NON DESTRUCTIVE INSPECTION OF WEAK BONDS IN ADHESIVELY BONDED JOINTS

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SUMMARY: For a convincing adhesively bonded joint or adhesively bonded reinforcement of a plate, non-destructive inspection (NDI) is an important procedure to assure the strength and the durability of the joint or the repair. A number of NDI methods are available for detection of lack of quality due to disbonds, voids, etc. However, the detection of weak bonds due to poor quality of the interface between the adhesive and the adherend is still not well established. This paper investigates the possibility of using sensitive optical interferometric measurement to detect adhesion weakness in bonded joints. Finite element analysis shows that the peel deformation in an unsymmetrically weak joint could be a feature for detection of weakness while in-plane deformation of weakly bonded joints is indistinguishable from that of well-bonded joints. Results using an overlay double exposure holographic interferometric system show promise as a potential NDI method for monitoring adhesion weakness.

KEYWORDS: Non-destructive inspection, Adhesively bonded joints, Weak bonds, Adhesive weakness, Bond durability, Bond integrity, Bonded lap joints, Peel deformations.

INTRODUCTION

Adhesively bonded joints are employed widely in aircraft construction as well as in repair of airframe structures due to their many advantages over mechanically fastened joints such as reduction in weight, reduced stress concentrations, enhanced fatigue properties, better sealing, lower part count, and so on. Among their few drawbacks, one of the most seriousness is the difficulty in inspecting them non-destructively, particularly for weaknesses in the bondline integrity. In recent years a number of non-destructive inspection (NDI) techniques, such as normal incidence ultrasonics, ultrasonic spectroscopy, and leaky Lamb wave have been developed for the detection and monitoring of cohesive weakness, or deterioration of the properties of the adhesive material. At the same time NDI[1-4] techniques such as thermography, ultrasonics and X-ray are being successfully applied for the detection of disbonds, i.e. complete failure of adhesion at the bondline. The detection of bondline weakness, i.e. partial loss of adhesive strength at the bondline interface, has however remained elusive. The weakness associated with adhesion or reduction in the strength of the adhesive bondline interface is generally caused by poor surface preparation and by environmental effects such as moisture ingression[5]. While destructive methods such as the Boeing Wedge Test are applicable for qualitative measurement of bond durability, there does not yet appear to be any acceptable non-destructive method for the detection of weak adhesive bonds.

The difficulty in inspecting for adhesion weakness arises from the fact that bondline weakness is mainly associated with a reduction in strength and not a reduction in stiffness. While structural behaviour in the pre-failure regime is governed by stiffness properties, strength properties come into effect only at the point of failure. NDI techniques founded on monitoring structural behaviour in the pre-failure regime are thus apparently incapable of detecting variations in strength without violating the criterion of non-destructiveness. This widely held belief has hitherto discouraged the exploration of the feasibility of traditional NDI techniques for detection of weakness in adhesion in bonded joints.

However, recent experimental and numerical analysis work at the Australian Defence Force Academy[6-10], using holographic interferometry for mapping out-of-plane displacements, suggest that variations in peel displacement patterns on the surfaces of the outer adherends of double lap and doubler bonded joints are symptomatic of variations in bondline strengths at the joint interfaces, and can therefore be employed to detect adhesion weakness in bonds non-destructively. The technique employed is Portable Holographic Interferometric Testing System (PHITS), which is an overlay reflective holographic interferometry technique that is off-table and hence easy-to-manage. The advantages of PHITS include high sensitivity, portability, good operability, robustness, and low-cost; the main disadvantage of the system is that the fringes do not lend themselves to a direct correlation with the displacements.

MODEL FOR LOAD TRANSFER IN WEAKLY BONDED JOINTS

The observed variations in out-of-plane displacement patterns on an adherend with a weak bondline as compared to that on an adherend with a perfect bondline is caused by changes in the load path eccentricity resulting from the differences in the magnitudes of the loads transferred to the adherends across the two interfaces. In this paper a physical model is

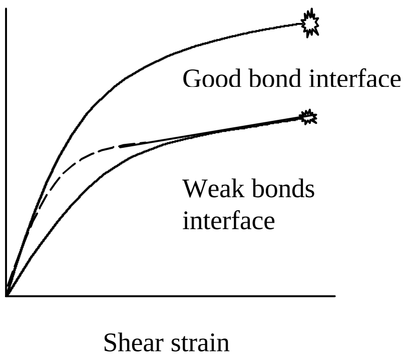


Fig.1. Reduced Stiffness and Strength

developed to describe the physics behind the apparent variation in peel stiffness caused by the differences in load transfer capability of good and weak bondlines. The model is based on the more acceptable concept that weakness in adhesion is equivalent to a reduction in the *strength* of the bondline, which may have arisen from a failure of some of the inter-molecular bonds between the outermost layer of the adherend and that of the adhesive. It is the strength reduction that causes the unsymmetrical load transfer. In fact, stiffness reduction is also considered in the FEA as in Figure 1, however, FEA results have shown that the influence of the stiffness reduction is negligible due to the infinitesimal thickness of the bondline interface. A reduction in bondline strength implies a local reduction in the load transfer capability of the interfacial layer, so that when the applied axial load is sufficiently high in a doubler joint or a double lap joint with unsymmetrical bondline strengths, more load is transferred to the outer

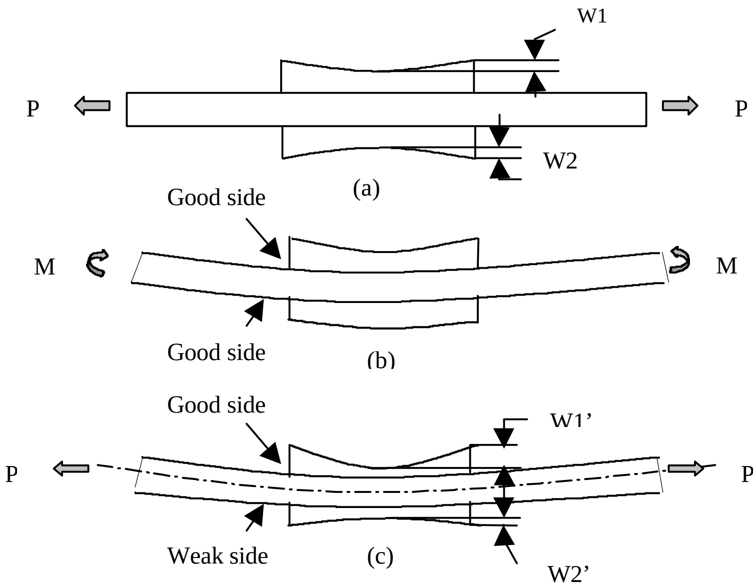


Fig.2. Effect of Bending on Peel Deformation

adherend with the stronger bond than the outer adherend with the weaker bond. The effect of the unequal distribution of the load transferred to the outer adherends in a doubler joint with unsymmetrical bond strength is depicted schematically in Figure 2. The unsymmetrical distribution of the load transferred to the outer adherends results in an overall bending of the whole joint, in addition to the local internal bending moments which produce peel deformations concentrated at the ends of the adherends even in a symmetrically loaded double lap joint. The latter peel deformations are symmetric in nature with respect to the mid-plane of the joint as shown in Figure 2(a), whereas the out-of-plane deformations caused by overall bending is antisymmetric in nature (Figure 2(b)). Thus the out-of-plane displacements due to bending adds to the peel deformation on one side of the joint, while it decreases the peel deformation on the other side, resulting in an appreciable difference in magnitude in the total out-of-plane displacements of the two sides, as shown in Figure 2(c). Thus an out-of-plane sensitive optical interferometric method such as PHITS can be a promising NDI method for singling out the weak interface between the good and weak sides by monitoring the out-of-plane displacement on the top surface of the joints, as well as a measure of the relative strengths of the two bondlines. In-plane moiré could also be employed at the side of the joints

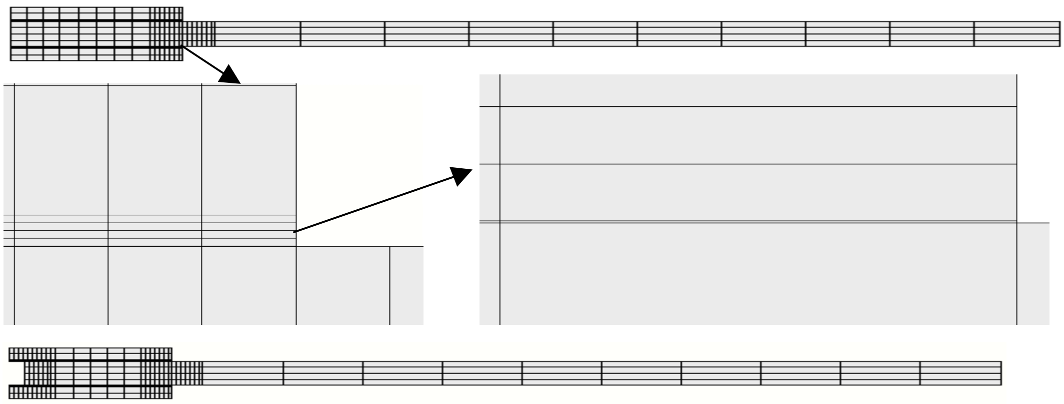


Fig.3. Schematic finite element mesh

but the replication of the very fine optical grating (1200 lines/mm) is time consuming and expensive.

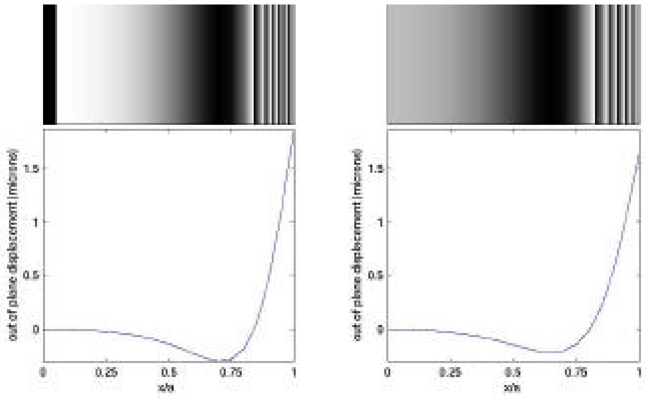
The applicability of the proposed model is investigated by finite element analysis of double lap joints and doubler joints with unsymmetrical bondline strengths on opposite sides. Two dimensional finite element models incorporating elastic-plastic material elements for the adhesive as well as the interfacial layers between the adhesive and the adherends are analysed to compute out-of-plane displacement distributions on the adherends on either side. The thickness of the interfacial bondline between the adhesive and the adherend is modelled as 2μm. The thicknesses of the adhesive, the outer adherend and inner adherend are 0.19mm, 1.6mm and 3.2mm respectively. The properties of the interface are assumed to be the same as those of the adhesive when the bond is good. The finite element software package ANSYS 5.4 was employed to perform 2D analysis of the doubler joint and the double lap joint, with 8 node quadrilateral plane strain elements (PLANE82) with mid-side nodes. Figure 3 shows schematic representations of the meshes generated in ANSYS for the doubler joint and the double lap joint (top and bottom respectively). The mesh sizes in the figure are representative only, since the actual meshes employed in the models are too dense to be shown with clarity. The outer adherent, adhesive layer, bondline interface and the inner adherend were respectively modelled with 4, 5,1, and 8 elements across the thickness. The mesh density was varied along the length of the joint to obtain greater accuracy in regions of high stress concentrations. The regions at the ends of the overlap were modelled with a fine mesh having a density of about 40 elements per mm over a length of about 5 mm. The mid-section of the double lap joint was also modelled with a similar fine mesh. Due to symmetry, it was necessary to model only a quarter of the symmetrically bonded joints, whereas for the specimens with different bond strengths on the two sides, it was required to model the full thickness along one half of the length of the joint. The half model joints in the latter case have a total of approximately 12000 elements with a total number of about 74,000 degrees of freedom. The material properties are listed in Table 1.

Table 1: Material Properties

Property	Adhesive (FM300)	Adherend (2024-T3)	Interface layer (Full strength)
Young's modulus(GPa)	2.9	70	2.9
Poisson's ratio	0.34	0.33	0.34
σ_1 (MPa)	38	338	38
ε_1	0.013	0.0048	0.013
σ_2 (MPa)	49	355	49
ε_2	0.02	0.006	0.02
σ_3 (MPa)	55	362	55
ε_3	0.024	0.0098	0.024
σ_4 (MPa)	60		60
ε_4	0.031		0.031

FINITE ELEMENT RESULTS AND NUMERICAL SIMULATION

Out-of-plane displacement contours simulating expected holographic fringe patterns on the outer adherend surfaces are generated from the finite element results to demonstrate the differences in fringe numbers and fringe distribution patterns between the weak side and the strong side of the unsymmetrically bonded joints. Typical results obtained for the case of doubler joint and double lap joints are illustrated in Figures 4-7. It is clear that in the case of



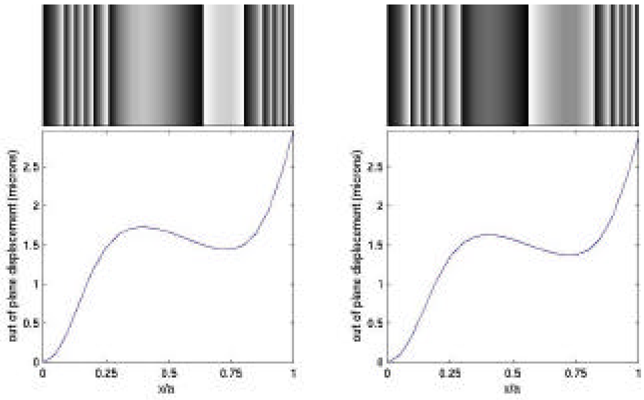
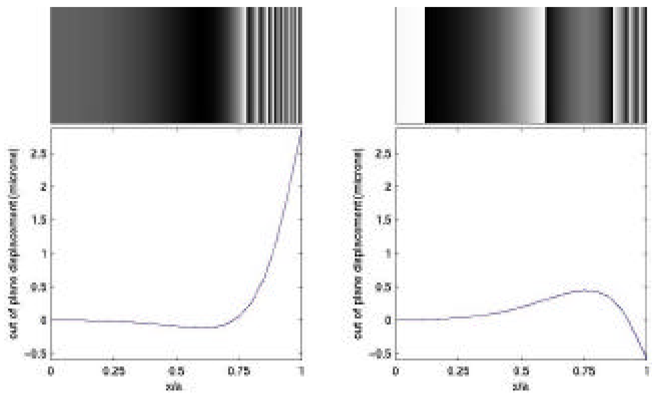


Fig.4. Fringe Patterns in Symmetric Doubler Joints at 150MPa (a) 100% (b) 50% Bond Strength

Fig.5. Fringe Patterns in Symmetric Double Lap Joints at 100MPa (a) 100% (b) 50% Bond Strength



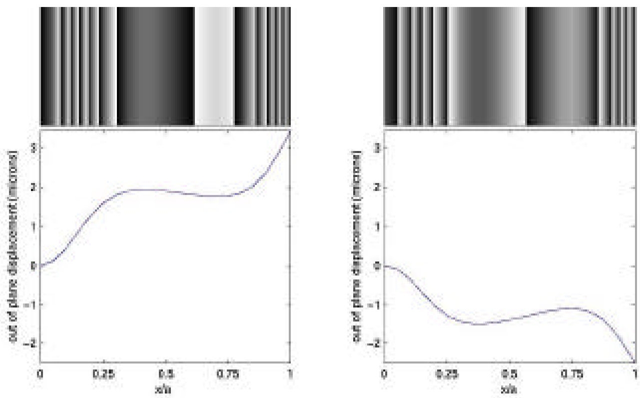


Fig.6. Fringe Patterns in Unsymmetric Doubler Joint at 150MPa (a) Good Side (b) Weak Side

Fig.7. Fringe Patterns in Unsymmetric Double Lap Joint at 100MPa (a) Good Side (b) WeakSide

symmetric strength, in Figures 4 and 5, the fringe pattern and density at the ends of the joint overlaps are practically the same for both the joint with the good bonds and the one with the weak bonds. However, when the joints are unsymmetric, as in Figures 6 and 7, where the bond strengths are reduced by 50% at one overlap in comparison to the other, there is a considerable difference in the fringe patterns and fringe densities observed on the two sides. For the doubler joint in Figure 6, the maximum out-of-plane deformations have a ratio of 1:5 at a load of 150MPa which gives rise to a distinct variation in fringe numbers and the fringe densities at the ends of the overlaps of the joint.

EXPERIMENTAL VERIFICATION

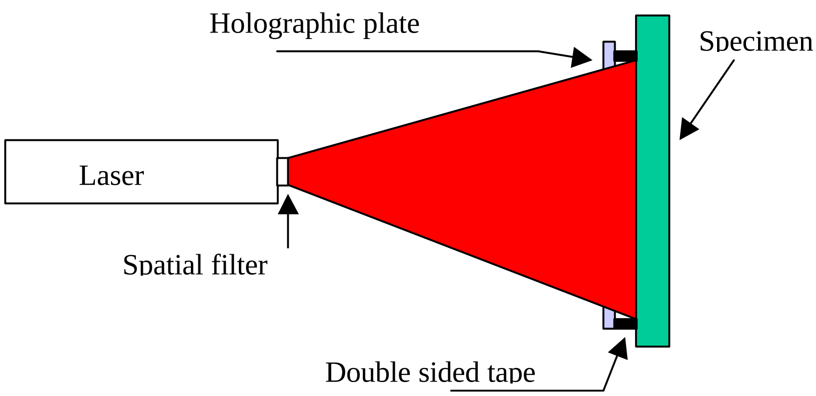
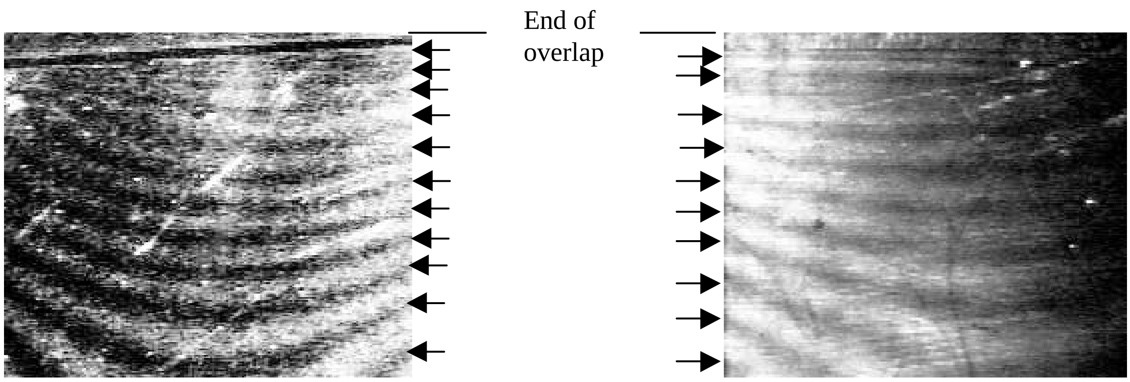
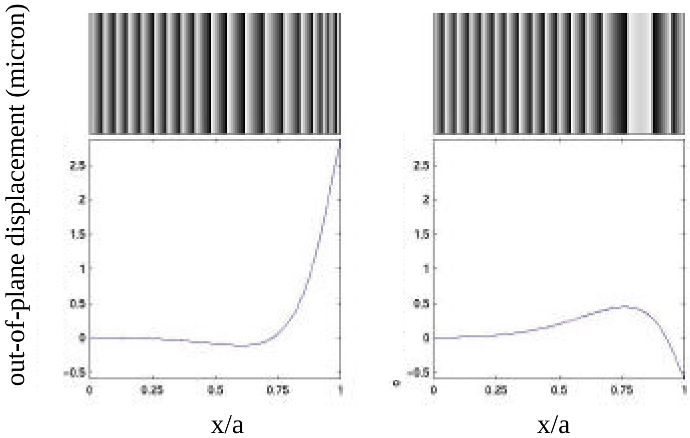


Fig.8. PHITS setup



(a) *(b)*

Fig.9. Holographic fringes (a) at good side (b) at weak side



(a) *(b)*

Fig.10. Fringe Patterns including in-plane displacement influence on Unsymmetrical Doubler Joint at 150MPa (a) Good Side (b) Weak Side

The proposed model and results of the finite element analysis are verified by experiments conducted on doubler joint specimens with good and weak bonds. Bondline weakness in the joints is created artificially by deliberately using poor surface preparation processes in controlled manner and measured by means of destructive tests on control specimens. The test specimens are subjected to static tensile loads and interrogated using PHITS to obtain fringe patterns. The object beam is the reflected wave from the specimen, the reference beam is the illumination laser beam as shown in Figure 8. The hologram is recorded in the emulsion of the holographic plate twice, with and without axial load respectively. The reconstructed image will consist of interference fringes which are basically contours of the out-of-plane displacement with the resolution of half a wavelength of the recording laser: for a bright fringe, $w=n\lambda/2$, for a dark fringe, $w=(2n+1)\lambda/2$. However, the double exposure holographic fringes represent the projection of the 3-dimensional displacement to the sensitivity vector which is at the bisection of the illumination and the observation pointwise during reconstruction. The 3D property of the fringes not only make the direct mechanical interpretation of the fringe pattern difficult but also let the in-plane displacements influence the formation of the final fringes. The fringes obtained experimentally on the two sides of a doubler joint with bonds of unequal strengths on the two sides are shown in Figure 9. Since it is hard to keep the sensitivity vector uniform across the image, the fringes are not as straight as expected, and there are almost equidistant fringes at the middle of the doubler joint which are caused by in-plane displacements only. The in-plane displacements also make the density of the fringes at the end of the joint overlap sparser. Nevertheless, the images still show the difference between the good side and the weak side of the doubler joint qualitatively. Figures 10(a) and 10(b) show the simulated fringe patterns computed from the finite element modelling taking into account the influence of the in-plane displacements when the sensitivity vector is slightly slant from the perpendicular. It is obvious that the fringe patterns observed in the experiment (Figure 9) are closer to the patterns in Figure 10 than those in Figure 6.

CONCLUSION AND FUTURE WORK

Doubler or double lap joints are representative of typical double side repairs as well as secondary joints in the aircraft. In this paper a phenomenological model is developed to explain the apparent difference in peel behaviour between the good side and the weak side of a double lap joint or doubler joint with unsymmetrical bond strengths. According to the FEA results out-of-plane deformation could be a feature of weak bonds while in-plane deformation is not. The phenomenon has been observed qualitatively by holographic interferometry experiments. However, quantitative correlation between the weakness of the bonded joints and the holographic fringes needs to be established. Other independent optical techniques such as in-plane moire interferometry are being employed to validate the finite element modelling, so that quantitative comparisons can be made between the Finite Element predictions for out-of-plane displacements and those observed using PHITS. Further numerical analysis and experiments are being conducted to investigate the applicability of holographic interferometry as an NDI tool for detecting weak bonds in real-life applications such as in single side bonded patch repair.

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