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Adhesive Joints Subjected to Impact Loading: A Review

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Abstract Adhesive joints have widely been used in many engineering applications due to their outstanding advantages over conventional joining methods. Developing strong adhesive bonds lead adhesive joints to be a very popular joining methods in the applications subjected to impact loadings. Especially, the automotive industry uses adhesive joints in order to reduce the weight of vehicles by bonding multilayer lightweight materials. Understanding the performance of adhesive joints subjected to impact loadings is significant to apply them into the applications that may be exposed to high loading rates. Even though there are many researches on characterizing the performance of adhesive joints subjected to quasi-static loading in the literature, there are few studies focused on the performance of adhesive joints under impact loading. In this paper, the researches on adhesive joints under high loading rates are reviewed. The different testing techniques of adhesive joints subjected to impact loading are discussed.

Keywords Adhesive joints, Impact loading, Rate sensitivity

1. Introduction

Adhesive joints have widely been used in many engineering applications due to their outstanding advantages over conventional joining methods. Developing strong adhesive bonds lead adhesive joints to be a very popular joining methods in the applications subjected to impact loadings. Especially, the automotive industry uses adhesive joints in order to reduce the weight of vehicles by bonding multilayer lightweight materials. Understanding the performance of adhesive joints subjected to impact loadings is significant to apply them into the applications that may be exposed to high loading rates. The mechanical behavior of adhesive joints subjected to quasi-static loading does not necessarily represent their performance under impact loading due to the viscoelastic behavior of most of the polymer-based adhesives. Hence, it is imperative to assess the behavior of adhesive joints performing dynamic tests. In the literature, the mechanical behavior of adhesive joints under quasi-static loading has been studied by many researchers [1-4]. On the other hand, the performance of adhesive joints under dynamic loading has been investigated by only a few researchers. This review paper provides a discussion on studies of adhesive and adhesive joints under impact loading. Impact tests on adhesive and adhesive joints are discussed under two main subjects, i.e., an impact test on a bulk adhesive material and an impact test on entire adhesive joints. Then, the influence of the high strain rate on the mechanical behavior of adhesive joints is discussed.

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2. Impact Testing on Adhesive and Adhesive Joints

Characterizing the adhesive joints subjected to impact loading can be divided into two techniques namely determination of intrinsic properties of the adhesive and evaluation of the overall behavior of the entire adhesive joint. The intrinsic properties of the bulk adhesive are only useful in the initial step of designing an adhesive joint. However, it is not adequate to estimate the behavior of the adhesive joint because the interfacial properties between the adhesive and the adherends, and stiffness of the adherends play a crucial role in the behavior of complete adhesive joint [5]. In other words, intrinsic properties of the adhesive can give initial information to estimate the response of the adhesive joint to the impact loading. These are the tensile strength and stiffness, the shear strength and stiffness. In order to establish these properties, universal tensile testing machines [6, 7], drop weight impact testing machines [8], pendulum impact test set-ups [9, 10], split Hopkinson pressure bar set-ups [11] are employed, among others. It should be known that there is no standard test for determining the fracture properties of adhesive joints under impact loading. For determining the fracture toughness of the adhesive, double cantilever beam (DCB) test for mode I, end-notched flexure tests for mode II and tensile Hopkinson bar apparatus with specially designed specimens for mode I+ II can be used. The tests for determining intrinsic properties of adhesive eliminate the effect of the adherends to some extent. Yet, it is important to understand the overall response of the adhesive joint to impact loading because the interfacial properties between adherends and adhesives or stiffness of adherends can affect the overall performance of adhesive joints. Therefore, some experimental techniques for testing adhesive joints subjected to the impact loading are devised. These tests can be fallen into three groups, i.e. low impact velocity, medium impact velocity and high impact velocity tests [12]. Low impact velocity can be considered as a vibration problem, on the other hand the events of a car crash or bird-strike can be in the range of medium impact velocity [13].

Pendulum impact test set-up [14] can be used for low velocity up to 5 m/s, drop weight test set-ups [15] can be utilized for medium impact velocity in between 5 and 10 m/s. For high impact velocity tests, which is between 10 and 100 m/s, split Hopkinson pressure bar can be employed [16], among others.

3. Strain Rate Effect on Adhesive Joints under Impact Loadings

Mechanical response of adhesive joints to the impact loading can be substantially different than quasi-static loading. It is well known that polymer-based adhesives can behave nonlinearly under different loading conditions due to their viscoelastic behavior. In the impact event, dynamic stress waves can be pronounced and create early failure even at low impact loading levels. It is apparent that the necessity of impact tests on the adhesive joints is obvious in order to implement adhesive joints in the structures that demand impact resistance. In this part of the paper, studies on the behavior of adhesive joints are discussed.

One of the pioneering test on polymers conducted by Perry [17] using a pendulum rig, which is later standardized and called block impact test (ASTM D950 OR ISO 9653:1998). His results show that absorbed energy by the adhesive joint is proportional to the square of its failure stress. However, the measured absorbed energy is not exactly caused by the adhesive bond because of the large compliance of the metal adherends. Harris and Adams [18] performed an impact test on single lap joints using a customized Izod pendulum impact machine and compared the results with quasi-static tests. Their test results show that the energy absorption capability of the joint is significantly caused by the plastic deformation of the adherends. In addition, the comparison of quasi-static and impact test results shown in Figure 1 indicate that the failure strength of the adhesive joints consisting of high strength aluminum alloy and different type of adhesives are not affected by the loading rate. It is apparent that quasi-static and impact failure strength of adhesive joints are quite similar for the different type of adhesives, i.e.MY750, AY103, ESP105 and CTBN (see Figure 1).

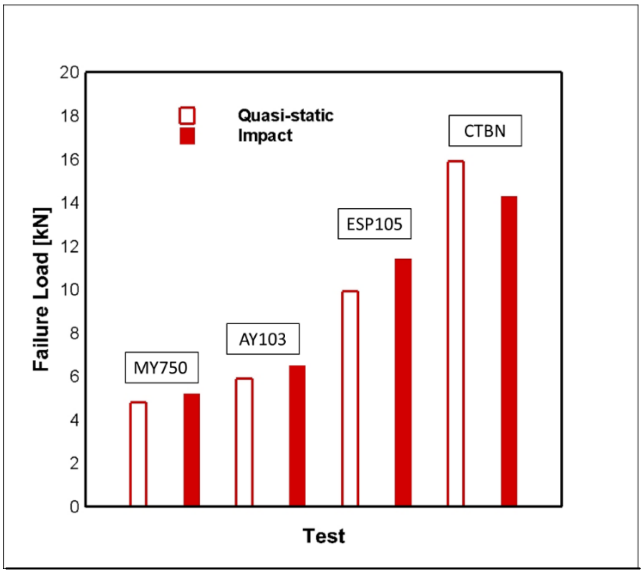

Figure 1. Influence of loading condition on the strength of adhesive joints. (Adapted from Harris and Adams [18]**)**

Adam and Harris [9] investigated the limitations of block impact test which is related to the difficulty in mounting the specimen in the test equipment. They investigated the effects of misalignment between the specimen and the pendulum head focusing on three different loading cases shown in Figure 2. Their results reveal that depend on the relative position of the pendulum head to the specimen, the stress state across the adhesive bond varies and this can affect the test results significantly. Therefore, special care must be taken while positioning the specimen to the test rig. The second issue with the block impact test is to have thick adherend which is not the case for real applications. To eliminate this problem, the impact wedge peel test has been devised. The specimen for this test technique is composed of two thin strips (30 mm in length and 0.6-1.7 mm in thickness) [19]. In this test, a wedge is employed to load the specimen in peeling mode.

The load is applied by a pendulum or an actuator at the speed between 2 or 3 m/s. Blackman et al. [20] studied the impact wedge peel performance of structural adhesives. Their results show that the impact wedge peel cleavage force is a function of both the adhesive and the adherends used in the adhesive joints. They also find that there is a linear correlation between impact wedge peel cleavage force and the adhesive fracture energy.

The test techniques explained above can provide a strain rate up to 100 s^{-1}. In order to understand the response of the material to higher strain rates (10^2 to $10^4 s^{-1}$), which are generally caused by an explosion or ballistic impact events, the split Hopkinson pressure bar (SHPB) or Kolsky bar can be utilized. SHPB shown in **Figure 3** consists of striker bar, incident bar, specimen and transmitter bar. The elastic wave propagation during the test is measured by the strain gages located at the certain locations of the incident bar and the transmitter bar. The unique feature of Kolsky bar is to have low stiffness ratio between the Kolsky Bar and the specimen, thus the specimen response to the load cannot be ignored in the experimental set-up design. In order to obtain an accurate experimental set-up, Kolsky bar set-up should be adjusted by running a test with a material whose response is known [21].

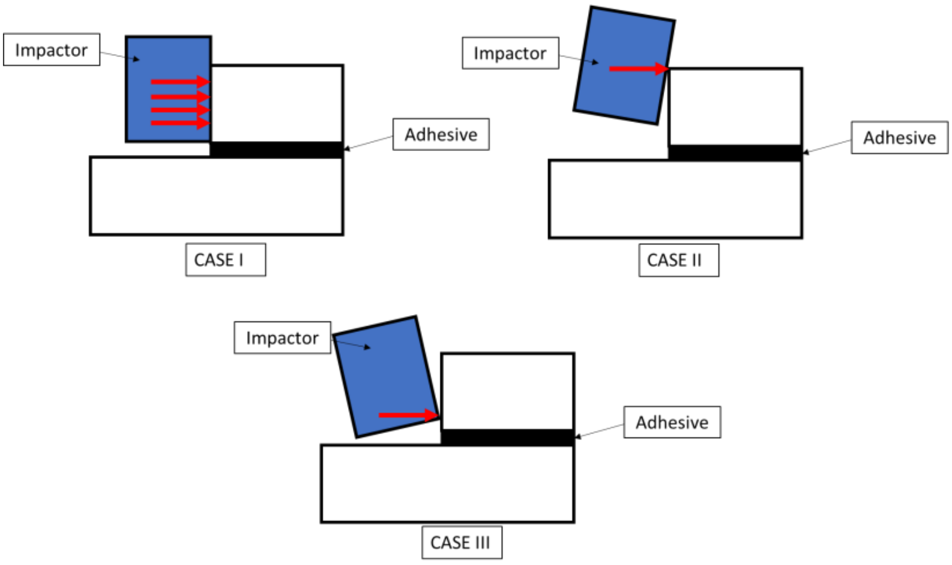

Figure 2. Possible mode of impact in block impact test (Adapted from Adam and Harris [18])

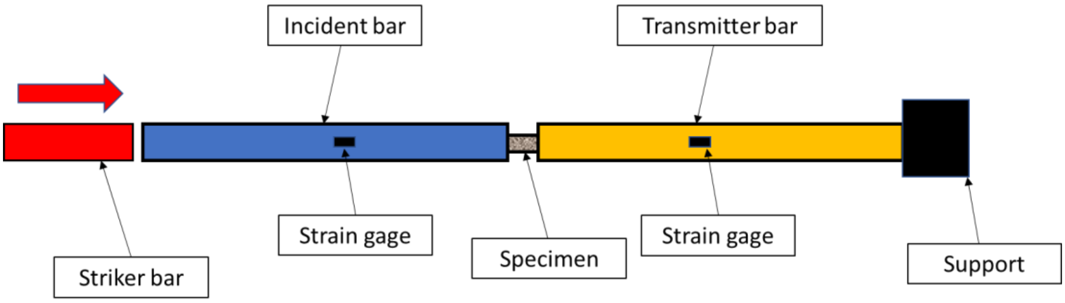

Figure 3. Schematic of a split Hopkinson bar

Even though the original design of SHPB is for a compression test, the SHPB test set-ups are adopted for tension, torsion, triaxial, and axial/shear combination. The distinct difference in these set-ups from the original one is loading and clamping methods of the specimen. Yokoyama and Nakai [16] performed impact tests on the hat-shaped specimens using modified tension SHPB. The hat-shaped specimen they used is a butt joint consist of Al alloy7075-T6 or commercially pure titanium bonded by an epoxy resin-based adhesive. They investigated the effect of loading rate ($\approx 10^6$ MPa/s) on the behavior of the adhesive joint. Their results displayed in **Figure 4** indicate that the tensile strength of the adhesive joint increases with increasing loading rate and decreases with adhesive thickness regardless of the type of adherend materials. They pointed out that the rate dependence of the joint is entirely caused by the inherent rate dependency of the epoxy. Challita et al. [22] studied the behavior of the adhesive joint under shear loading using an SHPB. They developed a specimen, which consist of a cyanoacrylate-based adhesive and steel adherends shown in **Figure 5**, that can transfer the compressive wave to the adhesive bond in a shear loading. Their results revealed that the shear strength of the adhesive is quite rate sensitive and increases with increasing loading rate.

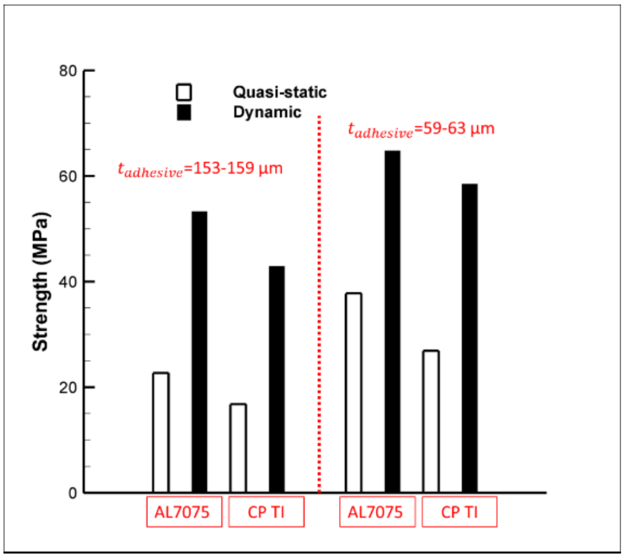

Figure 4. Comparison of dynamic and static test results of different adhesive joints (adapted from Yokoyama and Nakai [16])

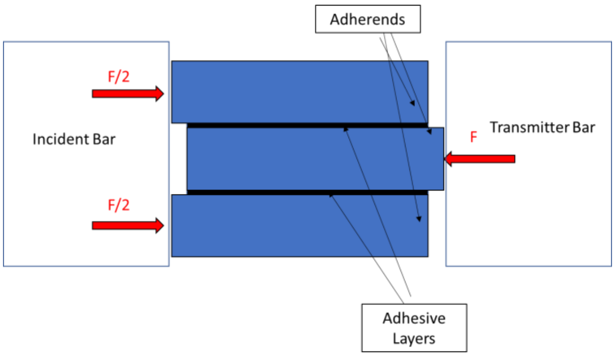

Figure 5. Schematic of the specimen for shear impact test in SHPB (adapted from Challita et al.[22])

Raykhere et al. [23] used torsional split Hopkinson bar (TSHB) to investigate the shear strength of adhesive joints under loading rate in the range of 0.6–1.2 MPa/µs. They used four different adhesives (i.e. Araldite 2014, Araldite 2011, Epibond 1590 and A/B Loctite 324) and two different adherends combinations, i.e. aluminum-aluminum, aluminum–GFRP. Their results indicate that the performance of the adhesive joint is influenced by the adherend and loading rate. The results shown in Figure 6 indicate that the dynamic strength of all adhesives is higher than the static strength. It can be inferred that the influence of the loading rate on the strength varies depends on the adhesive and the adherend. It is also apparent that Epibond 1590 A/B has a higher rate sensitivity than the others.

In order to characterize the adhesive joints under high loading rate, novel experimental set-ups have been developed by researchers, among others, Zachary and Burger [24] studied the stress waves on the single lap joint using dynamic photoelasticity technique. They generated an impulsive wave propagating through the specimen by exploding a 100-mg charge of lead azide at the end of the lower plate of the specimen. They glued the explosive charge to a drilled hole on the lower part of the specimen by a very weak adhesive in tension such that it allows the compressive part of the impulsive wave to enter the specimen (see Figure 7).

Their photoelasticity results show that there are severe tensile and shear stresses developed in the joint. They indicate that localized stress concentration can be dangerous when the dynamic stress waves superimposed onto the local shrinkage stress or the quasi-static loads. It is also noted that the brittle behavior of the adhesive under impulsive load and at the temperature below the glass transition temperature of the adhesive also worsen this type of dynamic failure.

Asgharifar et al. [25] studied the transient stress distribution over the adhesive joint impacted by a solid spherical projectile. They hit the bonded area on the single lap joint in the transverse direction at various projectile speeds (3.59 – 50m/s). Their FEM model, which is validated by the experimental results, reveal that the loci of the maximum compressive and tensile stress are not influenced by the adhesive properties. A projectile in small diameter, lower projectile velocity and a lower elasticity modulus of adhesive can provide a lower stress state in the adhesive layer. They show that the effect of strain rate on the stress level depends on the adhesive properties and strain rate level.

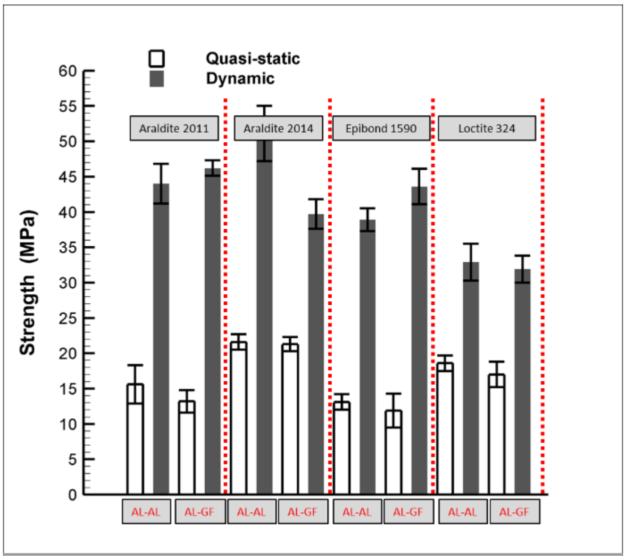

Figure 6. Quasi-static and dynamic test results of different adhesives with different adherend combinations (adapted from Raykhere et al. [23])

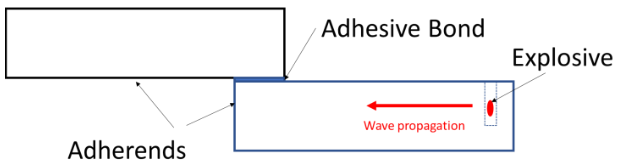

Figure 7. Schematic of the experimental set-up used by Zachary and Burger [24]

In addition to the experimental set-ups described above, the shock tubes have been used to understand the response of the material to the blast waves by researchers [26-28]. Yildiz et al. [29-32], among others, utilized a large-scale shock tube to characterize the adhesive joint under high loading rates. The shock tube they employed consists of driver, diaphragm and driven sections as shown in Figure 7. In order to simulate blast wave, driver section of the shock tube is pressurized by the compressed atmospheric air until the diaphragm ruptures. Immediately, rupturing diaphragm creates a shock wave that impinges on the specimen. They designed a blister-type specimen that can transfer the shock wave loading to the adhesive bond in dominant mode I form. In their study, they tested two different adhesive joints, i.e. aluminum/epoxy and steel/epoxy under shock-wave loading. Their results show that the adhesive under shock-wave loading behaves in brittle fashion compared to that under quasi-static loading. In their technique, they were able to test the adhesive joints under a various strain rate levels (500-13,000 s^{-1}). Additionally, they develop an FEM inverse solution technique that can estimate the material properties of the adhesive subjected to shock wave loading using radial strain measurements obtained from experiments.

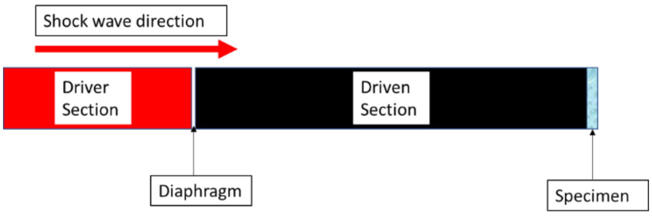

Figure 8. Schematic of a shock tube set-up

Using this technique, they found that the adhesive absorbs the energy in the form of plastic and damage dissipation energy. They concluded that the design of an adhesive joint subjected to impulsive loading must be done based on the data obtained by the impact experiments, not quasi-static tests.

4. Summary

It is almost impossible to cover all experimental studies on the adhesive joints under impact loading in a concise form. The goal of this review paper is to give brief information about the advancement on the experimental techniques to characterize the behavior of adhesive joints subjected to impact loadings, as well as to emphasize the importance of impact tests of adhesive joints in the designing impact resistance light structures.

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