USE OF TANGENTIAL RADIOGRAPHY AND RESONANCE ULTRASONIC TECHNIQUES TO EVALUATE BONDING QUALITY

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Abstract: Bonding is a useful thermomechanical assembling process allowing a perfect cohesion between two axisymetrical cylinders made of different materials. A perfect knowledge of the quality of the assembly (quantification of mechanical strength or detection of gap between the two parts) is an important step of the manufacturing process. The control that has been developed is performed with two non destructive techniques.
First, an ultrasonic method based on the resonance frequency and the electrical impedance measurement of a special piezo-electric transducer placed on the specimen is performed. The shift of the resonance frequency is directly related to the quality of the bonding, and particularly to the strength cohesion between the two parts. When the frequency value points out disbonding area characterized by a gap between the two cylinders, tangential microfocus radiography is performed to evaluate in an accurate way the nocivity of the flaw and particularly the width of the gap. These two complementary techniques have been evaluated and validated by using standard devices, with the same thickness, shape and nature than the real specimen. For the ultrasonic technique, first results show that it is possible to quantify very precisely the quality of the bonding, ranging from a perfect assembly characterized by a high strength between the two cylinders to a partial disbonding area. Small gaps of less than 50/G μm (G = magnification) have been evaluated with microfocus radiography.

1. Introduction: In industry, control of assemblies is an important step of the manufacturing process. The bonding assembly is a thermomecanical process allowing a perfect contact between two axisymetrical cylinders placed one inside the other. This assembling technique uses the different mechanical and thermoelastical properties of the two materials. Application of different state of pressure inside the specimen and choice of appropriate temperature variation involves, at the very beginning of the process, the contact between the two parts, and, if the process is continued, interface pressures. This paper presents the way used to evaluate the quality of the assembly in a non destructive way with two complementary techniques. First, ultrasonic spectroscopy is performed to quantify pressures at the interface between the two layers. Modeling is compared to experimental data from a calibration device to evaluate the ability of this technique to detect small pressure variations at the interface between the two layers. Then, a study based on tangential radiography have been led both theoretically and experimentally to find the best parameters of the experimental x-ray bench. By comparison of the radiographic model to the experimental densitometric profile, it is possible to quantify the assembly quality by measuring the gap between the two layers.

2. Strength Cohesion Measurement Using An Ultrasonic Spectroscopy Method:

1) PRINCIPLE OF THE METHOD:

The first non destructive testing technique evaluated in this study is based on the ultrasonic spectroscopy principle. This technique is designed to provide information about the cohesion quality of adhesively bonded joints. The instrument measures the resonance frequency and the electrical impedance of a piezo-electric transducer, which is placed on the surface of the bonded structure. The amount of frequency shift and change in impedance are indicators of the bonded joints quality.

2) MODELING OF THE CONTROL FOR DIFFERENT BOND STATES:

Determination of the evolution of the transducer resonance frequency coupled to the bonded joint is realized with the study of the mechanical behavior under vibrational loading in terms of system mass, stiffness, and losses [1]. The principle of the mass-spring model used in this study is described in Figure 1. The transducer is characterized by its weight Ms, stiffness coefficient k_S and by it sinusoidal excitation $F_0.\sin(2\pi ft)$. The specimen under control is represented by two layers characterized by their specific weight M_{p1} and M_{p2} and by the stiffness coefficient k_c which is proportional to the cohesion quality of the bonded joint.

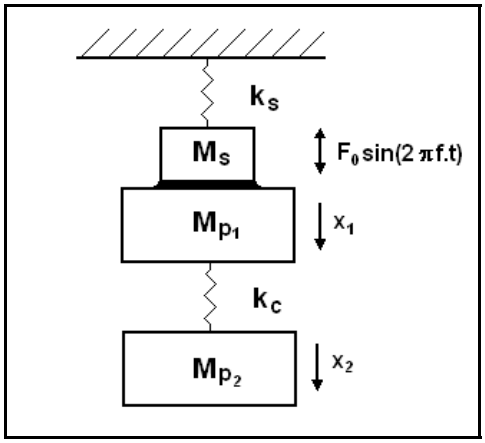


FIGURE 1: Schematically representation of the vibrating system

The mechanical system equation resolution gives the evolution of the interface stiffness k_c as a function of the frequency f of the transducer :

$$k_c = Mp_2 \times 4\pi^2 f^2 \frac{(Ms + Mp_1) \times 4\pi^2 f^2 - k_s}{(Ms + Mp_1 + Mp_2) \times 4\pi^2 f^2 - k_s} \qquad (1)$$

The experimental control of the assembly quality is realized with the Fokker Bond Tester Model 90 device. This instrument was developed by R. J. Schliekelmann [2] [3] as the result of an extensive program in non destructive testing in bonded aircraft structures dating in 1951. This device is used in several controls in industry to evaluate strength cohesion and allows the quantification of cohesion strength of a joint. It directly measures the effect of variations in loading upon the resonant frequency and vibrationnal amplitude of the transducer coupled to the bonded joint.

3) **Results:** In order to evaluate the assembly quality, a calibration device reproducing a variable amount of pressure at the interface between two layers has been developed. This calibration apparatus is made of two metal plates stacked one over the other. Gaseous pressure is applied under the first plate in order to induce a well-known interface pressure. A simulation of this calibration device behavior under pressure has been performed using the ABAQUS software. Results give the exact amount of gaseous pressure to inject under the first plate in order to create the desired interface pressure representative of the bonding process.

Experimentation is led by positioning the transducer on the external plate. When gaseous pressure is applied under the inner plate, modifications of mechanical properties of the two sheets are induced. Pressures are generated at the interface between the two layers. The gaseous pressure injected under the inner plate is measured as a function of the piezo-electric transducer frequency shift.

In this study, the upper sheet is composed of a 3mm thick Titanium plate placed over the lower sheet made of a 2mm thick Tantalum plate. Experimental results are illustrated in Figure 2 and are compared to the mass-spring model.

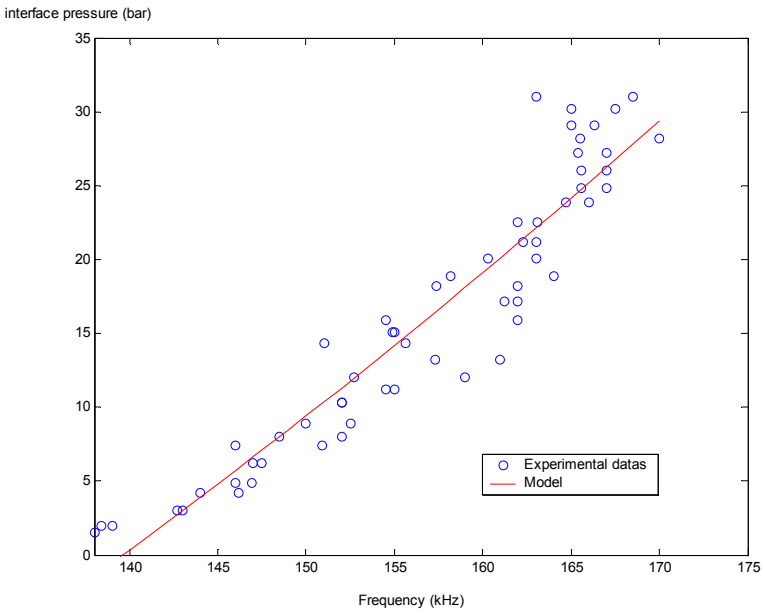


FIGURE 2: Comparison of experimental data to the mass-spring model

First results of this study show that it is clearly possible to point out bonded or disbonded areas (boolean result). Shifts in the frequency of the transducer appear to be proportional to the bonded joint quality. However, quantification of the exact state of the interface pressure is quite difficult with this technique. However, dispersions in the experimental results are frequently observed for the same state of assembly essentially due to the manual positioning of the transducer on the external layer. Future improvements in the mechanical holding of the transducer are necessary to validate the results repeatability.

3. Gap Measurement Using Microfocus Tangential Radiography:

1) PRINCIPLE OF THE METHOD:

When the ultrasonic spectroscopy technique points out a disbonding area, it is necessary to quantify in an accurate way the size of the gap between the two layers. In case of an axisymetrical geometry specimen, tangential radiography is then performed. The interface between the two layers is x-rayed with a microfocus generator. A particular attention on the location of the generator in front of the assembly gap must be performed experimentally as shown in Figure 3.

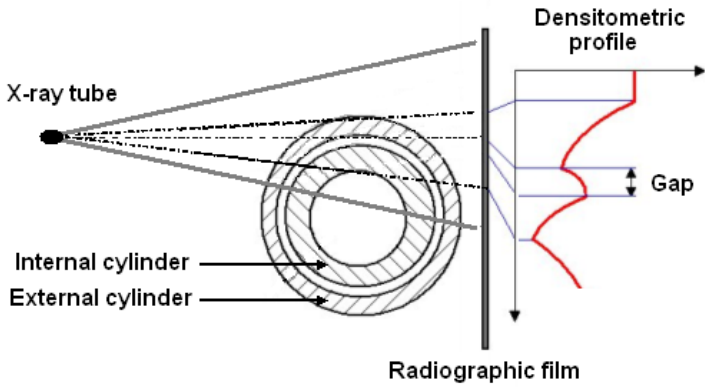


FIGURE 3 : Schematic representation of the tangential radiography principle for gap measurement

2) EXPERIMENTAL PARAMETERS OPTIMIZATION WITH SIMULATION TOOLS:

A first study based on the use of radiographic simulation tools (SINDBAD developed by CEA LETI [4], internal codes…) have then been performed to find the best radiographic

parameters. The main parameters that may enhance image quality in term of signal to noise ratio are then evaluated.

➢ ***Determination of the best x-ray tube parameters:***

First, these parameters are set-up in order to improve the object contrast. A maximum exposure time of 15 minutes is imposed to keep a total acceptable time of control of the specimen. On the other hand, the best combination of exposure time versus magnification is evaluated. A magnification of 4 is then chosen for this experimentation.

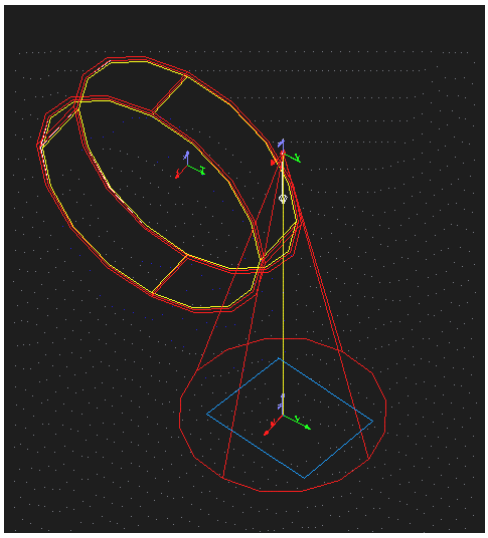
➢ ***Determination of the best radiographic film configuration:***

Several configurations of screen / film have been tested with the modulation transfer function technique and the choice of the best detector has been determined by comparing the different curves representing MTF (%) as a function of spatial frequency (mm^{-1}).

➢ ***Determination of the best digitization parameters:***

In order to quantify precisely the gap between the two layers, radiogram digitization using a microdensitometer is involved. The size of the digitized pixel is chosen at 5 x 50 µm and corresponds to a compromise between the need of the best lateral resolution, acquisition time and digitization noise. Optical radiographic film densities in the range of 0 to 5 are then digitized on 12 bits grey levels with a microdensitometer.

(a)



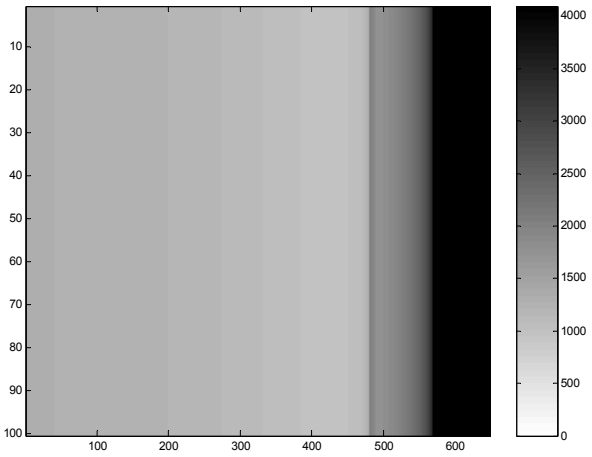


FIGURE 4: (a) 3-D representation of the experimental device
(b) Simulation showing a small gap between two layers.

3) DENSITOMETRIC PROFILE MODELING:

A complete modeling of the full experimental radiographic bench is performed [5]. The model is build from the characteristics of the generator, the nature and geometry of the

specimen, the global unsharpness, the response of the radiographic film after processing, the microdensitometer response and the build-up factor.
The parameters used in this modeling are :

- e_i: thickness of layer i;
- R_i: external radius of layer i;
- j: gap between the two layers
- G: magnification;
- I_0: intensity of the X-ray tube;
- T: time of exposure;
- $\mu_i(U)$: average attenuation coefficient of material i for an X-ray tube voltage of U;
- H: global unsharpness of the system (geometric and intrinsic unsharpness);
- B: Build-up factor;
- A, b, c: characteristic coefficients of the model of the radiographic film;
- α, β: gain and offset of the microdensitometer;

The model developed first takes into account the calculation of material thickness. Application of the Beer-Lambert attenuation law is performed and the final result of the densitometric profile is convolved by the global unsharpness factor (geometric and inherent unsharpness). Then, the responses of the radiographic film and the microdensitometer are evaluated experimentally and modeled in order to obtain the estimated density D_μ as a function of the distance along profile.

$$D_\mu(x,V,W) = K\left(H * e^{-g(x/G)}\right)^c + Offset \qquad (2)$$

where
$$\begin{cases} K = \alpha.A.B^c.T^c.I_0^c \\ Offset = \alpha.b + B \\ g(x/G) = function(e_i, R_i, \mu_i, j) \\ V \text{ corresponds to the vector of the known parameters } (R_i,\ e_i,\ G,\ H), \\ W \text{ corresponds to the vector of unknown parameters } (j,\ K,\ c,\ \mu_i,\ Offset) \end{cases}$$

An image representing a gap between two layers is simulated with this model in Figure 4. A characteristic densitometric profile is then extracted to evaluate the gap on the profile.

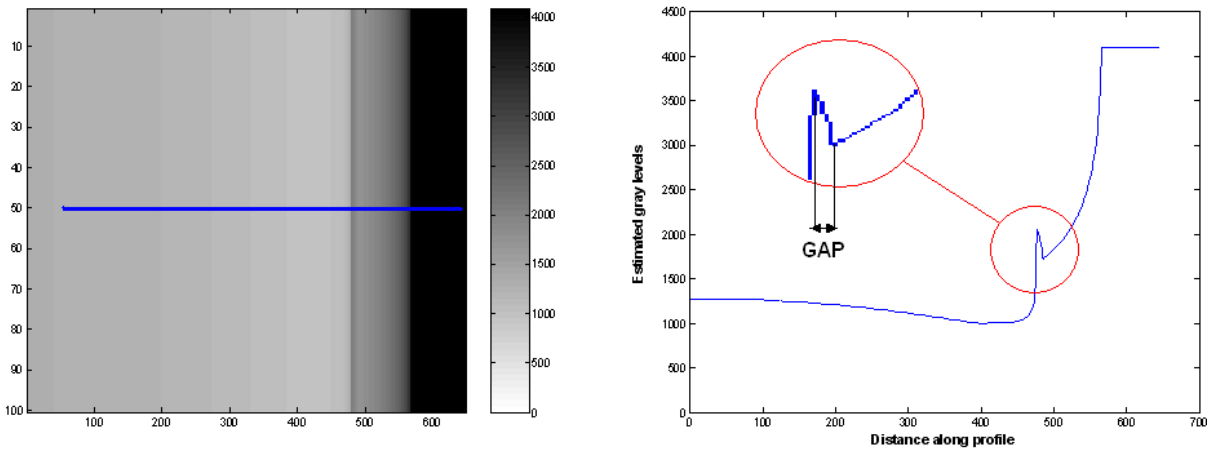


FIGURE 5 : Simulated image and densitometric profile showing a gap between two layers

4) RESULTS:

A calibration device has been developed in order to evaluate the possibility of detecting small gaps between the two parts of materials. This device consists in placing two half-

cylinders one over the other. A wedge of a given thickness is placed under the upper half-cylinder in order to simulate a well-known gap between the two layers. A tangential radiography of the calibration specimen is then performed and it gives information on the feasibility of detection of very small gaps.
In a first step, radiographs of the calibration device with wedges of given thicknesses are used to validate the visual measurement of the operator and to estimate the smallest visible gap with a micrometric gnarl. Several configurations simulating gaps ranging from 10 to 100 µm have been performed experimentally. Gap measurement has been evaluated by different qualified operators. For a magnification of 4, the smallest gap that can be measured with a suitable approximation is evaluated and validated to 12.5 µm. Results of this investigation are presented in Figure 6.

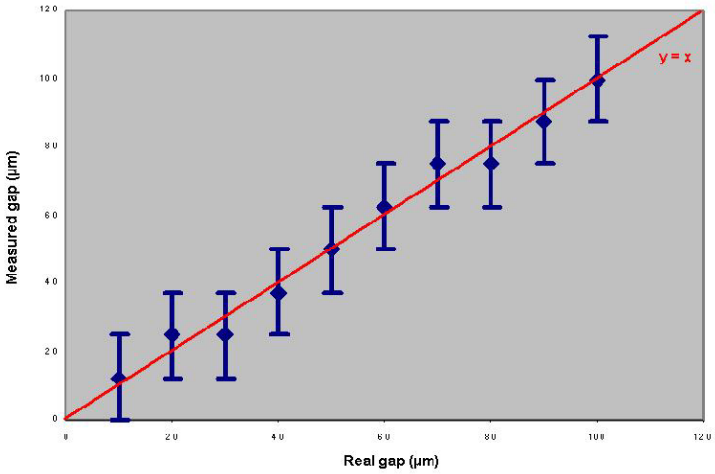


FIGURE 6: Comparison between visual gap measurement and real gap between the two layers (G = 4).

On the other hand, digitization of the area of interest of the radiogram is performed. As shown in Figure 7, a direct measurement of the gap on the densitometric profile appears to be quite impossible for very small gaps due to photonic and digitization noises. A technique allowing the indirect evaluation of the gap parameter by inverse problem solving is involved. First results show that this approach enables a better, accurate and automatic small gaps measurement.

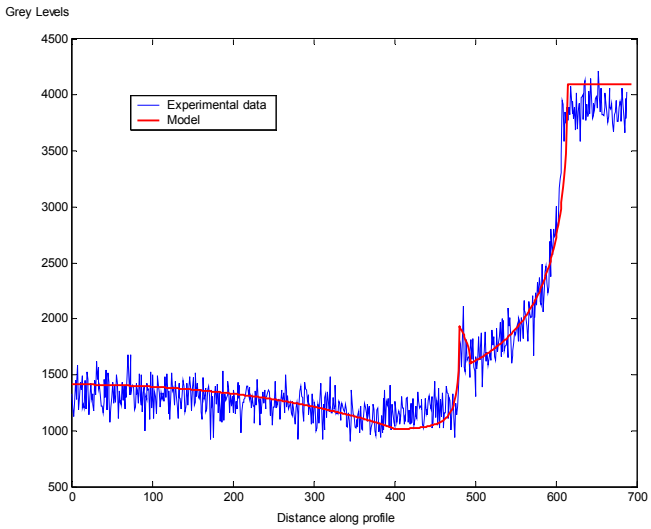


FIGURE 7: Comparison between experimental data and model

Future works will be achieved to enhance the detectability of very small gaps by using appropriate optimization techniques. First results show that this approach enables an accurate measurement of small gaps in an automatic way.

4. Conclusions: A complete study based on the comparison between modeling and experimental results on calibration devices have been performed for two complementary NDT techniques. This work explains the principle and validates the performance of these bonding characterization techniques, ranging from totally disbonding areas with gap measurement using tangential radiography to varying states of bonded assemblies with ultrasonic spectroscopy control.

The model developed for the ultrasonic spectroscopy control is based on a mass-spring model and shows the influence of the experimental parameters and the sensitivity of this nondestructive testing technique. In order to improve the exact characterization of interface pressure, future works based on the use of acoustic microscopy with a vibrating cantilever will be evaluated. Local mechanical properties of the materials at the near interface between the two layers will be evaluated and quantified.

An approach based on the use of simulation tools has been performed to evaluate the best experimental parameters for the radiography. Then, an approach based on the modeling of the whole radiographic experimental device has been performed. Suitable agreement between this model and experimental data is shown in this paper. Future works must be lead to improve the detection sensibility of smallest gaps by the use of accurate optimization tools to evaluate, in an indirect way, the gap between two layers by tangential radiography.

References:

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