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EFFECT OF REPAIR ON THE ELECTROMAGNETIC SHIELDING PROPERTIES OF COMPOSITE MATERIALS

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 97-001

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ABSTRACT

Composite materials are increasingly being used for the construction of aircraft because of their superior physical properties. Maintenance of adequate electromagnetic (EM) shielding inside the aircraft is often a concern because of the increasing use of sensitive avionics. Degradation of EM shielding provided by the skin of the aircraft during repair can be of particular concern.

In this report, we present results of measurements that we have made to examine the effect of repair on the magnetic and electric shielding properties of carbon/epoxy laminates. In carrying out this study, we have used the conventional repair techniques that are used for repair of the CF-18 aircraft. These methods include the application of epoxy bonded carbon/epoxy and titanium patches, and the use of a bolted aluminum rapid repair (battle) patch. In all cases the patches were applied over a 75 mm hole in an 8-ply AS-4 carbon/epoxy laminate.

The results show that the use of a carbon/epoxy or a titanium patch results in a degradation of the magnetic shielding of the carbon/epoxy laminates by as much as 40 dB. This large degradation is attributed to the loss of electrical contact between the patch material and the laminate. The degradation of magnetic shielding with a bolted aluminum patch is less severe (~20 dB) because the bolts provide some electrical contact between the patch and the laminate. Similar results are presented for the effect of repair on electrical shielding.

Limited results are presented that show that shielding can be substantially improved by providing electrical contact between the laminate and the patch material.

RÉSUMÉ

La popularité grandissante des matériaux composites en contruction aéronautique s'explique par leurs propriétés physiques supérieures. Étant donné l'emploi de plus en plus répandu de matériel électronique de bord (avionique) sensible, l'entretien d'une protection électromagnétique (EM) adéquate s'avère une préoccupation fréquente, surtout en ce qui concerne la déterioration, lors d'une réparation, de la protection EM fournie par le revêtement de l'aéronef.

Dans le présent rapport, nous exposons les résultats de mesures effectuées dans le but d'examiner les effets d'une réparation sur les propriétés de protection électrique et magnétique des stratifiés carbone-époxide. Lors de ces essais, nous avons employé les techniques de réparation conventionnelles des appareils CF-18. Ces méthodes comportent la pose de pièces de titane et de carbone-époxide liées à l'époxide, ainsi que la pose de pièces boulonnées de dépannage rapide (bataille) en aluminium. Dans chaque cas, les pièces ont été appliquées sur un trou de 75 mm, dans un stratifié carbone-époxide de type AS-4 de huit épaisseurs.

D'après les résultats, l'emploi d'une pièce en carbone-époxide ou en titane cause une déterioration de l'ordre de 40dB de la protection EM du stratifié carbone-époxide. Une telle déterioration s'explique par la perte de contact électrique entre le matériau de la pièce et le stratifié. Cependant, cette déterioration est moindre dans le cas de la pièce boulonnée en aluminium (20dB), les boutons assurant un certain contact électrique entre la pièce et le stratifié. Nous présentons des résultats similaires en ce qui a trait à l'effet de la réparation sur la protection électrique, alors que des résultats limités démontrent qu'il est possible d'améliorer considérablement la protection grâce au contact électrique entre le stratifié et le matériau de la pièce.

EXECUTIVE SUMMARY

The use of composite materials for the construction of aircraft and ships is becoming increasingly more common because of their superior specific strength and stiffness, light weight, low electromagnetic signature, flammability resistance, low cost and ease of manufacture. In almost all cases, however, successful operation of these vehicles depends on the reliable operation of sophisticated electronic systems for flight control, navigation, self-defence and fire control. Protection of these electronic systems from the severe electromagnetic environment, including high power microwave (HPM) sources, that can be encountered during operation is a necessity. The increased susceptibility of modern microelectronic systems to electromagnetic interference (EMI) makes the job of providing adequate shielding all the more difficult.

In order to ensure adequate EM shielding, a knowledge of the electromagnetic (EM) properties of these anisotropic laminated materials is necessary. Because of their limited conductivity, composite materials generally provide poorer shielding than metallic structures. Other aspects requiring close attention during the design, construction and life cycle phases include electrical bonding of composite panels, repair and EM hardness maintenance. In previous studies, we have examined the intrinsic EM shielding properties of aircraft composites.

In this report, we present the results of measurements that we have made to examine the effects of using conventional aircraft repair techniques on the EM shielding that is provided by the skin of the aircraft. The results have shown that repair can reduce EM shielding by two orders of magnitude (40 dB). This large degradation is attributed to the loss of electrical contact between the patch material and the laminate. Poor EM shielding could result in a degradation of aircraft performance.

Preliminary experiments were carried out to examine if the electromagnetic shielding of the repaired composites could be improved by improving the electrical contact between the repair patch and the main composite aircraft structure. Limited results obtained in this work show that shielding can be substantially improved by providing electrical contact between the laminate and the patch material. Further work is required to see if repair techniques can be developed that maintain both structural strength and improved electrical contact.

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1.0 INTRODUCTION

Composite materials are increasingly being used by the designers of military aircraft, ships and land vehicles. As an example, Figure 1 shows the use of carbon/epoxy composites in the CF-18 aircraft. Traditionally, the use of composites for the construction of aircraft has been driven by the superior specific strength and stiffness of these materials which allows a significant reduction in weight. More recently, other factors such as the ease of shaping composites has led to their use for the minimization of radar cross-section (RCS).

A number of techniques have been developed for the repair of the composite sections of aircraft when damage occurs. In general, however, these repair techniques either provide no or poor electrical contact between the patch and the composite structure. Because of this loss of electrical contact, it can be anticipated that the EM shielding of composite aircraft will be degraded after repair. In this report, we report results of measurements that we have made to examine the effect of repair on the magnetic and electric shielding effectiveness of carbon/epoxy laminates.

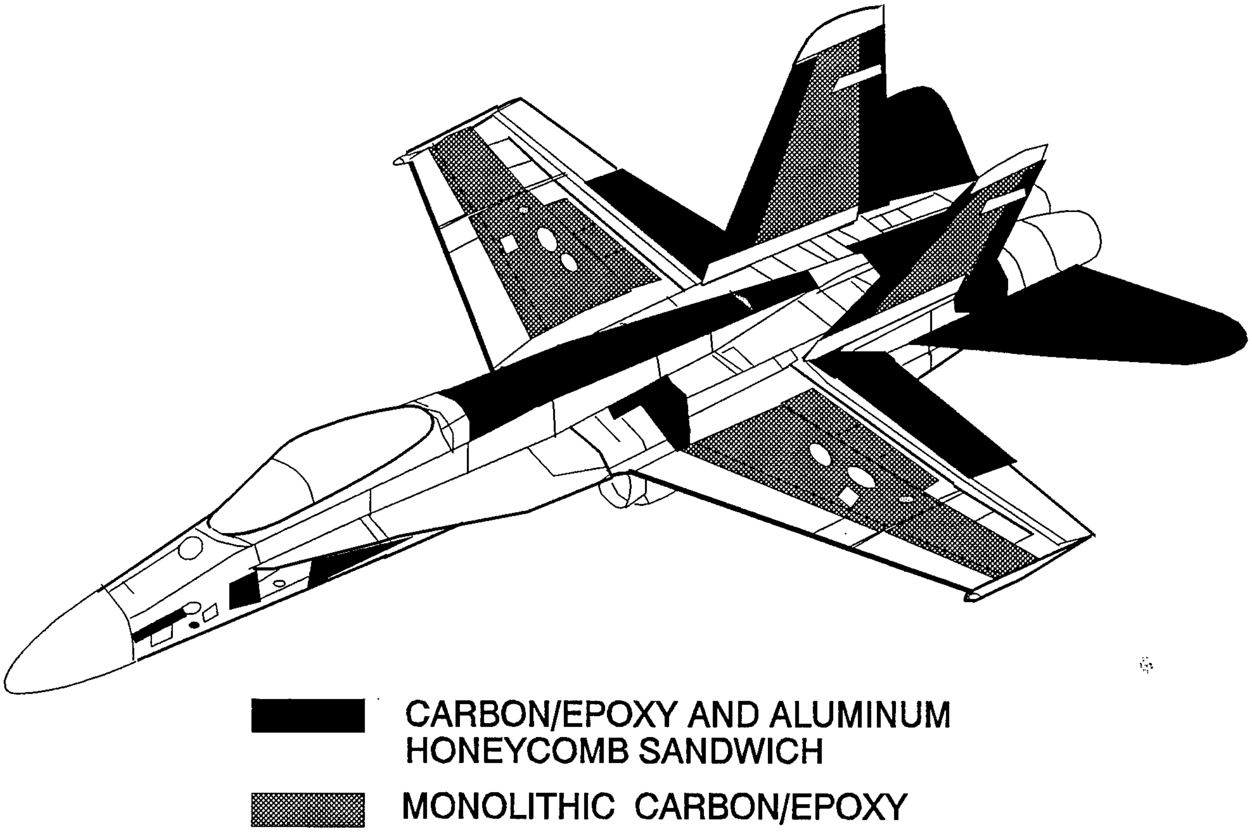

Figure 1 - Use of Composites in the CF-18

2.0 ELECTROMAGNETIC PROPERTIES OF COMPOSITE MATERIALS

In the previous section, some of the advantages of composite materials have been described. These advantages are leading to an increased use of these materials in military vehicles, In almost all cases, however, successful operation of these vehicles depends on the reliable operation of sophisticated systems for flight control, navigation, self-defence and fire control. Compatibility of these electronic systems with their operational electromagnetic (EM) environment, that can include lightning, high power radars, internally generated electromagnetic interference (EMI), high power microwaves (HPM) and nuclear electromagnetic pulse (EMP), is an obvious requirement if the aircraft are going to fly safely and operate effectively.

Composite materials have conductivities that are several orders of magnitude less than metals thus hampering the EM shielding provided by the fuselage. In addition, modern microelectronics are becoming increasingly more sensitive to EMI. To ensure adequate EM shielding, a knowledge of the EM properties of composite materials is necessary [1,2]. Table 1 provides a summary of some of the characteristics of composite materials. The conductivity of commonly used reinforcements is poor compared to metals. This Table shows that even graphite has a conductivity 2 or 3 orders of magnitude lower than commonly used metals. Other reinforcements such as glass and aramid are non-conductive. Because of their limited conductivity, structures made from composite materials generally have poorer EM shielding when compared to metallic structures. For many military applications, it is therefore necessary to either incorporate one or more conductive layers within a laminate or to apply a metal coating to the surface.

EM shielding requirements can also influence the design, construction and life cycle maintenance of composite structures. The need to ensure continuity of conductive pathways wherever composite panels are joined together or connected to adjacent metallic structure can add considerably to the cost and complexity of fabrication. This is especially true where galvanic corrosion concerns would dictate that no electrical contact should exist. Corrosion in fact poses a double threat, reducing the life of the metal components present and slowly degrading the EM shielding by increasing the electrical resistance of the joints. Standard structural repair methods may have to be modified to ensure that EM shielding is not compromised.

TABLE 1 - CHARACTERISTICS OF COMPOSITE MATERIALS

1. **EM SHIELDING EFFECTIVENESS IS NOT AS GOOD AS METALS**

CONDUCTIVITY	**- COPPER**	**- 5.8 X 10^7 MHO/M**
	- ALUMINUM	**- 3.5 X 10^7**
	- STEEL	**- 1.0 X 10^7**
	- GRAPHITE	**- 7.0 X 10^4**
	- GLASS	**- 1.0 X 10^{-12}**

2. **ELECTRICAL BONDING OF COMPOSITES IS DIFFICULT**
3. **CORROSION PROBLEMS**
4. **DIFFICULT TO MAINTAIN EM SHIELDING DURING REPAIR**

3.0 EXPERIMENTAL

3.1 Sample Preparation

The composite materials used in these studies were made from unidirectional pre-preg of carbon fibres in an epoxy matrix. The 18 cm square samples were prepared [1] by laminating eight plies together using standard composites autoclaving procedures. Throughout this paper, fibre orientations are designated with respect to the direction of propagation of the EM waves in the transverse electromagnet (TEM) cell that was used for the measurements.

The degradation in the EM shielding properties of carbon/epoxy components caused by typical structural repairs was investigated to the extent that the geometric constraints imposed by the TEM cell would allow. Thus while, for example, it was not possible to study honeycomb sandwich panels typical of the avionics doors on the CF-18, the same repair materials and procedures normally used for these components were applied to the test samples. Eight ply quasi-isotropic laminates of AS4/3501-6 carbon/epoxy containing a 75 mm diameter hole in the centre were repaired in three different ways. In two of the repairs 152 mm circular patches of either 6 ply $(0°, \pm 60°)$ carbon/epoxy or titanium (Ti-6Al-4V) were adhesively bonded over the hole on one side of the sample using FM-300 epoxy film adhesive from American Cyanamid. The third repair involved a rapid repair technique in which sixteen 7mm diameter blind fasteners were used to attach a thick aluminum patch, drilled with a square array of 7 mm holes equally spaced at 25 mm, to one side of the laminate. These methods of repair are illustrated in Figure 2.

In order to obtain a proper measurement of the shielding properties of these composite samples, good electrical contact must exist between the sample and the body of the TEM cell used to make the measurements. To achieve this, the edges of all of the samples were copper plated. The use of finger stock and application of pressure to top of the upper cell ensured good electrical contact between the two cells.

3.2 Measurement Technique

Measurements of the shielding properties of composite materials have been made using the dual TEM cell technique that was developed by Wilson and Ma [3]. In this method, two TEM cells are coupled by a common aperture. Measurements are made of the penetration of the EM fields from the driven (lower) cell into the receiving (upper) cell. Insertion loss measurements are made by comparing the results when the aperture is loaded with a composite sample with results for the open (unloaded) aperture.

The theory of the dual TEM cell has been developed by Wilson and Ma [3,4]. Provided the aperture dimension is small compared to the wavelength used, small aperture theory can be used and the penetration of the EM fields into the upper cell treated in terms of the equivalent electric and magnetic polarizabilities of the aperture. The output of the cell in the forward direction is related to the sum of the electric and magnetic polarizabilities and in the backwards direction, to the difference. Expressions [3] for the forward and backward insertion losses (defined as the ratio of the transmitted power with the material in place to that of an open aperture) are given below.

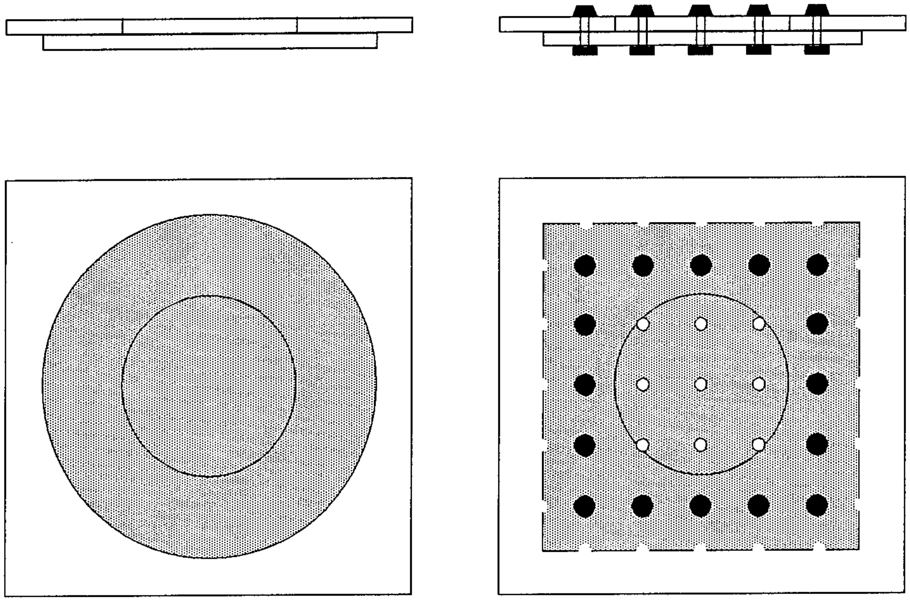

Figure 2 - Illustration of Repair Methods: Carbon and Titanium Patches, Left; Rapid Repair Patch, Right.

$$IL_{forward}=20\log\left|\frac{\alpha_{ey}+\alpha_{mx}}{\tilde{\alpha}_{ey}+\tilde{\alpha}_{mx}}\right| \quad (1)$$

and

$$IL_{backwards}=20\log\left|\frac{\alpha_{ey}-\alpha_{mx}}{\tilde{\alpha}_{ey}-\tilde{\alpha}_{mx}}\right| \quad (2)$$

where α_{ey} and α_{mx} are the electric and magnetic polarizabilities of the open aperture and $\tilde{\alpha}_{ey}$ and $\tilde{\alpha}_{mx}$ are the electric and magnetic polarizabilities of the loaded aperture.

Experimentally, [5] it is possible to separate the electric and magnetic properties of the material by adding or subtracting the two outputs of the receiving cell which gives;

$$IL_e = 20\log\left|\frac{\alpha_{ey}}{\tilde{\alpha}_{ey}}\right| \tag{3}$$

and

$$IL_m = 20\log\left|\frac{\alpha_{mx}}{\tilde{\alpha}_{mx}}\right| \tag{4}$$

The cell used for these measurements had a 15.5 cm sqaure aperture. Measurements of the magnetic and electric insertion loss of the materials were made over the frequency range from 0.3 to 500 MHz using a Hewlett Packard HP8753B Network Analyzer. Output data from both ends of the receiving TEM cell were collected and numerically combined to give both the sum or difference signals.

4.0 RESULTS AND DISCUSSION

4.1 Carbon/Epoxy Patch

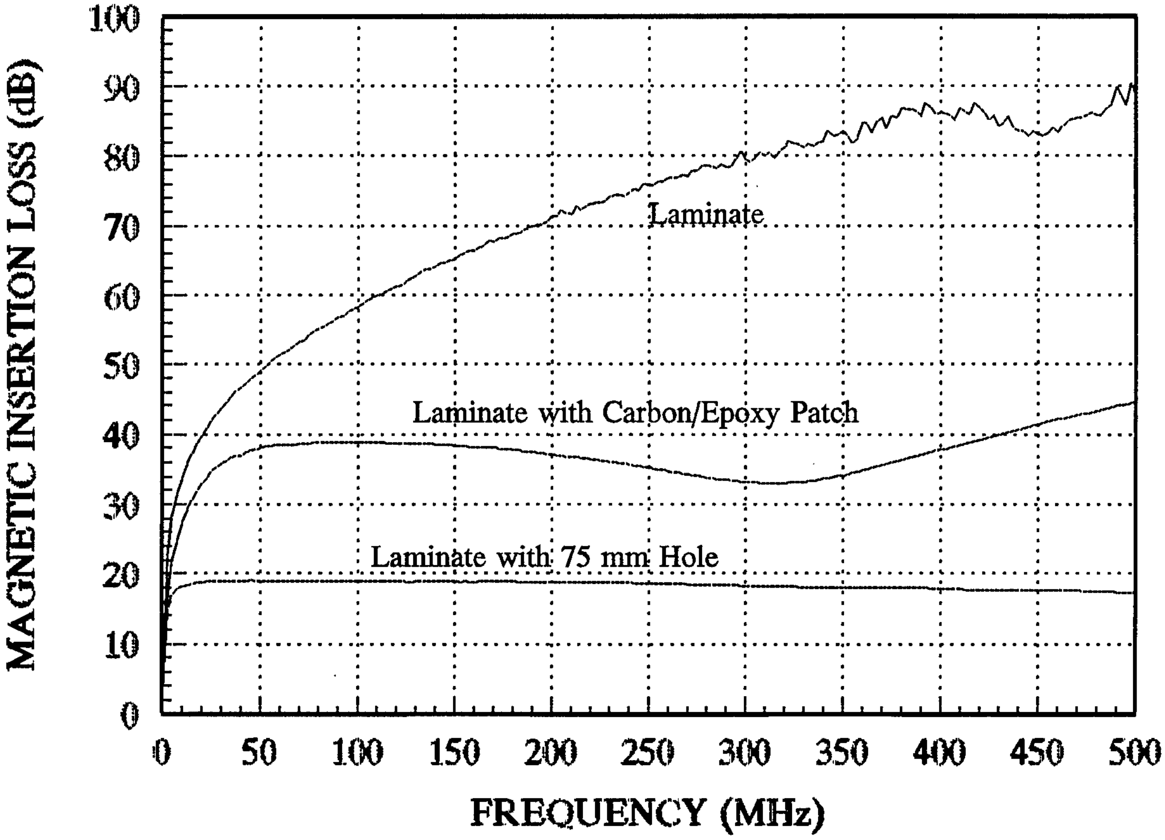

Figure 3 - Effect of Repair on the Magnetic Insertion Loss: Carbon/Epoxy Patch

Figure 3 shows the magnetic insertion loss of a carbon/epoxy laminate with a 75 mm diameter hole that has been repaired with a bonded carbon/epoxy patch. Also included in this figure are the results for a complete carbon/epoxy laminate and an unrepaired laminate with a 75 mm dia. hole. From these results it is seen that the repaired laminate offers considerably poorer shielding than the undamaged laminate, especially at high frequencies where the shielding degradation can be as high as 40 dB. In the application of the epoxy bonded patch, no effort is made to electrically connect the graphite fibres in the patch to those in the bulk material. It is interesting therefore that the patch still provides 10 to 20 dB additional shielding over almost all of the frequency range (0.3 - 500 MHz).

There is apparently sufficient coupling (capacitive or inductive) between the carbon/epoxy laminate and the patch to allow some current to flow through the patch. This suggestion is supported by the observation that the amount of shielding that the patch provides depends (Figure 4) on the orientation of the patch in the aperture of the dual TEM cell. The shielding provided by the patch is generally better when the fibres in the upper layer of the carbon/epoxy laminate (ie. the layer next to the patch) are oriented so that current can flow through this layer (i.e.when the fibres are parallel to the direction of propagation in the TEM cell). The difference in shielding between the two orientaions is not large, about 5 dB maximum, probably because the distance between adjacent layers is small and not much difference in coupling is to be expected. The reason for the cross-over over the two curves at high frequency is not understood.

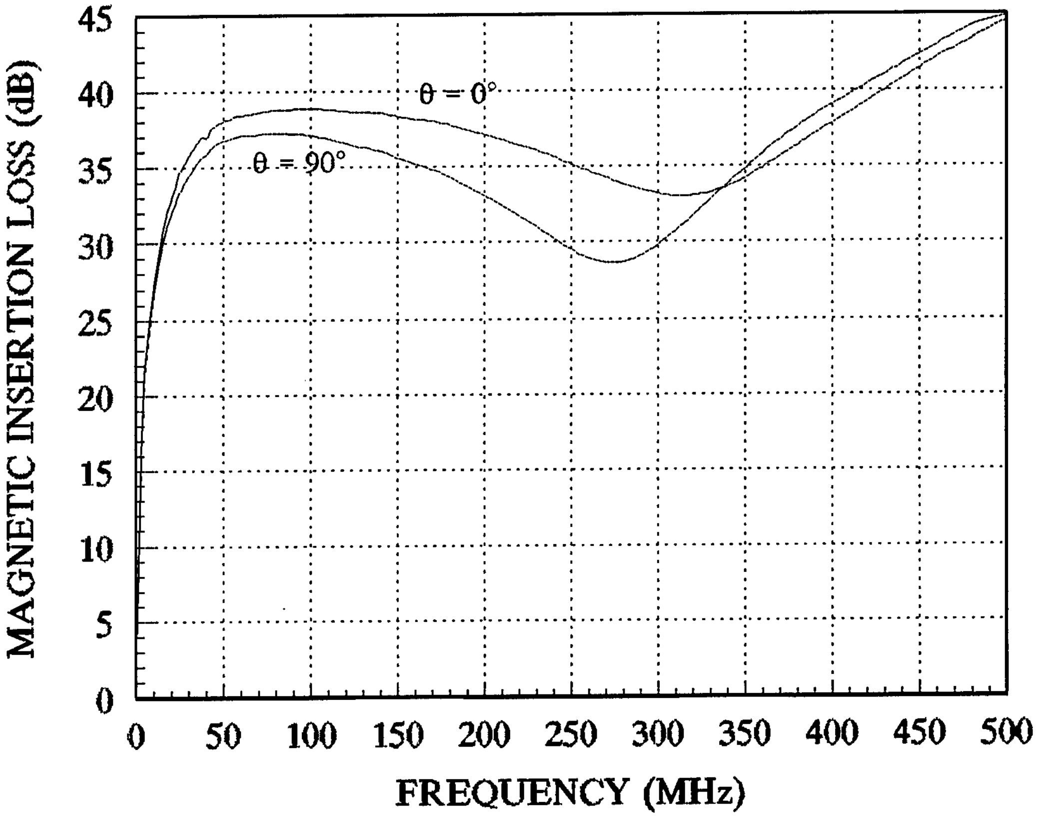

Figure 4 - Effect of Orientation of the Patch on the Magnetic Insertion Loss

Figure 5 shows the electric insertion loss of the same repaired sample. From this data, it is seen that, while the repair results in at least a 20 to 30 dB degradation in electric shielding, the shielding still remains in excess of 50 dB over almost all of the range measured. Exact measurement of the insertion loss of the undamaged laminate is not possible because of the limited (~100 dB) dynamic range of the network analyzer.

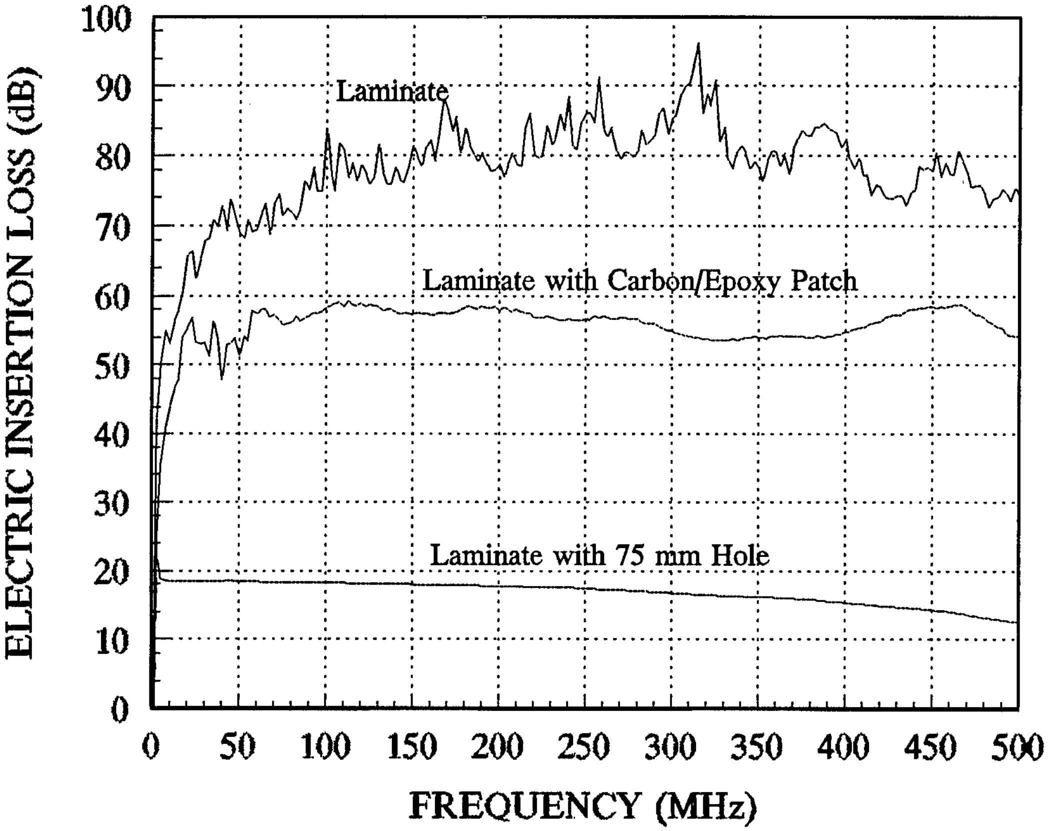

Figure 5 - Effect of Repair on the Electric Insertion Loss: Carbon/Epoxy Patch

4.2 Titanium Patch

Figure 6 shows the magnetic insertion loss of a carbon/epoxy laminate with a 75 mm diameter hole that has been repaired with a bonded titanium patch. As before, we have included the results for the complete (undamaged) carbon/epoxy laminate and the unrepaired laminate with a 75 mm dia. hole. From these results it is seen that the repaired laminate offers considerably poorer magnetic shielding than the undamaged laminate, especially at high frequencies where the difference can be as high as 40 dB. The results show that the titanium patch provides approximately the same level of shielding as the carbon/epoxy patch.

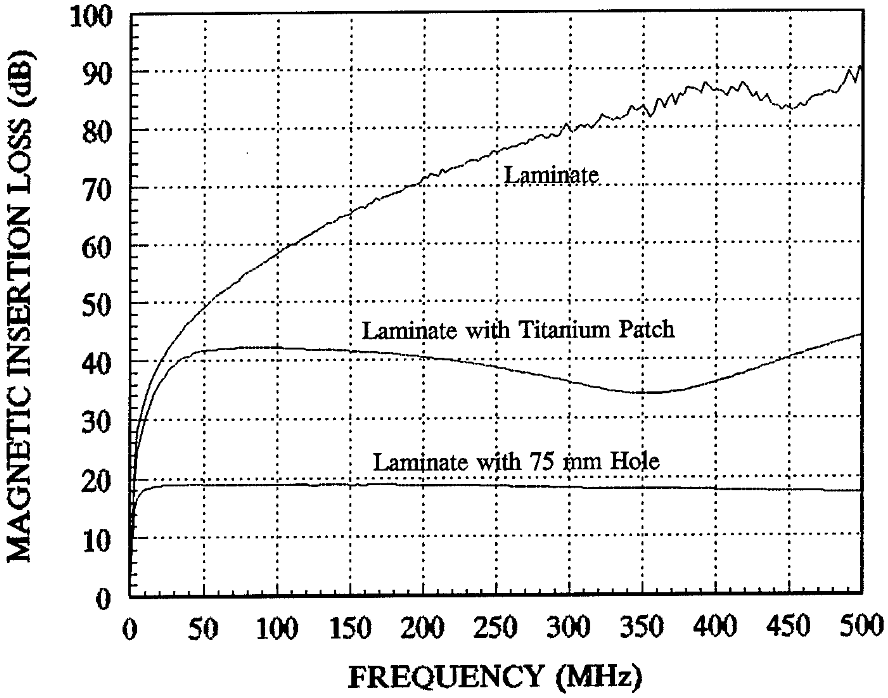

Figure 6 - Effect of Repair on Magnetic Insertion Loss: Titanium Patch

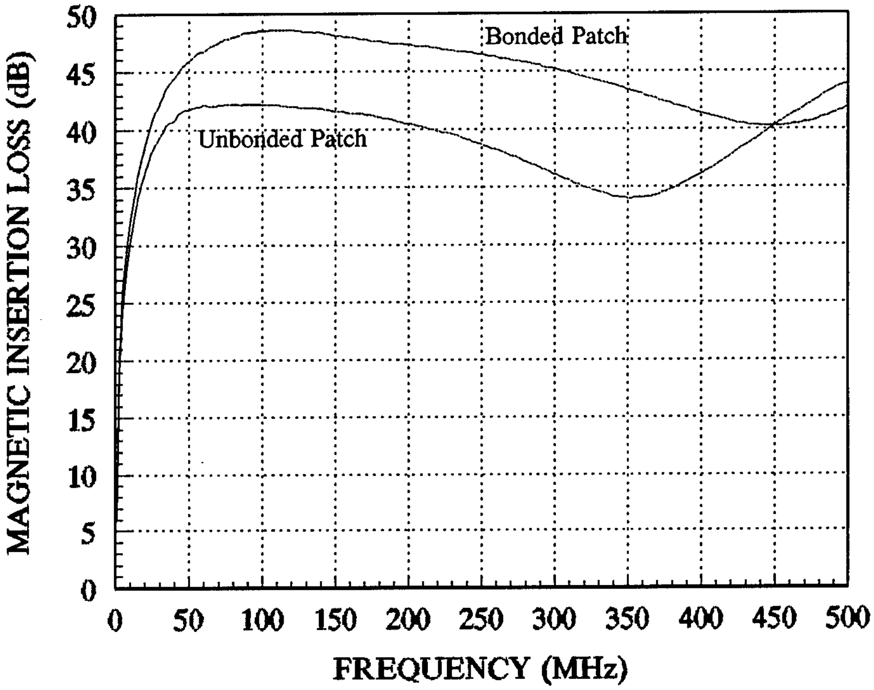

Figure 7 - Effect of Limited Electrical Bonding on the Magnetic Insertion Loss of the Titanium Patch

In the application of the bonded patches, no effort is made to electrically connect the patch to the bulk material. To investigate the improvement that could be obtained by providing electrical contact between the patch and the laminate, two 0.6 cm copper strips were attached between the copper plated edges of the laminate and the titanium patch using silver epoxy. When the laminate was oriented with the connections parallel to the direction of propagation in the TEM cell, an improvement of up to 10 dB was obtained in the magnetic shielding as shown in Figure 7 by providing even this minimal amount of bonding. The cross-over of the curves at high frequency is not understood.

The electric shielding of the carbon/epoxy laminate repaired using a titanium patch is shown in Figure 8. From this data it is seen that, while the repair results in at least a 20 to 30 dB degradation in electric shielding, the shielding still remains in excess of 50 dB over almost all of the frequency range measured. Very little improvement in the electric shielding was observed when the copper strips were used to electrically connect the patch to the laminate. Because shielding of the normal component of the electric field is provided by a circular flow of current, attachment of the copper strips is expected to have minimal effect.

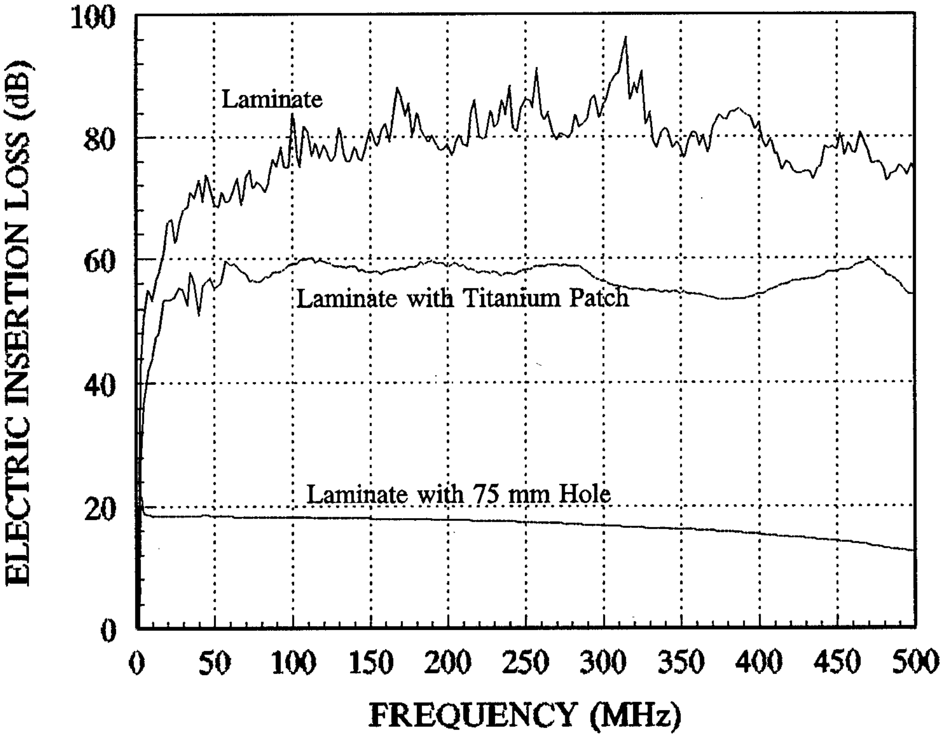

Figure 8 - Effect of Repair on the Electric Insertion Loss: Titanium Patch

4.3 Rapid Repair (Battle) Patch

Figure 9 shows the magnetic insertion loss of a carbon/epoxy laminate with a 75 mm diameter hole that has been repaired using a rapid repair technique in which sixteen 7 mm diameter blind fasteners are used to attach a thick aluminum patch, drilled with a square array of 7 mm holes equally spaced at 25 mm, to one side of the laminate. Also included are the results for the complete (undamaged) carbon/epoxy laminate and the unrepaired laminate with a 75 mm dia. hole.

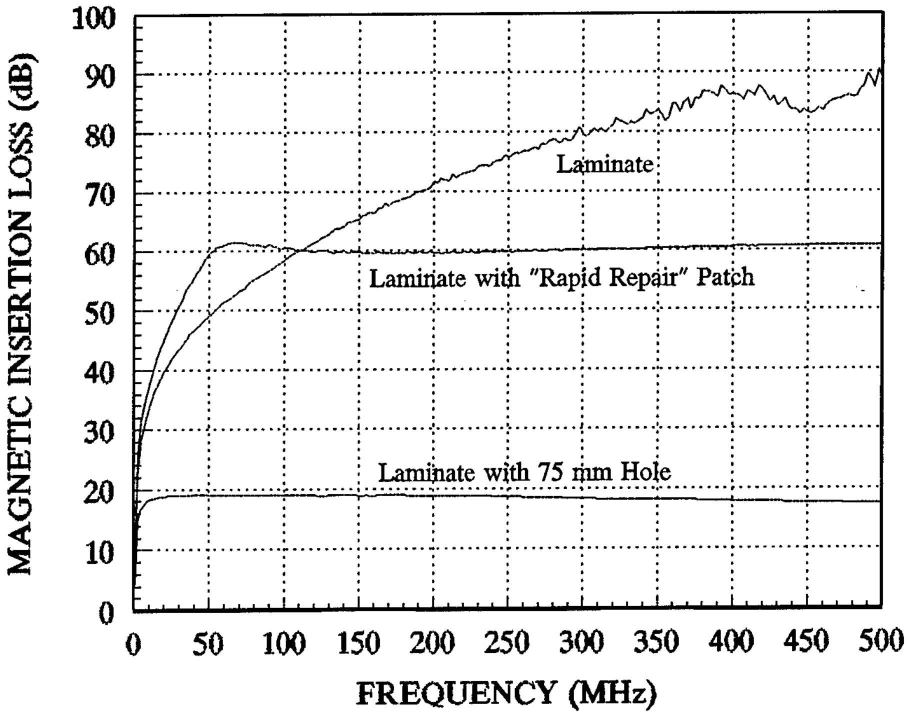

Figure 9 - Effect of Repair on the Magnetic Insertion Loss: Rapid Repair Patch

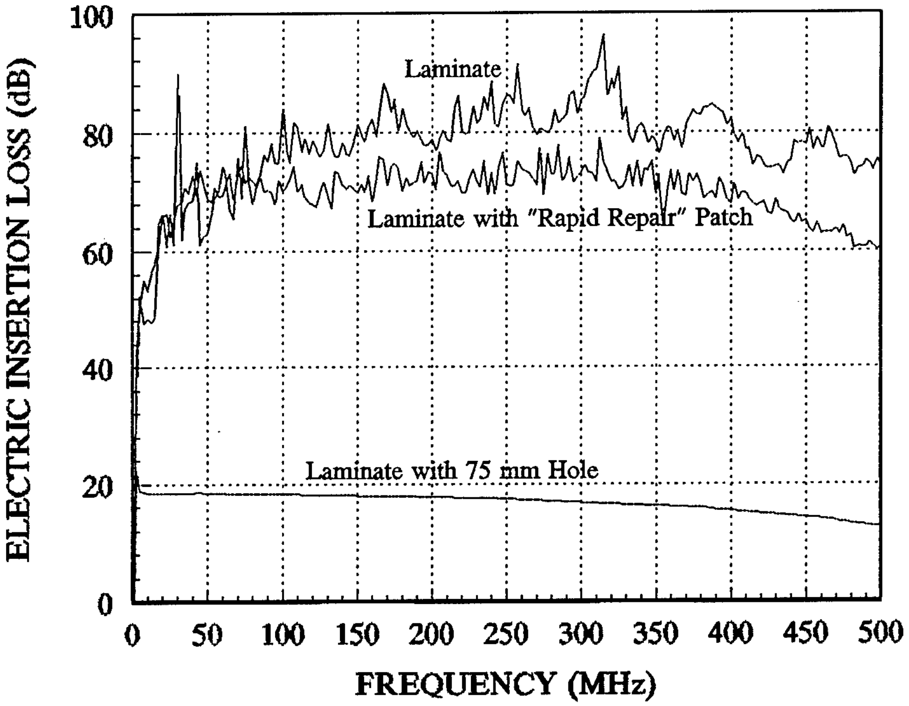

Figure 10 - Effect of Repair on the Electric Insertion Loss: Rapid Repair Patch

These results show that the rapid repair patch provides very good shielding. While there is about a 20 dB degradation at high frequency, at low frequencies the repaired sample actually provides better shielding than the unrepaired laminate presumably because of the higher conductivity of the aluminum plate. At higher frequencies the leakage through the 7 mm holes apparently becomes dominant.

The electric insertion loss of the sample repaired using the rapid repair patch is shown in Figure 10 together with the results for the complete laminate and a laminate with a 75 mm dia. hole. The results show that the electric shielding of the sample repaired in this way is in excess of 70 dB over most of the frequency range.

4.4 Comparison of Repair Methods

A comparison of the magnetic insertion loss of the three patch types is given in Figure 11. The magnetic shielding provided by the carbon/epoxy and titanium patches is very similar. The bolted patch, on the other hand, provides about 20 dB greater shielding over the frequency range examined. With the bolted patch, some electrical contact between the carbon fibres in the carbon/epoxy laminate and the aluminum patch is provided by the bolts. Presumably the shielding would be even higher if the aluminum patch did not contain the 7 mm bolt holes in the area of the patch that covers the hole.

A comparison of the electric insertion loss of the three patch types is given in Figure 12. The electric shielding provided by the bonded carbon and titanium patches is similar and about 60 dB. The shielding provided by the rapid repair patch is at least 10 dB greater over most of the frequency range.

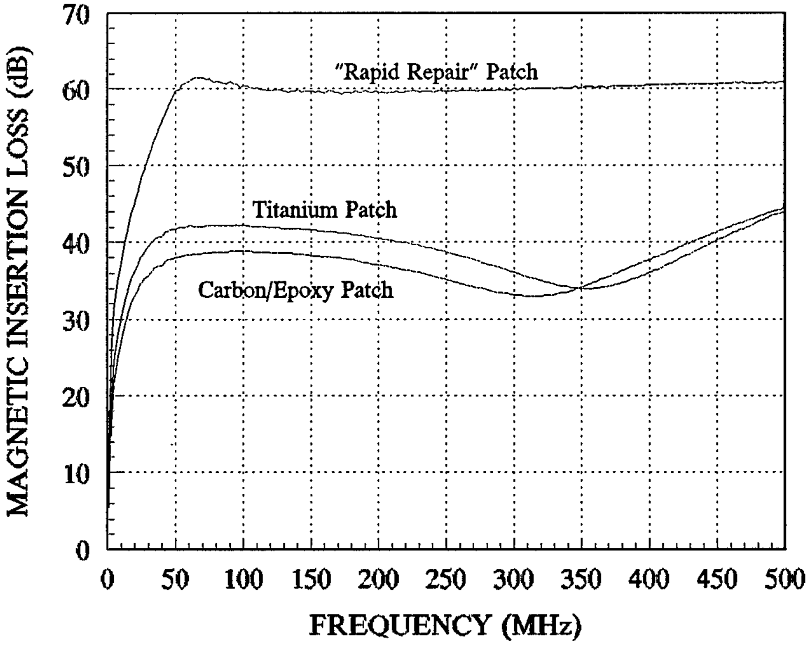

Figure 11 - Comparison of Magnetic Insertion Loss of the Three Patch Types

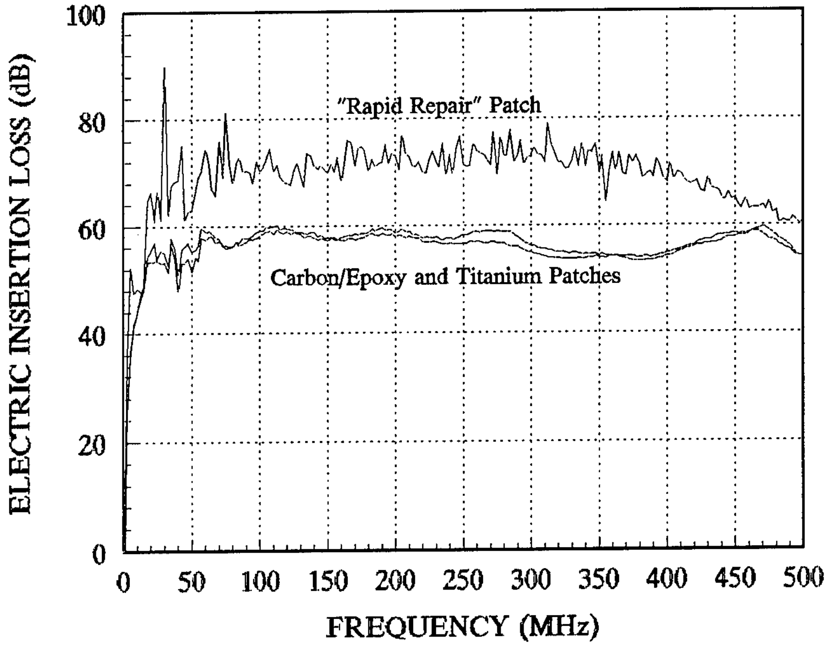

Figure 12 -Comparison of the Electric Insertion Loss of the Three Patch Types

5.0 CONCLUSIONS

This study has shown that the repair of composite structures using prescribed techniques for applying bonded patches can result in a substantial degradation of EM shielding. This results because electrical contact is completely or partially lost between the conductive fibres in the bulk material and the patch material.

The degradation of the magnetic shielding effectiveness has been found to be about 40 dB at high frequencies when a carbon/epoxy or a titanium patch is used. The degradation is less severe with a rapid repair patch probably because the bolts are in electrical contact with the conductive carbon fibres inside the laminate. In this case, the loss of magnetic shielding is about 20 dB at high frequencies. At low frequencies (< 100 MHz), the application of the rapid repair patch actually improves the magnetic shielding because of the higher intrinsic conductivity of the patch material.

The degradation of the electric shielding appears to be less, however, this may well be a result of the inability to properly measure the electric shielding properties of the bulk laminate because of limitations of the measurement system. When a carbon/epoxy or a titanium patch is applied, the apparent degradation is about 20 dB and, when a rapid repair patch is applied, the degradation is about 10 dB.

Results indicate that the EM shielding of the repaired samples could be improved if techniques were developed to provide good electrical contact between the patch and bulk materials.

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(U) Composite materials are increasingly being used for the construction of aircraft because of their superior physical properties. Maintenance of adequate electromagnetic (EM) shielding inside the aircraft is often a concern because of the increasing use of sensitive avionics. Degradation of EM shielding provided by the skin of the aircraft during repair can be of particular concern.

(U) In this report, we present results of measurements that we have made to examine the effect of repair on the magnetic and electric shielding properties of carbon/epoxy laminates. In carrying out this study, we have used the conventional repair techniques that are used for repair of the CF-18 aircraft. These methods include the application of epoxy bonded carbon/epoxy and titanium patches, and the use of a bolted aluminum rapid repair (battle) patch. In all cases the patches were applied over a 75 mm hole in an 8-ply AS-4 carbon/epoxy laminate.

(U) The results show that the use of a carbon/epoxy or a titanium patch results in a degradation of the magnetic shielding of the carbon/epoxy laminates by as much as 40 dB. This large degradation is attributed to the loss of electrical contact between the patch material and the laminate. The degradation of magnetic shielding with a bolted aluminum patch is less severe (~20 dB) because the bolts provide some electrical contact between the patch and the laminate. Similar results are presented for the effect of repair on electrical shielding.

(U) Limited results are presented that show that shielding can be substantially improved by providing electrical contact between the laminate and the patch material.

14. **KEYWORDS, DESCRIPTORS or IDENTIFIERS** (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thsaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus -identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Composite Materials
Electromagnetic Shielding
Repair