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Comparison of different non-destructive testing techniques for bonding quality evaluation

Bengisu Yilmaz
Ultrasound Research Institute
Kaunas University of Technology
Kaunas, Lithuania
bengisu.yilmaz@ktu.lt

Abdoulaye Ba
IREENA
University of Nantes
Nantes, France
abdoulaye.ba@etu.univ-nantes.fr

Elena Jasiuniene
Ultrasound Research Institute
Kaunas University of Technology
Kaunas, Lithuania
elena.jasiuniene@ktu.lt

Huu Kien Bui
IREENA
University of Nantes
Nantes, France
huu-kien.bui@univ-nantes.fr

Gerard Berthiau
IREENA
University of Nantes
Nantes, France
Gerard.Berthiau@univ-nantes.fr

This paper discusses the possible non-destructive testing (NDT) techniques for a novel bonding quality evaluation technique based on comparison of different inspection methodologies. The goal of this paper is to guide a way for bonding quality evaluation with high reliability by comparing different NDT techniques including ultrasonic, electromagnetic, and thermography. The advantages and limitations of each different NDT technique have been reported systematically. Two case studies have been investigated with two different NDT techniques, namely ultrasonic and induction thermography. The results suggested the limitations and advantages of NDT techniques. In order to compensate the limitations of each technique, data fusion of the selected techniques is proposed.

Keywords—NDT, composites, adhesive bond, weak bond, ultrasound, induction thermography, data fusion

I. Introduction

The significant improvements in material science technology had affected the way we understand engineering materials, specifically in highly developed industries such as aerospace. One of the greatest questions regarding the aerospace industry materials is the joining technologies for the advanced materials such as composites. Currently available joining technologies includes mechanical fasteners (such as rivets), fusion bonding (such as induction welding) and adhesive bonding [1], [2]. Compared to mechanical fasteners, adhesive bonding is superior with the homogenous load distribution over the joint, the ability to join dissimilar materials and high performance to weight ratio. Additionally, adhesive bonding does not interfere with the integrity of the materials. Specifically, for composites, integrity of the fibres is very important for homogenous stress distribution through specimen and strength protection. Although fusion bonding and adhesive bonding have common advantages, for it is preferable to join high fibre density thermoset composites with adhesive bonding due to possible distortion on fibre integrity with fusion bonding [2]. Moreover, adhesive joints allow us to design complex geometries and they are favourable with electrolytic corrosion protection, vibration and sound damping. The above-mentioned advantages make adhesive bonding a profitable manufacturing solution compared to other joining methodologies for advanced materials, particularly for aerospace composites.

Although the adhesive bonding has numerous advantages over other joining techniques, there are several concerns that limits its applications in aerospace industry. Safety regulations require highly reliable non-destructive testing techniques for every part manufactured and used in aircrafts. The adhesive bonding can only be used in secondary load carriers in aircrafts due to the lack of reliability. In order to use the advantages of the bonding, the quality of bonding should be ensured with non-destructive testing techniques.

The non-destructive evaluation of bonding quality is a challenging task because adhesive bonding is an interfacial phenomenon involving a thin layer of material, usually less than 10 microns [3]. Although the adhesive bonding evaluation with different non-destructive testing techniques had been performed over the past decades, there is a lack of information regarding the advantages and limitations of the NDT techniques. This study aims to close the gap in the reliability of NDT techniques for bonding quality evaluation. In addition to the comparison of previously used NDT techniques for bonding quality evaluation, CFRP-epoxy bonded structures with different bonding quality had been investigated with ultrasound and induction thermography.

II. Materials and Method

A. Bonding Quality

The adhesive bonding quality can be affected by multiple factors in production phase such as surface preparation, environmental conditions -humidity, temperature, pressure-, and curing process. Additionally, in service, other defects such as crack, delamination, and porosity may start to develop or current defects may propagate because of fatigue and usage.

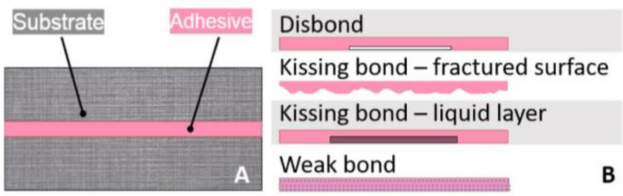

Fig. 1 A) Schematic of adhesive bond adhesive and substrate (adherend) B) Different quality of bonding with interface defect.

The defects reducing the interface quality of bond are usually porosity, moisture, contamination, and pure curing (variations in temperature and pressure during curing of bonding may decrease the quality of adhesive). Disbond or debonding is the most common interface condition that causes bonding quality reduction. These anomalies usually occur due to porosities, lack of adhesive, contamination, and fatigue. On the other hand, moisture, contamination, and pure curing may lead to more severe interface conditions such as the kissing bond and weak bond. Kissing bond is defined as where adherend and adhesive bond are in intimate contact; however, there is no physical bonding at the interface [4], [5]. Furthermore, these defects may decrease the integrity of the adhesive resulting with quality decrease, also known as weak bonds [6]. Kissing and weak bonds cause unreliable behaviour of the structure and are hardly detectable by conventional NDT techniques. As all these interface conditions may affect the quality of bonding, it is essential to apply reliable non-destructive testing methods during the production and the usage of adhesively bonded structures.

Inspired by single lap joints, 6 layer 5H-satin carbon-fiber epoxy composite laminate plates that have the size of 280mm x 120 mm (2.22 mm thick) have been bonded together with AF163 epoxy (0.24 mm thick) film by 25 mm bondline after surface preparation. In addition to the neat samples (here in after as called as “perfect bond”), three different type of inclusions had been added to the interface between CFRP-epoxy and epoxy prior to curing. As first inclusion, artificial debonding had been created by placing 12.7 mm x 12.7 mm square (2 layer folded together, total thickness of 0.063 mm) release film (polymethylpentene - PMP) at the interface as seen in Fig.2A. Secondly, two different size (12.7 mm x 12.7 mm and 6.35 mm x 6.35 mm) square folded brass inclusions (total thickness 0.05 mm) had been placed on the second sample as seen in Fig.2B. After artificial defects had been placed, all samples had been cured at the hot press according to instructions in the material datasheet.

Fig. 2 A) Artificial debonding created by release film inclusion and perfect bond prior to bonding. B) Artificial debonding created by different size brass inclusions prior to bonding.

B. *Non-destructive Testing Techniques for the Evaluation of Bonding Quality*

Among all non-destructive testing techniques, visual inspection is the most widely used, and for bonded specimens, it is used to ensure the geometry, dimensions and the surface quality prior to bonding [7]. As well as visual inspection, high frequency electromagnetic inspection such as microwave and terahertz imaging are used to investigate surface quality in structures, and interface quality where adherend is non-conductive material [8]. On the contrary, another widely used NDT technique eddy current can only be used for electrically conductive materials and the skin (penetration) depth is limited [9].

Furthermore, thermography is another well-known NDT technique to investigate bonding quality [10]–[12]. It has advantages such as being responsive, sensitive, and suitable for automation, but the depth of investigation is limited. Just like thermography, shearography can have pretty high resolutions and very small response time, however, it is only effective with surface and sub-surface defects and require high stress solicitation [7]. It is reported that shearography is very suitable to detect disbond and subsurface defects in aluminium bonds [11]. On the other hand, where possible, x-ray tomography can be used to investigate inner defects in bonded structures [12].

Ultrasonic NDT had been used to investigate the adhesive bond quality with adherend integrity and interface quality evaluation including disbond detection [13]–[17]. In addition, the investigations to detect weak and kissing bonds had been performed in the previous studies [4], [6], [18].

Not only conventional longitudinal pulse-echo ultrasonic inspection, but also advanced measurement techniques such as acoustic microscopy, air-coupled ultrasound, and guided waves have been used to evaluate bonding quality [19]–[26]. Moreover, the nonlinear behaviour has been related to bonding quality with nonlinear ultrasonic NDT [27], [28]. The nonlinear ultrasound requires high power, which leads to the question of destructive level on the bonded structure.

In addition to the conventional NDT techniques, recent studies discusses the potential applications of electromechanical impedance NDT to inspect interface defects [29] and weak bonds caused by contaminations, moisture, and pure curing [30], [31]. Also, laser based techniques such as laser shock adhesion test had been reported to be a promising technique to detect weak bonds, even though the damage caused by laser is irreversible [32].

For evaluation of bonding quality, there are several aspects that limit the application of NDT techniques such as the geometry and dimensions of component, material properties of adhesive and adherend, defect types (debonding, delamination, crack, surface damage, kissing/weak bonds etc.). The limitations of the above mentioned ultrasonic and electromagnetic non-destructive testing techniques have been reported on Table I.

TABLE I. REVIEW OF PREVIOUSLY PERFORMED EXPERIMENTS WITH ULTRASONIC AND ELECTROMAGNETIC NDT TECHNIQUES FOR EVALUATION OF BONDING QUALITY

NDT Technique	**Bonding Quality Evaluation**		
	Defect Inclusion type	***Applicability***	***Ref a***
Pulse-echo ultrasound	Disbond	Limited due to attenuation on adherend	[13], [14]
	Interface quality		[15]–[17]
	Moisture & Humidity	Limited detectability	[33], [34]
	Weak bond & Kissing bond	Not sufficient	[4], [6], [18]
Air-coupled ultrasound	Interface quality	Limited due to high amplitude loss in air	[19]
	Weak bond & Kissing bond	Not sufficient	[20], [21]
Guided-wave ultrasound	Disbond	Lamb waves with vibrometry	[22], [23]
	Weak bond	Limited to bonding thickness	[24]
	Interface quality		[25]
Acoustic Microscope	Interface quality	High frequency & high attenuation	[26]
Nonlinear ultrasound	Weak bond & Kissing bond	Questionable destructive level	[27], [28]
Visual Inspection	Prior to bonding	Limited to surface defect detection	[7]
Microwave & Terahertz Imaging	Interface quality	Limited to non-conductive adherend	[8]
Eddy current	Interface quality	Limited to conductive adherend	[9]
Thermography	Disbond		[10]

NDT Technique	Bonding Quality Evaluation		
	Defect Inclusion type	*Applicability*	*Ref* [a]
	Interface quality	Limited to adherend thickness	[11], [12]
Shearography	Interface quality	Limited to adherend thickness	[11]
Radiography	Internal structure	Expensive	[12]
Electromechanical Impedance	Weak bond	Reliability issues	[29]–[31]
Laser shock adhesion test	Weak bond	Questionable destructive level	[32]

[a] Ref. stands for references for previous works.

C. *Ultrasonic Non-Destructive Testing Technique for The Evaluation of Bonding Quality*

The samples containing different artificial debonding inclusions had been investigated with ultrasonic longitudinal wave propagation inside immersion tank. Flat transducers with 5 MHz central frequency have been used to evaluate bonding quality.

Each ultrasonic measurement throughout the whole bonding area has been recorded as A-scans. These point measurements have been aligned according to the surface reflection at -6 dB. The beginning of the signal (ultrasonic wave traveling in water) is eliminated, in order to have better representation of the bonding response. C-scan images corresponding to bonding interface have been created to visually evaluate bonding quality. The gate was selected at time interval were interface reflection is expected as shown in Figure 3.

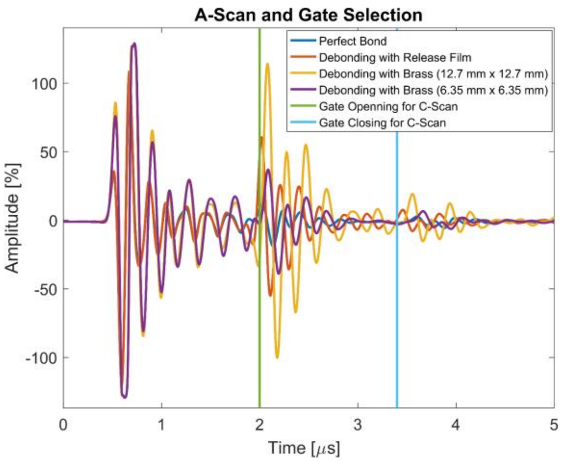

Fig. 3 Ultrasonic inspection A-scan results for perfect bond, artificial debonding with release film, and artificial debonding with brass inclusion with two different size. Gate selection for C-scan image is shown.

D. *Induction Thermography for the Evaluation of Bonding Quality*

The samples containing different artificial debonding had been investigated with induction (eddy current stimulated active) thermography.

Prior to experiments, numerical investigations had been performed to determine the optimum experimental parameters. In the previous work, it is shown that the temperature contrast between defects and composite adherend is dramatically affected by the choice of coil frequency [35]. The induction power ratio results indicate that only for excitation frequencies lower than 100 kHz can achieve 50 percent of contrast.

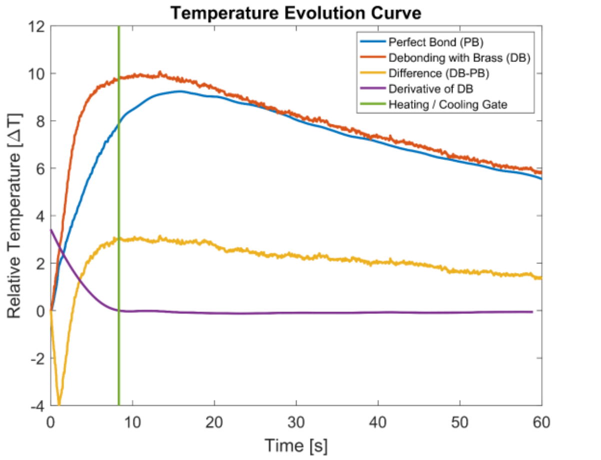

Fig. 4 Temperature evolution curve for perfect bond, artificial debonding with brass, and the difference of two curves. The filtered derivative of artificial debonding with brass inclusion is shown along with heating/cooling gate.

In order to achieve higher signal to noise ratio, the design of the coil has been selected as a helical coil inductor (inner diameter 15 mm, outer diameter 25 mm, height 30 mm, 5 turns). It has been placed on the bonding line with zero lift-off. The coil had been excited for 1 second with 200 Ampere power. The frequency has been measured as 105 kHz. The infrared camera recorded the surface temperature on the other surface of the sample (transmission mode) with 25 frame per second sampling frequency for 60 second.

III. Results

The results of ultrasonic and induction thermography inspections had been reported. The samples containing perfect bond, artificial debonding with release film inclusion, and artificial debonding with brass inclusion had been investigated. For each nondestructive testing technique and each different defect type, qualitative and quantitative results have been indicated in this section.

The ultrasonic inspection measurement had been represented with the C-scan images as seen in Fig. 5. The ultrasonic inspection results show that the release film debonding inclusions had been detected (Fig. 5). On the other hand, for the sample containing artificial debonding with brass inclusions, while the half inch square metals (12.7 mm x 12.7 mm) had been detected clearly, it is very difficult to see the size and the position of the small (quarter-inch-squared) brass inclusions.

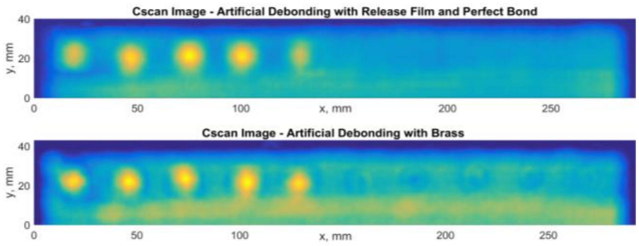

Fig. 5 Ultrasonic inspection C-scan results for artificial debonding with release film, perfect bond, and artificial debonding with brass inclusion. The gate selection has been done according to Fig. 3.

The induction thermography results had been evaluated by using singular value decomposition based principal component analysis (PCA). PCA allows to eliminate ununiformed heating and to increase defect contrast in thermography [36], [37]. PCA is a dimension reduction technique, which calculates the eigenvectors of induction thermography video (treated as independent variables) and arranges them in descending order of variance. Therefore, the first principal component (PC) carries the most information of the original data [37].

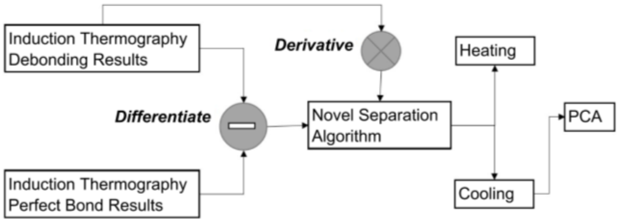

Fig. 6 Schematics of analysis algorithm for induction thermography bonding quality evaluation.

In order to eliminate edge and coil non-uniform heating effects from the results, defected sample video and perfect bonding sample video has been differentiated after alignment according to bondline. The recorded temperature results had been separated for heating part and cooling part as seen in Fig. 4. Novel algorithm has been developed to separate cooling and heating automatically. The differentiated temperature profile has been cut when the rate of change (derivative) of defected sample temperature is zero. Only for the cooling part, PCA algorithm has been applied with MATLAB software. First principal components of different debonding conditions have been shown in Fig. 7. As seen in the PC figure, the brass inclusions have been detected with high contrast. However, the release film inclusion at the interface is not detected with the same precision.

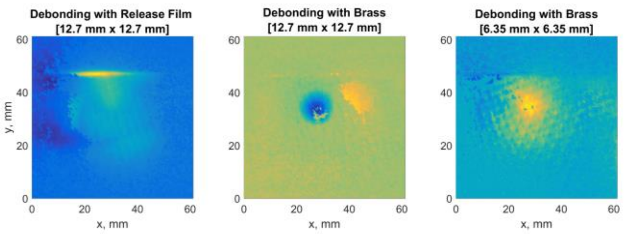

Fig. 7 Principal component analysis of induction thermography results for artificial debonding with release film inclusion and artificial debonding with brass inclusion.

In order to have quantitative comparison of ultrasonic inspection and induction thermography performance for the evaluation of bonding quality, signal to noise ratios (SNR) have been calculated. For each defect, the ratio of the average of defected regions to the average of the sound region have been calculated (1). In the following expression; SNR stands for signal to noise ratio, i is the assigned number of pixels, N is the expected number of defected pixel number, M is the total number of sound area pixel number, D_i is the pixel values of defected pixels, and S_i is the values for sound pixels.

$$SNR = \frac{\sum_{i=1}^{N} D_i / N}{\sum_{i=1}^{N+M} D_i + S_i / N+M} - 1 \quad (1)$$

For ultrasonic inspection results, signal to noise ratios calculated for five different defect have been averaged. The averaged signal to noise ratio values have been indicated in the Table II. For induction thermography results, signal to noise ratios have been calculated for one defect inspection (Table II). As the quantitative comparison indicates, the artificial debonding with release film has been better detected with ultrasonic inspection than induction thermography. On the other hand, debonding with brass inclusion for both sizes has been detected better with induction thermography than ultrasonic inspection.

TABLE II. SIGNAL TO NOISE RATIOS

Sample	Signal to Noise Ratio (SNR)	
	Ultrasonic Inspection	**Induction Thermography**
Debonding with Release Film [12.7mm x 12.7mm]	0.54	0.11
Debonding with Brass [12.7mm x 12.7mm]	0.54	1.38
Debonding with Brass [6.35mm x 6.35mm]	0.11	1.12

IV. DISCUSSION AND CONCLUSIONS

This paper reports on the different non-destructive testing techniques for the evaluation of bonding quality. In order to identify the limitations and advantages of different NDT techniques, CFRP-epoxy bonded structures containing different interfacial defects had been investigated with ultrasonic and induction thermography techniques.

As ultrasonic C-scan results indicate, relatively big (12.7 mm x 12.7 mm) artificial debonding with release film and brass has been detected (Fig. 5). On the other hand, small artificial debonding with brass is barely visible. The selected transducer diameter for the ultrasonic inspection is one of the most significant reasons behind this scenario due to beam divergence. Since the focusing type of the selected transducer is flat, beam divergence affects the visibility of small size defects more than the inspections with focused transducers. As well as the focusing type, the uncertainties in size and position have a strong relationship with the selected frequency of the transducer. Although the low frequency of the transducer is increases the angle of divergence, it is not high enough to separate the interface reflection from multiple reflections. Furthermore, the highly attenuated composite adherend causes drastic ultrasonic amplitude decrease, which makes the defect detection challenging. The reported quantitative comparison, agrees with the qualitative discussion. These combined results suggest that the ultrasonic pulse-echo NDT technique is an advantageous method for debonding detection, however, the small size inclusions may be disregarded.

The induction thermography results show that the detection for brass inclusion had been performed with high signal-to-noise ratio (Fig. 4, Table II). However, the release film inclusion at the interface is not detected with the same precision as the brass inclusions. This difference in the detection of different inclusions is caused by their electrical conductivity levels. While the brass is electrically conductive material, which allows eddy current to form within, the debonding with release film only affects the thermal diffusion. Therefore, induction thermography is a successful technique to detect inclusions that are electrically conductive, even for the small sizes.

It is important to mention that both ultrasonic inspection and induction thermography have advantageous and limitations for bonding quality evaluation. Although ultrasonic inspection with immersion technique is a successful method to detect debonding with release film inclusion, it requires the samples to be under water, which may not be applicable to every specimen. Induction thermography is, on the other hand, a non-contact NDT technique that does not require any contact medium, however, the non-conductive material inclusions and debonding may not be determined as successful as ultrasonic inspection.

In conclusion, the challenges continue for bonding quality evaluation although the advantages and limitations of ultrasonic and electromagnetic non-destructive testing has been established in over the last decade. The complex geometry, unknown material properties and manufacturing details makes the inspection of bonded structures challenging and unreliable. In order to eliminate the limitations of the techniques, highlight their advantages, and increase the reliability in evaluation of bonding quality; the combination of different ultrasonic and electromagnetic NDT techniques can be a solution to determine the bonding quality.

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