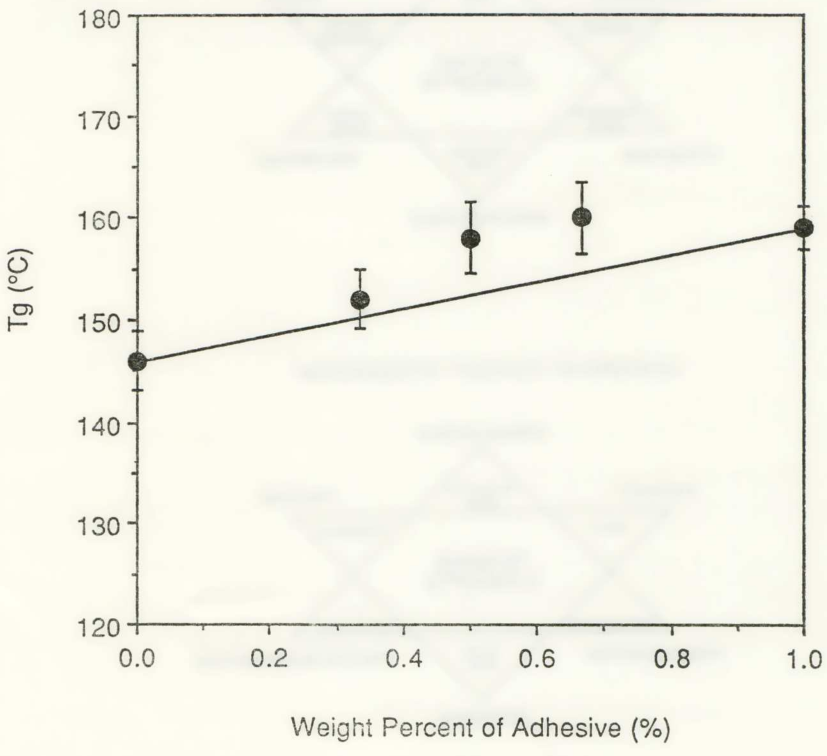

Figure 6. Glass Transition Temperature Measured by MDSC of Prepreg/Adhesive Resin Mixtures Used in Manufacturing and Repair.

CONCLUSIONS

In the future, the driving force for technology incorporation in commercial aircraft will not take place solely on its own merits [1]. New technologies such as advanced composite structures will need to be seen as a net benefit to the customer (i.e. airlines and eventually the flying public) [3]. This will include traditional factors such as cost of fuel saved, payload capacity, and costs of composite repairs that are comparable to metal repairs. However, considerations

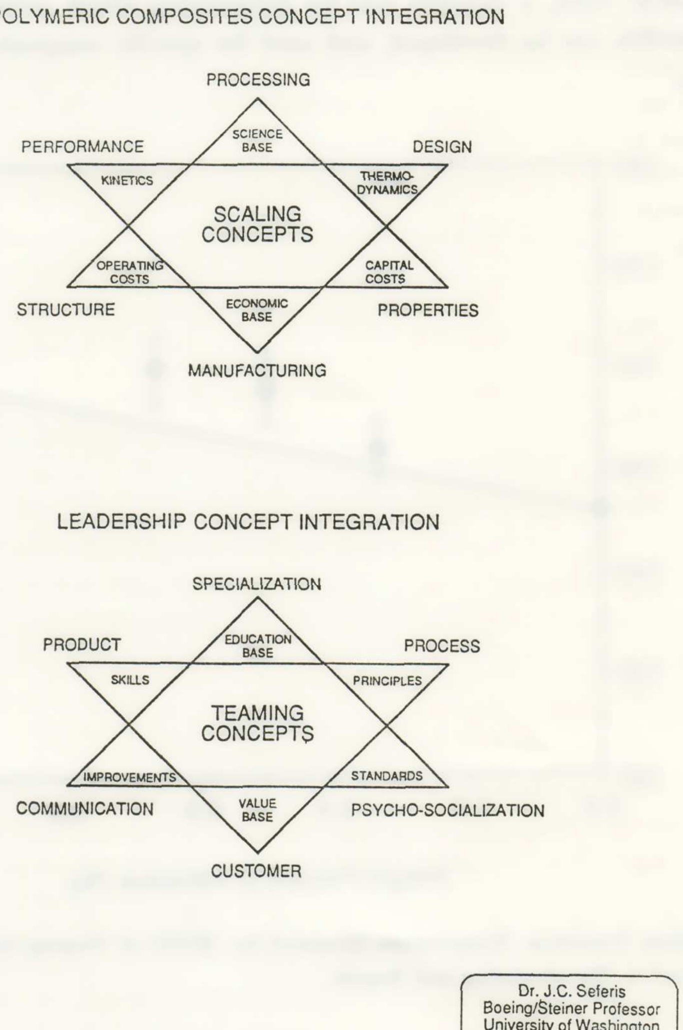

Figure 7. Methodologies for Technical and Non-technical Developments.

will also include factors such as maintenance base facilities, required personnel skill levels, and the overall airplane operating system infrastructures. Therefore, repairability and maintenance will become major issues in the future. The material suppliers, airplane manufacturers, and academia must begin to increase their appreciation of the difficulties associated with repair and maintenance, and concentrate more resources upon understanding both technology and difficulties of working together. More importantly, a team effort involving suppliers, manufacturers, academia, and customers has to be implemented.

Indeed, by analogy to the well established «double trinity» methodology by which basic science principles of polymeric composites through heterogeneous, anisotropic, and viscoelastic scaling concepts provide the foundation for economic integration of manufacturing, design and performance, a «double trinity» for leadership development has emerged and summarized in Figure7 [9]. Although this new «double trinity» cannot be fully quantified, it can serve as a road map for our future. Specifically, by using «teaming concepts» for composite repair with analogy to the scaling concepts, a methodology is evolving for future development of education and training. Specifically, teams that are

SCALING CONCEPTS

Heterogeneous

Anisotropic

Viscoelastic (Liquid - Solid)

TEAMING CONCEPTS

Heterogeneous

Global

C - C (Competitive - Collaborative)

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Figure 8. Analogy between Technical Scaling Concepts and People Teaming Concepts.

heterogeneous (e.g., engineers vs. economists), global (e.g. U.S., Europe, Asia), and whose members are viewing the functions both in competitive and collaborative terms (e.g., Boeing vs. Deutsche Airbus) will be necessary in future developments (Figure 8). Additionally, to quickly resolve problems that invariably come up, this integrated team with capabilities from different disciplines must be able to work together long enough to develop the internal knowledge and cross-functional skills. Only through this approach, the incorporated essential aspects of customer needs, enhanced design and manufacturing simplifications, basic understanding of fundamentals and improved quality characteristics can be achieved through people going through major changes in their learning processes.

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ΠΕΡΙΛΗΨΙΣ

Σύνθετα ὑλικὰ σὲ ἀεροπορικὲς κατασκευές. Ἀπὸ τὴν ἔρευνα στὴν ἐφαρμογὴ καὶ χρήση

Τὰ σύνθετα ὑλικὰ ἀνοίγουν νέους ὁρίζοντες εἰς τὴν σύγχρονον ἀεροπορίαν. Ἤδη ἔχουν εἰσέλθει καὶ ἀποτελοῦν τμήματα εἰς ὅλας τὰς ἀεροπορικὰς κατασκευὰς τῆς τελευταίας δεκαετίας καὶ ἡ περαιτέρω συμμετοχή των προμηνύεται ἀκόμη μεγαλυτέρα. Ὁ λόγος αὐτὸς τῆς ἐξελίξεώς των, ὀφείλεται εἰς τὰ πολλὰ πλεονεκτήματα τὰ ὁποῖα παρουσιάζουν τὰ ὑλικὰ αὐτὰ ἐν συγκρίσει μὲ τὰ παραδοσιακὰ τοιαῦτα. Ἰδιαιτέρως σημαντικὴ εἶναι ἡ συμπεριφορὰ τῆς ἀντοχῆς των, ἐν συγκρίσει πρὸς τὸ βάρος των, ἡ ηὐξημένη διάρκεια κοπώσεώς των καθὼς καὶ ἡ ηὐξημένη ἀντίστασίς των εἰς διάβρωσιν. Ἡ σημαντικὴ συμπεριφορὰ τοῦ λόγου τῆς ἀντοχῆς των πρὸς τὸ βάρος των συνεπάγεται ἐλαφροτέρας ἀεροπορικὰς κατασκευὰς καὶ ἑπομένως μεγαλύτερα ὠφέλιμα φορτία μεταφορᾶς μὲ περιορισμὸν τοῦ κόστους λειτουργίας των. Ἐξ ἄλλου ἡ περιορισμένη ἐξέλιξις διαβρώσεως καὶ ὁ περιορισμὸς τοῦ φαινομένου κοπώσεως τῶν ὑλικῶν αὐτῶν ὁδηγεῖ εἰς λειτουργίαν τῶν ἀεροπορικῶν κατασκευῶν μακροτέρας διαρκείας μεταξὺ περιόδων συντηρήσεων καθὼς ἐπίσης καὶ ὀλιγωτέρας ἀπαιτήσεις ἐπιθεωρήσεων. Τὰ ἀνωτέρω συνεπάγονται μικροτέρας δαπάνας συντηρήσεως μὲ τὴν αὐτὴν ἀπόδοσιν.

Κατασκευαὶ ἐκ συνθέτων ὑλικῶν δημιουργοῦνται γενικῶς μὲ στρωματώσεις ἰνῶν ἀποκλειστικῆς διευθύνσεως, ἢ καὶ μεμβρανῶν μὲ διαπεπλεγμένας ἴνας, αἱ ὁποῖαι συγκρατοῦνται μεταξύ των τῇ βοηθείᾳ τῆς πολυμερικῆς μήτρας διὰ καταλλήλου προπαρασκευῆς σὲ αὐτοκλείστους συσκευὰς ὅπου ὑφίστανται διαδικασίας ἑψήσεως. Ἡ τοιαύτη προετοιμασία εἶναι μιὰ διαδικασία μᾶλλον ἐφθηνὴ καὶ ἡ ἀνάγκη συνεργασίας μεγάλων τεμαχίων ἐλαττώνουν σημαντικῶς τὸ ὑψηλὸν ἀρχικὸν κόστος τῶν ὑλικῶν. Τὰ ἀνωτέρω δύνανται νὰ ἐπιτευχθοῦν καὶ πλήρως νὰ χρησιμοποιηθοῦν ἐφόσον ἀποφεύγονται ἀστοχίαι καὶ καταστροφαὶ τῶν συνθέτων κατασκευῶν κατὰ τὴν διάρκεια τῆς ζωῆς τῶν ἀεροπλάνων.

Διὰ τοὺς λειτουργοὺς τῶν ἀεροπλάνων ἡ βασικὴ ὑποχρέωσις συνίσταται εἰς τὴν ἐξασφάλισιν τῆς ἀσφαλείας τῆς κατασκευῆς καὶ τῆς οἰκονομίας καὶ ἀντοχῆς τῶν ἐπισκευῶν. Δεδομένης τῆς ηὐξημένης τιμῆς τῶν ἀνταλλακτικῶν αἱ ἀεροπορικαὶ ἑταιρεῖαι εἶναι ὑποχρεωμέναι νὰ προβαίνουν σὲ ἐπισκευὰς σημαντικῶν τμημάτων τῶν ἀεροπλάνων ἀποφεύγουσαι οὕτω τὴν ἀπόρριψιν μεγάλων τμημάτων.

Ἡ ἐπισκευὴ τῶν συνθέτων δομῶν εἶναι ἀπαραίτητον νὰ ἀκολουθήσῃ ἐντελῶς διάφορον φιλοσοφίαν ἀπὸ τὸν κλασσικὸν τρόπον κατασκευῆς τῶν ἀρχικῶν τεμαχίων. Ἑπομένως εἶναι ἀπαραίτητον νὰ μελετηθοῦν καὶ νὰ γίνουν ἀντιληπταὶ αἱ ἀπαιτήσεις ἐπισκευῶν εἰς τὰς ἀεροπορικὰς ἑταιρείας αἱ ὁποῖαι εἶναι ἀνάγκη νὰ ἐκπαιδεύσουν καταλλήλως τὸ προσωπικόν των.

Ὁ σκοπὸς τῆς ἀνακοινώσεως αὐτῆς ἀφορᾶ τὴν μελέτη τῶν συνθέτων ὑλικῶν ὡς συνόλου ἡ ὁποία συμπεριλαμβάνει τὴν ἔρευνα καὶ τοὺς τρόπους ἐφαρμογῆς των σχετιζομένους μὲ τὴν κατασκευὴ καὶ τὴν συμπεριοφρὰν τοῦ περιβάλλοντος τοῦ ἀεροπλάνου. Τέλος μία διαδικασία ὁμαδικῆς συνεργασίας εἶναι ἀπαραίτητη νὰ ἀναπτυχθῆ μεταξὺ τῶν προμηθευτῶν τῶν ὑλικῶν, τῶν κατασκευαστῶν τῶν ἀεροπλάνων, τῶν ἀεροπορικῶν ἑταιρειῶν ὡς πελατῶν καὶ τῶν ἐπιστημόνων τῶν ἐρευνητικῶν καὶ πανεπιστημιακῶν κέντρων ἡ ὁποία θὰ ὁδηγήση εἰς τὴν ὁλοκλήρωσιν τῆς ἀντιμετωπίσεως τῆς καλῆς λειτουργίας καὶ τῆς ζωῆς τῶν ἀεροπλάνων.