DYNAMIC STUDY OF ADHESIVELY BONDED DOUBLE LAP COMPOSITE JOINTS

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SUMMARY

Composite structures may be subjected to high loading rates in naval applications. Hence, the composite assembly's dynamic behaviour needs investigation. This paper presents an investigation on the structural rate dependent behaviour of adhesively bounded double lap joints. High rate tests showed ringing in the force/displacement curves. An attempt was made to determine the origins of this phenomenon.

Keywords: Composites, structures, Double lap joints, Adhesive joints, High rates, Tensile tests, Stress wave, Rate-dependent behaviour, F.E.A.

INTRODUCTION

The dynamic behaviour of composite materials has been successfully investigated through a wide range of strain rates [1-3], but more investigations are required. In addition, the dynamic behaviour of composite assemblies remains largely uninvestigated, where it is known that the failure of composite structures generally occurs within the connections between components.

The improvement of structural adhesive bonding performance has led to the progressive replacement of the traditional assembling methods (welding, riveting or bolting). This technique ensures load transmission through whole connection area, preserves the structure integrity when composites are used (i.e. no fibre discontinuity due to the presence of holes) and permit the joining of materials of dissimilar nature [4]. Furthermore, the weight of the assembly and the costs are reduced. These advantages have to increasing application of structural adhesive bonding of components in the domains of automobile, aircraft, aerospace and shipbuilding industries. But this increasing interest is faced by an inadequate knowledge on the dynamic behaviour of adhesive bonds.

The properties of an adhesive joint material in-situ are different from that of a bulk adhesive, due to the physical and chemical interactions with the substrates and the confinement of the strain [5]. Thus, the adhesive behaviour needs to be investigated using adhesively bounded assemblies. Testing adhesive joints under high strain rates is not an easy task. Many difficulties can be encountered in the set up of the tests, and the processing of the results. The physical phenomena involved are more complicated than in quasi-static tests: rate dependent material behaviour [6], inertia effects and even wave propagation phenomenon [7]. It is of great importance to understand how the structures behave under high rate loads before assessing the adhesive material's rate dependent behaviour.

Few experimental studies have investigated the dynamic high strain rate behaviour of adhesive assemblies. Attempts were made to use the Izod and Charpy test machines to perform tests on adhesive joints. Adams et al. [8] showed that the fracture energy assessed by the impact bloc test [9] is very dependent in the specimen geometry and the test parameters. Thus, this quantity cannot be considered as a material property. Goglio et al. [10] adapted the Charpy test machine to apply high-speed tensile load to a single lap joint and to measure the efforts using a piezoelectric cell. They were successful in obtaining a failure stress curve for a brittle adhesive based on the estimation of the maximum stress at the edge of the single lap joints.

Yokoyama and Nakai [6] used the split Hopkinson pressure bar to test butt joint hat shaped specimens. When the strain rate is increased, the tensile strength of the adhesive increased whereas the energy dissipated decreased.

Zachary et al. [11] presented a very interesting study of strain wave propagation in a single lap joint using photo-elasticity. A blast load is provided by an explosive detonation at the extremity of one substrate. Different frames were used to show the evolution of the initial compressive wave through the specimen. The compressive wave reverses at free surfaces and generates a dilatational wave. Also, this study showed that the edges of the adhesive joint are subjected to an equal-biaxial state of stress.

These studies gave an idea about the complexity of phenomenon existing when high strain rates are applied. More complex than classic dynamic material testing (where the specimen geometry is simple), the structural effects needs to be considered carefully when adhesive bonds dynamic behaviour is investigated.

The aim of the present work is to increase the knowledge about the dynamic structural effects when adhesively bounded assemblies are tested. In the first part of this paper an experimental investigation of the adhesively bounded double lap joints (DLJ) is presented. Different tensile load velocities were applied (5mm/min, 50mm/min, 1m/s, and 10m/s). Substrates made of glass/epoxy laminated woven composite and aluminium were used to construct composite/composite and aluminium/aluminium specimens. The experimental results showed the effects of increasing the loading rate on the joint strength. Then a comparison was drawn on the strength and the damage of the two specimens' types. The increase of the loading rates introduces a ringing response in the data, which further complicated the processing of the tests results. The second part of the paper presents an investigation into the origins of the ringing phenomenon. The understanding of the physical phenomenon is of high interest to develop tests to study adhesive assemblies to ultimate failure.

EXPERIMENTAL PROCEDURES

Materials

The adhesive used in this study, is Araldite® 2015 manufactured by Huntsman. It is a two-part epoxy adhesive with good shear and peel strengths. It also exhibits a good resistance to water aging and impact load. It is recommended for metals, glass/epoxy laminates and combinations of these kinds of materials. The static shear modulus G_a =

0.49 GPa and the shear strength τ_r= 18 MPa were evaluated using single lap joint tests [12].

Two materials were used to make the substrates. The first material is a Glass/Epoxy laminate. Six layers of plain weave glass fibres were stacked up with the same orientations to manufacture the composite. The thickness of the laminate was 3 mm. Substrates were cut parallel to the direction of the fibres. The Young modulus and the longitudinal strength to failure are equal to E = 20 GPa and σ_r = 430 MPa, respectively. The second material is an aluminium alloy (T6082 T6). It has minimal yield strength of 260 MPa perpendicularly to the rolling direction and strength to failure of 310 MPa. The specimens were cut in the direction perpendicularly to the rolling direction and had a thickness of 4 mm.

Specimen geometry

The double lap joint (DLJ) was selected because due to its symmetry eliminates the global bending moment found in a single lap joint. Therefore, it subjects the adhesive to less peeling effects under shear load. However, some peel stress remains at the external edges of the joints due to internal bending moments resulting from the eccentric load path. Regardless of the fact that the test does not give a pure shear stress state within the adhesive, it is a simple and widely used geometry for joining materials.

To compare the structural DLJ behaviour at different tensile rates, the same specimen design was used for the static and dynamic tests (Figure 1a). The specimen's width was 30 mm. It had two different superposition lengths, so one can control where the joint will break first. The first superposition length was 30 mm whereas the second was 100 mm. The length of the first bounded area was calculated to preserve the integrity of the substrates. The selected thickness of the adhesive was 0.7 mm.

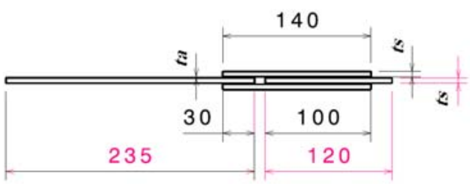
Static and dynamic tests devices

Two load velocities were selected for the quasi-static tests (5mm/min and 50 mm/min) to see the effect of the relatively small variation of loading rate. Two others were selected also for the dynamic tests at moderately high speeds (1m/s, 10 m/s). Quasi-static tests were performed with a conventional "Instron" servo-hydraulic machine, at ENSIETA, whereas the moderately high-speed tests were carried out with a high strain rate (HSR) "Instron" servo-hydraulic machine at the University of Southampton.

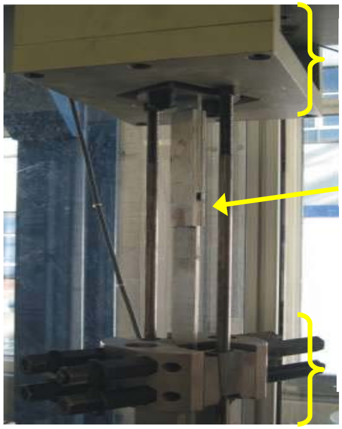
The HSR testing machine can produce a loading velocity up to 20 m/s and a maximum load of 100 kN. It is fitted with grips designed to carry out tensile tests on samples with slender geometry and a prismatic cross section.

The specimens were fixed in that way to have the shortest joint down, near to the loaded extremity of the specimen, Figure 1b. When the test machine is launched, the actuator accelerates until it reaches the desired velocity, then the specimen is gripped and pulled down. In this manner, no shock wave is generated and the tests are performed at constant velocities.

At least, two aluminium and three composite DLJ specimens were used for each test. The true velocities of the load were ranging between [0.8–1.5 m/s] and [8.8–9.6 m/s] for the tests at 1 m/s and 10 m/s respectively.



(a)



(b)

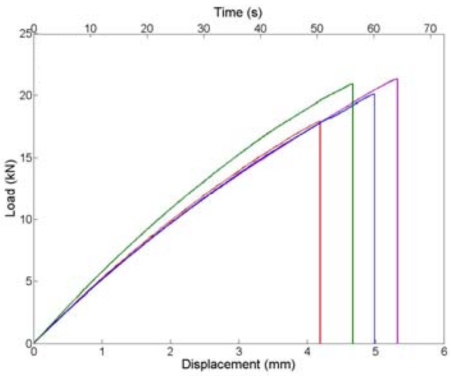
Figure 1. Geometry of DLJ and (b) The HSR test machine

EXPERIMENTAL RESULTS

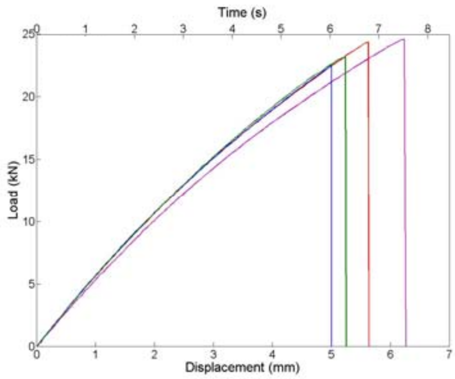
The test results of the composite DLJ for the different velocities are shown in figure 2. The rigidity of the DLJ is determined by measuring the slope of the curves for small displacements (less than 0.5 mm). For the quasi-static tests with the two rates, the rigidity is nearly the same, K=5.65±0.38 N/m and K=5.68±0.17 N/m for tests at 5 mm/min and 50 mm/min respectively. But when the velocity of the test is increased to 1 m/s, the rigidity increase is not negligible (K=8.88±0.95 N/m). Similar effects can be seen in the maximum strength of the specimens as shown in figure 4. An increase of 20% in the maximum load is shown for relatively small increases in the load rate. Then the strength of the DLJ increased more gradually when dynamic loads are applied. This rate dependency seems to be attenuated for the range of moderately high loading rates.

Aluminium DLJ were tested for comparison with the composite DLJ. The aluminium is known to be a rate independent material [13]. The results of the dynamic tests are shown in figure 3. Similar to the composite DLJ, the results show an increasing rigidity and strength for the aluminium DLJs as the loading rate increased. The aluminium DLJ exhibited a higher rigidity than for the composite DLJ, K=23.055±1.32 N/m and K=22.11±0.02 N/m respectively for the tests at a velocity of 5 mm/min and 50 mm/min. The rigidity of specimens tested at 1m/s is K=29.8±7.71 N/m. The rise of the loading speed from 5 mm/min to 50 mm/min induced a 19% higher strength. It was accompanied by an increase in the displacement to failure. This indicates that the contribution of adhesive material behaviour is not negligible. The increase of the specimen strength is less important between the subsequent loading rates.

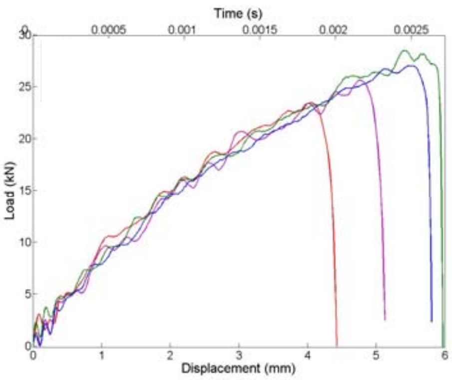
An effect of ringing in the curves is shown for the moderately high loading rates, for both composite and aluminium DLJs. A moderate ringing appears at the dynamic tests at 1m/s. The amplitude of this ringing seems to increase as the speed of loading increases. At velocity of 10 m/s, the shape of the curves changed dramatically. The amplitude and the wave length of the oscillations become important. The rigidity of the samples increased considerably. For composite DLJ at 10 m/s, the load seems to increase periodically. For the aluminium DLJ tested at tensile velocity of 10 m/s, the ringing is showed to reach an amplitude nearly equivalent to the amplitude of the applied load (figure 3). This amplitude is higher than the strength of the aluminium substrates. The highest load captured here is equivalent to 580 MPa within the inner substrates whereas the stress strength of the aluminium T6082 T6 does not exceed 330 MPa.



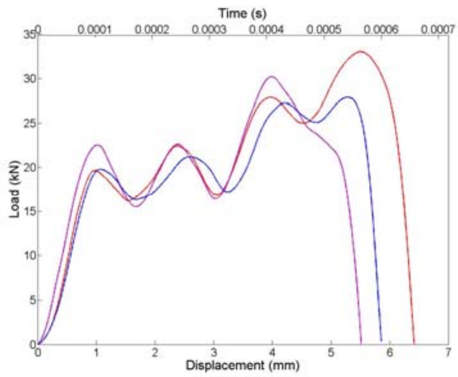
V=5 mm/min



V=50 mm/min

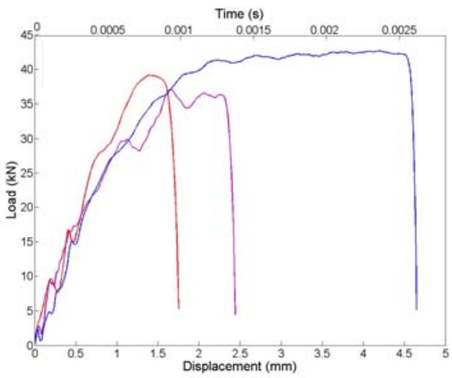


V=1 m/s

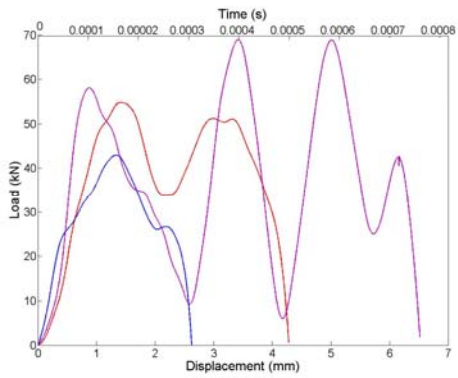


V=10 m/s

Figure 2. Quasi-static and dynamic responses of composite DLJ



V=1 m/s



V=10 m/s

Figure 3. Dynamic responses of aluminium DLJ

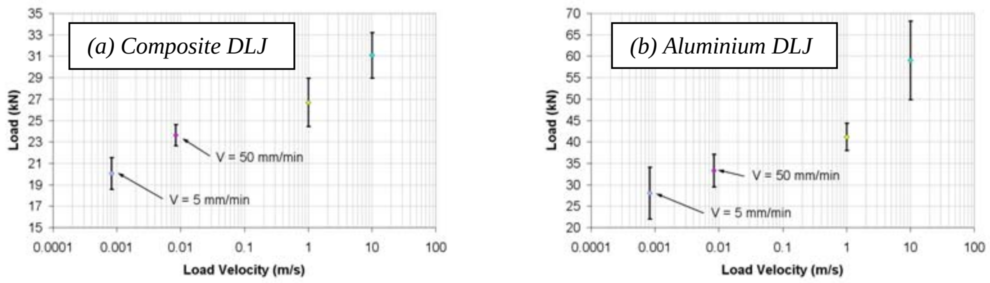


Figure 4. Evolution of load maximum amplitude versus the load velocity

The failure of composite DLJ took place in the substrates. The strength of the interface between the epoxy-matrix and adhesive is higher than the strength of the interface between the epoxy-matrix and the glass fibre ply. The rupture is caused by failure of the interfaces epoxy-matrix/glass fibre at the vicinity of the adhesive joint (Figure 5a). This is frequently accompanied by the delamination of the first glass fibre ply and/or fibre rupture and/or, less frequently, a cohesive failure.

Figure 5a shows an example of damaged laminated composite specimen. The damage initiation produced near to the external edge of the inner interfaces (Zone1). In fact it occurs at the first epoxy/fibre ply interface inside the composite. “Zone 2” indicates the location of the first ply delamination and fibre rupture. Two varieties of failure path can be generated: the first path is along the first fibre ply inside the inner substrate, the second possibility is that fracture initiates as before then switches in the middle of the superposition length to the first ply of the outer substrate.

The failure for the aluminium double lap joints is a mix of adhesive and cohesive fracture near to the interfaces. The damage initiation occurs at the external free edges of the joints; close to the inner-substrate/adhesive interface then it propagate in the same interface or migrates in the second half of the superposition length to the external-adherent / adhesive interface (Figure 5b).

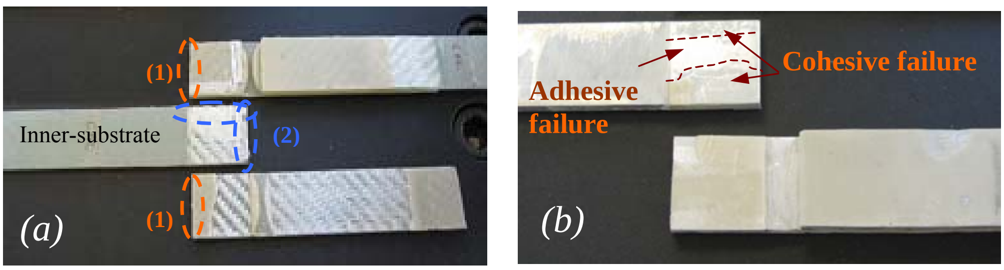


Figure 5. Failure of (a) composite DLJ (b) aluminium DLJ

STRUCTURAL DYNAMIC EFFECTS INVESTIGATION

Simulations of static and dynamic tensile tests on DLJ were performed using ABAQUS standard and ABAQUS explicit respectively. Different inner substrate lengths were examined. An Isotropic linear elastic behaviour was assigned to the substrates. Adherents were considered in aluminium with a Young modulus of 70 GPa. The adhesive joint was modelled with cohesive elements. A bilinear cohesive law was used with the following properties: fracture energies G_{IC}= G_{IIC}=1500 J/m², maximum strengths t_I = t_{II} = 30 MPa, and rigidities K_I = K_{II} = 1e12 N/m^3. No material rate dependency are considered, thus we can easily analyse the structural effects under dynamic loading. The geometry of the samples was simplified to reduce the calculation times (Figure 6).

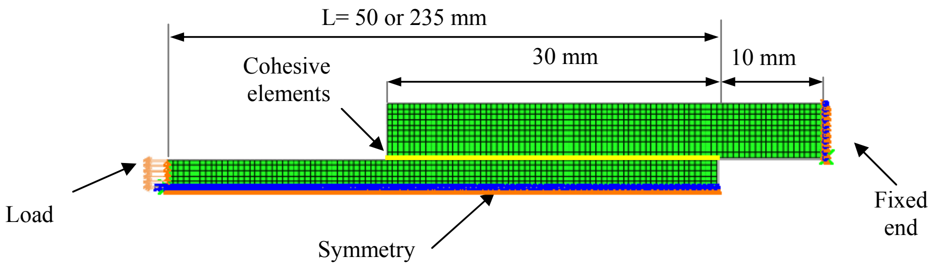


Figure 6. DLJ geometry

Static tensile load and several tensile velocities ranging between of 0.1 m/s and 10 m/s were applied to the DLJ with two different incident inner-substrate lengths. Figure 7 shows the influence of the load velocity on the structure behaviour.

The shorter DLJ showed a wavy load evolution. The amplitude and wavelength increased as the velocity is increased. Another dynamic structure effect is the increase of the maximum load strength and displacement of the assembly as the velocity of the load increases. But there is no increase in the rigidity of the substrates.

In the case of a DLJ with a long incident inner substrate, under a tensile velocity of 1m/s (Figure 7b), the load curve had a "stepped" shape. This is due to the phenomenon of wave propagation and reflection at the extremities of the substrates. This is amplified as the load velocity increases (Figure 9b).

The DLJ with a long inner substrate showed a closer dynamic response to the static than the DLJ with the short inner substrate within a range of velocities between 0.1 m/s and 1 m/s.

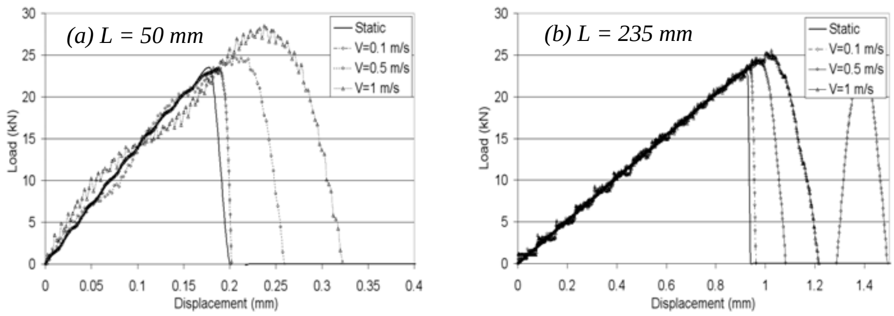


Figure 7. Load-displacement response of DLJ under different tensile velocities

There is no evident reason for why the shorter DLJ presents higher dynamic structural effects. The load transmitted to joint is slower when the inner substrates length is increased for the same velocity. It is more relevant then to compare structures under loads transmitted to joint area with equivalent strain rates in the incident substrates. Two strain rates speed were selected 3 s^{-1} and 24 s^{-1}. For a strain rate of $\dot{\varepsilon}_{average} = 3\,s^{-1}$, the structural behaviour of the DLJ geometries remains nearly the same as under static loading. A high number of stress waves are propagated through the specimen and a dynamic equilibrium is fulfilled. The oscillation post-rupture, due to the inertial phenomenon are more important using a longer geometry (Figures 8).

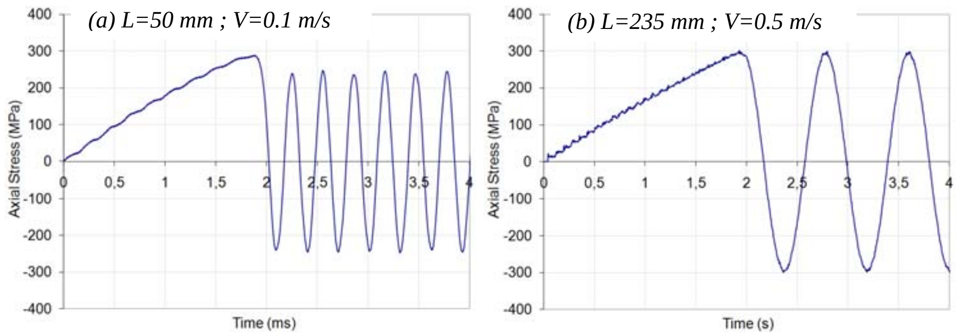


Figure 8. Load stress evolution within the inner substrate in the vicinity of the bonded area for $\dot{\varepsilon}_{average} \approx 3\ s^{-1}$: (a) L=50 mm at V=0.1 m/s , (b) L=235 mm at V=0.5 m/s

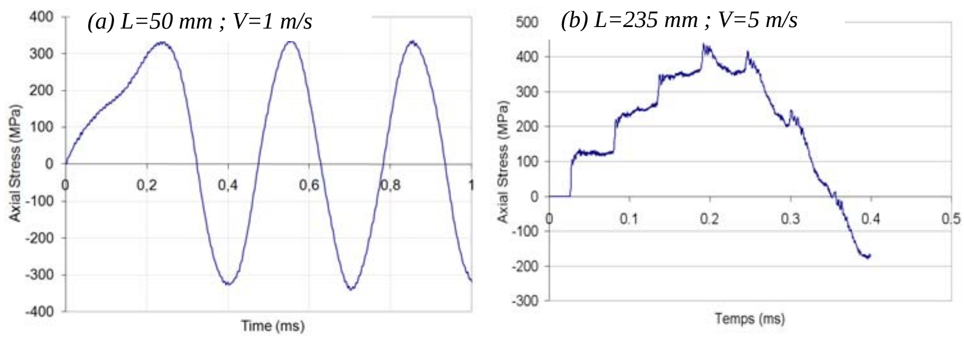


Figure 9. Load stress evolution within the inner substrate in the vicinity of the bonded area for $\dot{\varepsilon}_{average} \approx 24\ s^{-1}$: a) L=50 mm at V=1 m/s , b) L=235 mm at V=5 m/s

In the case of double lap joints with bonded area submitted to transmitted load at the strain rate of $\dot{\varepsilon}_{moyenne} = 24\,s^{-1}$, the inertial effects are more visible. When a high load velocity is applied, the load rising time is very short compared to the time of wave propagation throughout the specimen. Thus the material experiences a greater quantity of strain locally before it propagates. The phenomenon is accentuated when the specimen is long. In the case where L=235 mm and V=5m/s the material experience a very short load rising time that resemble a shock wave and a small number of stress waves are introduced (Figure 9).

In this way the strain can reach high values locally before the failure of the assembly. As the velocity and the specimen length increase, the time needed to homogenise the strain (to propagate the load) in the specimen become greater compared to the test duration. And thus successive waves are on their way to the jointed area when the joint breaks. This implies an increase in the strength of the assembly under dynamic loading without involving material rate dependent behaviour [14].

The load introduced at high velocity, imparts high oscillation amplitude. This could be due to the excitation of the load cell to its natural frequency, which would result in the acquisition of poor quality data.

DISCUSSIONS & CONCLUSIONS

The experimental study investigates the behaviour of double lap joints under quasi-static and moderately high velocity loading. The behaviour is found to be highly rate dependent. The comparison of the results of static and moderately high rate loading tests showed an increase of the strength of the specimens when the load velocity is increased. In the case of composite DLJ, rigidity increased by more than 50% between static and dynamic tests. Whereas in the case of aluminium DLJ the rigidity increased by more than 30% from static to dynamic loading. The strength of the DLJ is more rate dependent. For both aluminium and composite DLJ the strength increased by nearly 20% when the tensile velocity is increased from 5mm/min to 50mm/min. Then when the tensile velocity is increased to 1m/s the strength increased by 12,5% and 24% respectively for composite and aluminium DLJs.

It is shown using FEA that this rate dependency is not only due to the materials viscosity, it is partly due to the structural behaviour under dynamic loads. Models of DLJ with elastic rate independent materials, showed a growing strength and the displacement to failure when the applied tensile load velocity increases.

A phenomenon of ringing appears for the dynamic tests and increased with the load velocity. Analysing the numerical solutions, we can draft a scenario to explain the origin of this phenomenon. The loss of time evolution homogeneity of the strain through the length of the specimen when the load velocity increases, generates a wavy shape of load curves. But for the highest strain rates, a stepped shape load evolution with high amplitudes takes place. The load evolution resembles a shock wave. This can cause the load cell ringing at its natural frequency.

The numerical modelling of the tests can be helpful in designing specimens to master the experimental dynamic effects and avoid load cell ringing, within a range of applied strain rates. The numerical solution showed that the reduction of the length of the specimen implies higher strain rates applied to the joint area, and less dynamic structural effects. The reduction of the length of the specimen can also help to reduce the ringing phenomenon by increasing the number of waves propagated thus enhancing the homogeneity of strain evolution throughout the specimen's length.

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References

1. J. Fitoussi, F. Meraghni, Z. Jendli, G. Hug, D. Baptiste (2005), Compos. Sci. Technol., 65, p.2174.
2. M. Tarfaoui, S. Choukri, A. Neme (2008), Compos. Sci. Technol., 68 (2), p.477.
3. X. Xiao (2008), Polym. Test, 27 (2), p.164.
4. E.M. Petrie (2000), Handbook of Adhesives and Sealants, McGraw-Hill, New York.
5. A.J. Kinloch (1987), Chapman and Hall, London.
6. T. Yokoyama, K. Nakai (2006), J. Phys. IV France 134, p.789.
7. C. Sato, K. Ikegami (2000), Int. J. Adhes. Adhes., 20, p.17.
8. R.D. Adams, J.A. Harris (1996), Int. J. Adhes. Adhes. 16 (2), p.61.
9. NF EN ISO 9653 (2001), AFNOR, Paris.
10. L. Goglio, M. Rossetto (2007), Int. J. Impact. Eng., 35, p. 635.
11. L.W. Zachary, C.P. Burger (1980), Experimental Mechanics, 20 (5), p.162.
12. F.M. daSilva Lucas, R.J.C. Carbas, G.W. Critchlow, M.A.V. Figueiredo, K. Brown (2009), Int. J. Adhes. Adhes. (Author's Accepted Manuscript).
13. M.A. Meyers (1994), John Wiley and Sons Inc., New York.
14. W. Wang, G Markov, R.A. Shenoi (2004), Composite Structures, 69, p.45.

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