Laser Bond Inspection Device for Composites: Has The Holy Grail Been Found?

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Summary
Extensive experimental development, supported by 1-and 2-D hydrodynamic code simulations has demonstrated that the strength of bonds can be tested using calibrated weak shock waves (stress waves) generated at the surface of composite (and other) joints. Previously full-scale proof testing of bonded structure has been the only sure method of detecting "kissing" or weak bonds. Laser bond inspection (LBI), using high-intensity stress waves, has been shown to provide a method for localized testing of bond strength.

Controlled stress waves of sufficient intensity have been shown to be useful for adhesion evaluation. Gupta, et.al. demonstrated that internal bonds could be evaluated with shock waves [3-5]. Recently, high peak power, short burst laser systems have been shown to reliably and repeatedly test the strength of internal bondlines in composite joints of reasonable (6 to 15 mm total thickness) [6]. Modeling of the method has shown that the laser beam shape results in controlled, very localized testing of bond strength. A compact high peak power laser system and beam delivery method has been designed for factory implementation. To date, numerous tests on composite to composite bonds have shown the method to be sensitive to weak bonds created by poor adhesive mixing, improper surface preparation and/or contamination.

Figure 1 illustrates the fundamental process lf laser-generated stress wave evolution in a substrate. The energy delivered by the laser is absorbed in a sacrificial overlay such as black paint at the incident surface of the sample. Mo sample heating takes place, and there is no surface damage. Vaporization of some elements of the overlay produces locally high pressure that is enhanced by inclusion of a transparent overlay layer, such as a water film, that briefly confines vapor expansion. This pressure pulse duration can be tailored to a few hundred nanoseconds. The magnitude of the pressure is a function of the laser input intensity, which facilitates the generation of calibrated stress waves. The shock from the laser pulse produces a compression wave that propagates to the back surface of the sample where it reflects back in tension. In the 1-D approximation, it is this tensile wave propagating through the sample that provides the proof-test loading. When the wave arrives back at the front surface, it reflects into compression again, and the cycle repeats. The lower part of Figure 1 illustrates the time evolution of the stress wave for a simplified one-dimensional case in which the laser beam diameter is at least several times larger than the sample thickness. The actual two-dimensional case of practical interest is considerably more complex, but the basic principles are the same.

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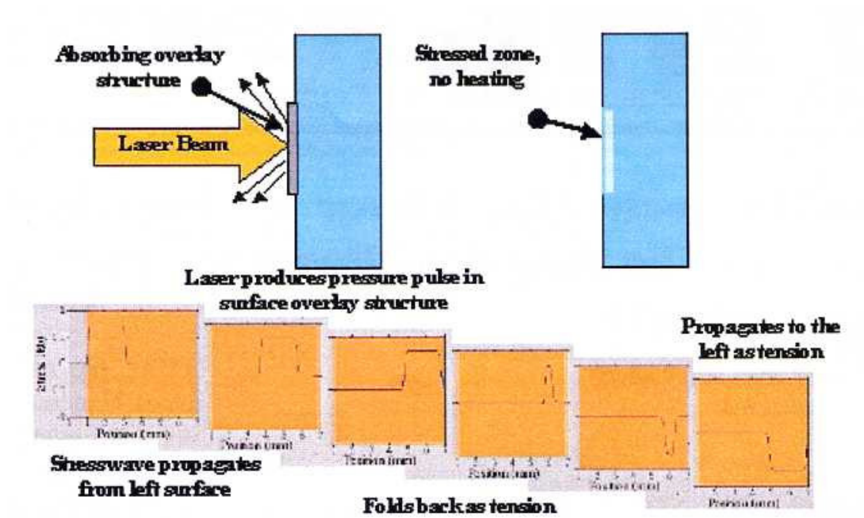

Figure 1. One-dimensional approximation for laser based shockwave generation and stress pulse propagation in a solid slab.

As the wave reflects from a free surface, it folds back through the incoming wave and relieves stress to zero in the overlap region. Net tension appears only after the reflected wave clears the tail of the incident wave. Thus, in the simple 1-D approximation, without attenuation, all portions of the sample experience equal tension duration except for an excluded region near each surface where the duration of tension decreases linearly to zero with proximity to the surface. Dynamic failure is frequently dependent on both stress and duration. This suggests the near surface regions may not be inspectable at the same level as the sample bulk. However, with typical input pressure pulse lengths adjustable from about 100 ns to 300 ns, the excluded regions are only 0.15 to 0.45 mm respectively in graphite/epoxy composites. In addition, the actual stress pulses are not square, and 2-D effects tend to produce additional sources of tension waves so that the excluded regions are lessened in extent.

Experimental measurements of bonded joint response have been conducted primarily with bonded Cytec Fiberite 3K-70-PW T300 934 graphite/epoxy laminate coupons. Bonds were made with Loctite Hysol EA 9394 epoxy mixed in the standard hardener-to-resin ratio (B/A) of 0.17, with B/A = 0.05, and with B/A = 0.03. These mixtures provide full static strength, 70% strength, and 50% strength bonds respectively. Various surface preparations were also employed. They included grit blast (GB), "over-" or double-grit-blast (OGB), sanded and solvent cleaned (S), surfaces roughened with ScotchBrite, (SB), and as tooled with solvent wipe (Sol). Surfaces have also been prepared with various levels of silicon release agent contamination. Bondlines were prepared with nominal thickness (~0.5 mm) and with thickness steps up to 3 mm. Baseline samples used 20 plies bonded to 20 plies with thickness/ply = 0.21 mm. Additional laminate pairings were also studied using 10, 16, 20, 30, and 46 plies in all combinations to evaluate range performance of bondline response.

Figure 2 shows the comparison of LBI failure fluence versus tensile test results for variable strength paste adhesive mixtures. Figure 3 shows a comparison of double cantilever beam (DCB) tests with LBI failure fluence for grit blasted surfaces that have been contaminated with a silicone based release agent that reduces the bond strength. Experiments to date have shown the LBI method to be very sensitive to bond joint assembly factors including surface preparation changes.

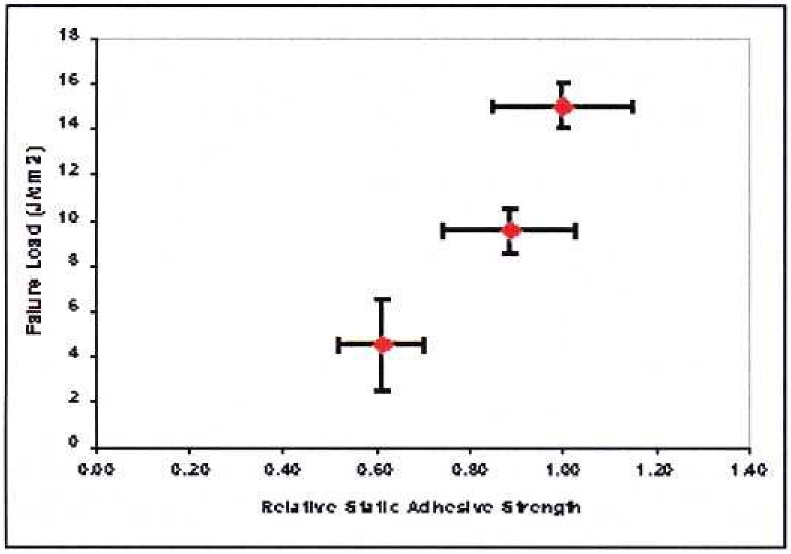

Figure 2. Comparison of LBI failure fluence with tensile tests for variable adhesive quality.

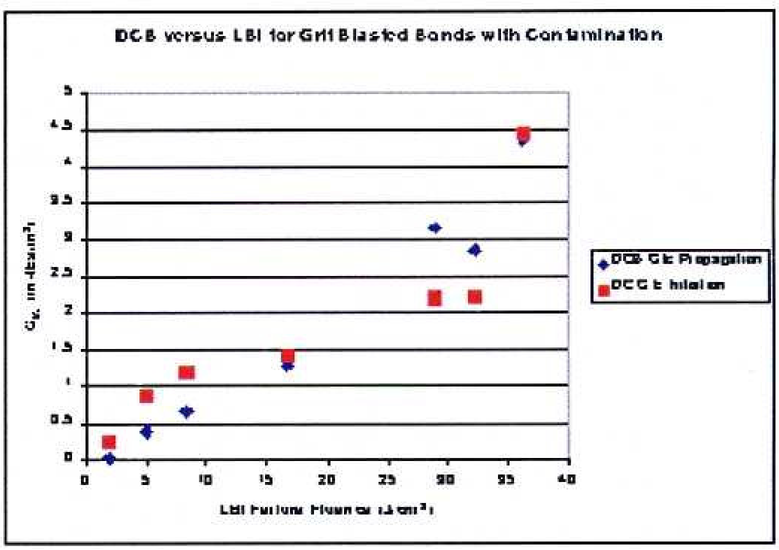

Figure 3. Comparison of DCB tests with LBI failure fluence for contaminated surface bonds.

The results have been sufficiently positive that an implementation program has been undertaken to address key issues of a practical laser bond inspection device (LBID). Figure 4 shows an articulated arm for beam delivery with a practical process head for the LBID laser energy delivery and response monitoring of a structural test article. The structural test article represents the open end of a box structure with bonds at the corners and stiffeners along the side walls. The inspection in Figure 4 is of angle bracket bonds.

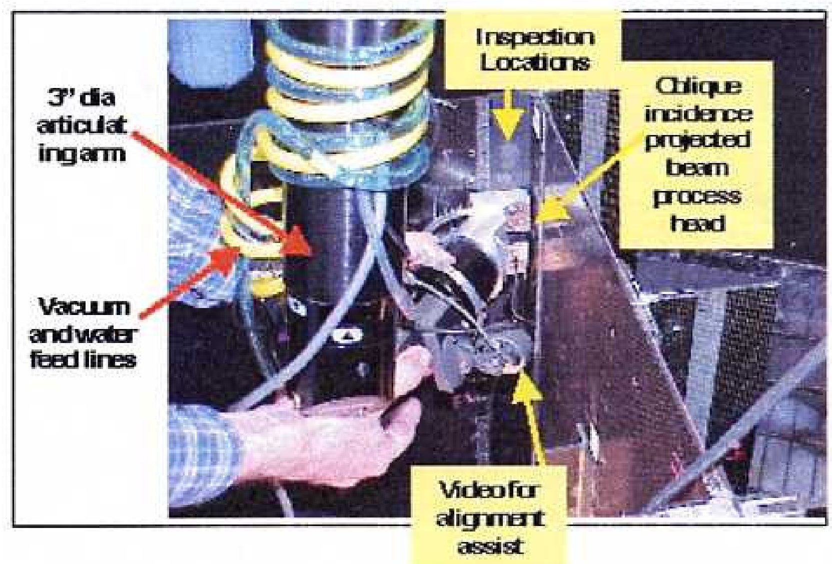

Figure 4. Beam delivery system with process head for use in an assembly environment.

This LBID prototype permits the operator to work using only laser goggles for protection. It has successfully completed inspection exercises on a composite assembly test article that demonstrated good access to most joints of an open, but confining geometry.

The prototype device shown in Figure 4 is not the only approach for applying this technology. The method can be considered for material testing using a variety of beam delivery approaches. Unlike mechanical tests, such as lap shear and DCB, LBI is not restricted to sample size or layer thickness specification, and the results are not affected by the edge quality. Some limitations on joints that may be inspected by this method are expected. Chief among these are limitations in thickness. To date, tests have been successfully performed on samples up to 23 mm thick.

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