IMPACT BEHAVIOR OF COMBINED COMPOSITE ALUMINIUM TUBE FOR AUTOMOTIVE APPLICATIONS

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SUMMARY

An experimental investigation was conducted to study the crushing behavior of aluminum tubes wrapped with fiber reinforced plastic composites. The influence of surface treatments of aluminum on failure mode and on the energy absorption capacity of multi-material tubular elements was determined under dynamical compression conditions. No significant differences were observed on the energy absorption capacity whatever the surface treatments are. The composite reinforcement applied onto aluminium tube with 2 mm thickness, constraint to deform it, in a favorable manner for dissipating energy and a better deceleration is obtained.

KEYWORDS : multi-material, surface treatments, energy absorption, circular tube

INTRODUCTION

One of the main objectives of car manufacturers is to lightweight vehicles and more particularly their structures, improving their crash behavior. Energy absorption is an important parameter for the development of the vehicle passive security concept, resistive force and acceleration must not exceed a certain impulse span. The objective is to reduce the disparities between the initial and final levels of deceleration and force by increasing the energy absorption capacities within the free crushing space available in the vehicle front part, so that damage to people is minimized. During a collision, the vehicle front longerons are one of the most important components for energy absorption, so the improvement of car ability to dissipate collision energy needs a good optimization of longerons crash behavior. A great deal of works have been done with the energy absorbing properties of thin walled metal structures such as steel and aluminium to improve the vehicle safety [1-3]. When subjected to an axial compressive load, tubes can compress in a variety of modes depending on the material and the tube geometry, especially the ratio of wall thickness to internal diameter [4]. Steel and aluminium alloys collapse by plastic buckling in a concertina or diamond with the formation of a series of plastics folds in a progressive crushing like manner absorbing typically 15-30kJ/kg in energy [5]. Polymer composite materials have been introduced in the automotive industry primarily to reduce the overall weight of the vehicle, which results in energy

economy. Previous work on the axial crushing of fiber reinforced plastic composite tubes has indicated that significant energy absorption can be obtained from these materials, under some circumstances exceeding the ones can be obtained from metal tube [6-8]. Plastic deformation is not the governing mechanism, but the extensive microcracking development, which may be easily controlled depending on many factor as fiber orientation, matrix, geometric parameters [9-10]. Now, the energy absorbing mechanism of metal and composites is relatively well known. We considered a composite/aluminium multi-materials. Indeed, the two materials may each confer on an energy-absorbing element their own particular characteristics [11-13]. The objective of this study is to bring out the influence of surface treatments on aluminium alloy before bonding with a carbon epoxy composite on the crash behavior of multi-materials tubular structures. The objective of the surface treatment is to improve the practical adhesion between the composite and the aluminium.

But as these materials are highly anisotropic, the response of composite to an impact is complex and complete understanding of the energy absorption mechanism is difficult. Besides, with conventional experimental devices, it is not possible to correctly study composite structures dynamic behavior. Indeed, we cannot obtain dynamic behavior laws and high incident energy. We have used a modified version of the split Hopkinson pressure bar (SHPB). To achieve a test with it, a specimen is inserted between two bars of the same material (usually steel or aluminum) with a higher yield stress than the tested material. Then, a projectile produces a longitudinal compressive wave in the input bar. A part of the compressive pulse is reflected at the bar specimen interface, the other part is transmitted through the specimen and the output bar. We can then study this wave propagation with different strain gauges stuck on the output bar. We can obtain the stress at the interface specimen-bar, but we cannot produce high energy plastic deformations in the input bar. So, we have developed an experimental system based on the Hopkinson bar and called "block bar" in order to better comprehend damage and energy absorption mechanism.

I. EXPERIMENTAL

I.1. Device

This experimental device has ever been described elsewhere [12,14]. As shown in figure 1, the block-bar is composed of three parts: a compressed air gun, a measuring bar and instrumentation and a hydraulic shock absorber. The 5m long gun is fed with compressed air from the laboratory system (P_{max}=7 bars) and allows the use of projectiles, which vary up to 300 mm in diameter and 540 mm long. The incident energy of the projectile can reach 20 kJ and its speed 20 m/s. A high-velocity hydraulic stopcock developed in the laboratory triggers the shot of air contained in the tank. By adjusting the pressure in the tank, this allows a much greater reproducibility of the impact speed than shots triggered by a split membrane. A system of optical measurement allows us to know the projectile speed at the time of impact on the test tube and thus, its kinetic energy.

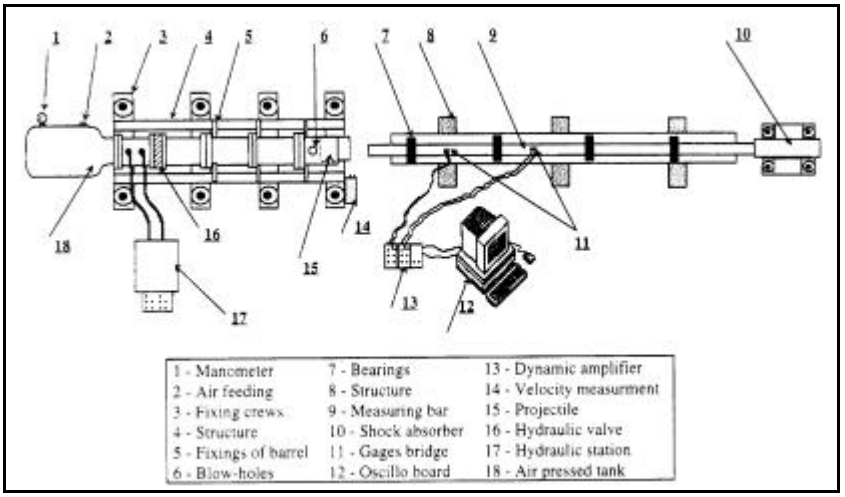

Fig. 1: Illustration of the "block-bar" device

The measuring bar is 80 mm in diameter and 4 m long. All the measurements are carried out by strain gauges glued onto the bar in a full bridge lay-out, in order to cancel the effects of bending. The signals are collected by differential amplifiers which have a large bandwidth (2MHz) and a maximum gain of 1000. An oscilloscope board installed into a personal computer allows us to record 500000 samples (12 bits) on two 10 MHz tracks and to display them. However, in practice, many problems are related to dynamic measuring: radial inertia, bar/test tube friction, stress homogenization in the test tube and dispersion correction. Correction relationships, which deal with these well-known problems have been published and most of the software for treatment of the results of Hopkinson bar tests, include these corrections. The wave propagation velocity is dispersive because it is a function of wavelength, particularly for large bars. After they have been reflected many times at the bar's extremities, waves are shifted in time. These dispersions can be corrected using the following relation:

$$s(t) = FFT^{-1}\left\{\exp(-i\Delta x(x(w) - \frac{w}{w_0}))FFT(s(t))\right\} \qquad (1)$$

The impact span achieved in these composite structure tests can reach 50 to 100 ms according to the impact device speed and the test tube length. The measurement made will equal the sums of waves which travel along the measuring bar in the opposite direction. A wave separation method based on a knowledge at one point in the bar, of the load, P(t), and the

particle velocity, v(t), has been developed. These two functions depend on the incident wave i(t) and reflected wave r(t):

$$\begin{cases} F(t) = i(t) + r(t) \\ Zv(t) = r(t) - i(t) \end{cases} \tag{2}$$

The last two terms must be assimilated with the direction of the waves and not for the real incident or reflected waves.
A method with frequency decomposition has also been developed:

$$uz_B(t) = FFT^{-1}\left\{\exp(i\boldsymbol{x}(w)(Z_B - Z_A))FFT(uz_A(t))\right\} \tag{3}$$

Software for the PC has been developed by these methods in our laboratory. In this investigation, a hydraulic gun with a projectile of 45 kg and an impact speed of 5 m/s were used.

I.2. Materials

Metallic tubes (100 mm long, 50 mm external diameter, 2 mm wall thickness (tube 1) and 100 mm long, 48 mm external diameter, 1 mm wall thickness (tube 2)), used in this study are a commercial aluminium alloy (5754 from Pechiney). Aluminium tubes dimensions are chosen to allow stable crushing mode (concertina and diamond mode) because the energy absorption for tubular composite is controlled by obtaining stable crushing modes. Prior to bonding, two different surface treatment were used:
(i) degreasing (samples were ultrasonically immersed in acetone for 10 min, and wiped dry),
(ii) chromic-sulfuric etching (after degreasing, samples were submerged in a solution of 250g/l sulfuric acid, 50 g/l chromium acid, 87 g/l aluminium sulfate octadecahydrate, at 60°C for 20 min, rinsed in running tap water for 1 min, stood in distilled water for 5 min, and wiped dry). Immediately after surface treatments, specimens were stored in an air conditioned room (20±2°C and 50±5% RH) for 2 hours.
Chemical etching treatment improves practical adhesion between the metal and the organic layer compared to the degreasing treatment. To compare the influence of surface treatments applied onto aluminium, we used the same aluminium alloy as received. The unidirectional prepregs used in this investigation are carbon fiber and epoxy prepolymer DGEBA with a hardening amine DDM (THR/150/M10/NS/38% from Hexcel). The prepreg had a volume fraction of carbon fibers of 32%. Multi-materials tube were made by wrapping six layers of the prepreg onto aluminium tube. A mold with 3 bars of pressure was used. The adhesive curing cycle was 2 hours long at 150°C in a conventional oven. The fibers were perpendicular to the longitudinal axis of the tube (90°). Mechanical properties of both aluminium alloy and composite are listed in table I.

Table 1 : Mechanical properties of materials.

Tube	*Al-5754*
E (MPa)	70 000
ν	0.33
σ_r (MPa)	130
Reinforcement	*Carbon HR*
E (MPa)	90000
σ_r (MPa)	1300

Thickness (mm)	0.14
Matrix	*DGEBA-DDM*
E (MPa)	3200
σ_r (MPa)	85
Tg (°C)	135

II. RESULTS AND DISCUSSION

Specific energy absorption is defined by the equation (4) as the ratio of the energy dissipated during the impact to the crushed tube weight.

$$E_S = \frac{\int_0^{d_F} P(d)dd}{A r d_F} \approx \frac{P_{moy}}{A r} \qquad (4)$$

where A is the cross-sectional area, ρ is the material density and P_{moy} is the average crush load, δ_F is the tube crush. This parameter allows direct comparison of identically shaped elements.

II.1. Tubes without reinforcement

Two types of failure mode depending on aluminium tube dimensions were observed according to [4]. For the tube 1, a concertina mode and for the tube 2, a diamond mode (figure 2).

Tube 1 (concertina mode) Tube 2 (diamond mode)

Fig. 2: Failure mode of aluminium tube

The experimental results presented in fig. 3 are obtained with different aluminium dimension tubes.

The principal results are listed in table 2.

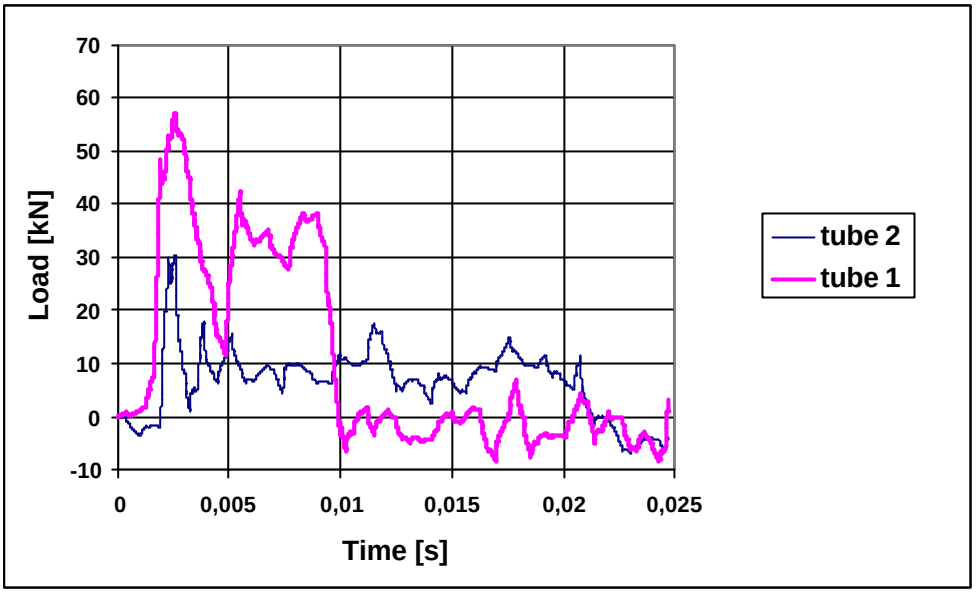

Fig. 3: Force-time response for the impacted metal tubes without reinforcement

Table 2. Results obtained with tube without reinforcement

Tube	P_{max} (kN)	P_{moy} (kN)	Crush time (ms)	E_s (kJ/kg)
1	57	35	10	21.7
2	30	9.5	22	11.4

A ticker tube presents a high degree of energy absorption compare to the thinner one but the crush time is shorter. The deceleration level is of prime importance on the vehicle occupants. The diamond mode permits to have a better crush time than axisymmetric deformation mode.

II.2. Tubes with reinforcement

The results obtained for the tubes 1 and 2 with reinforcement are respectively shown on fig. 4 and 5.

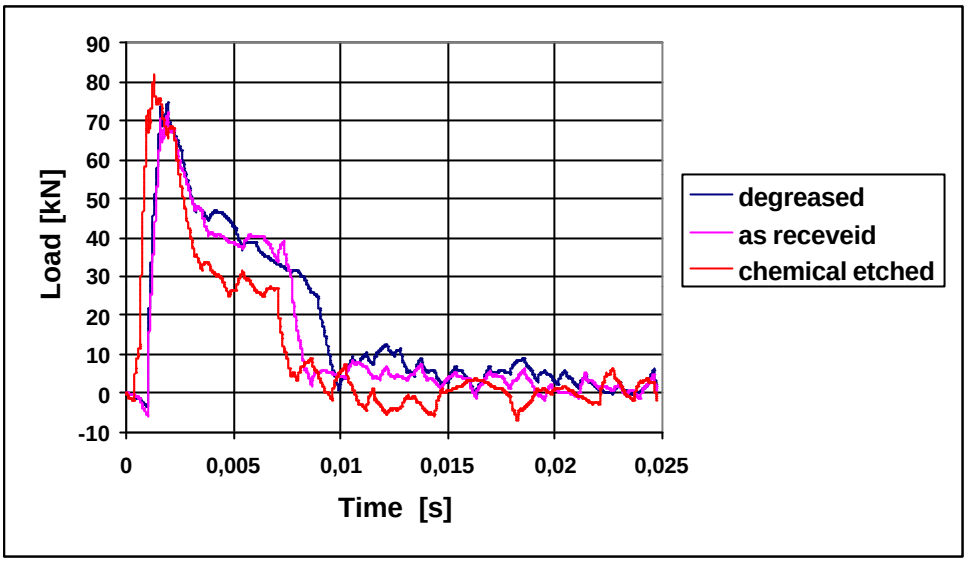

Fig. 4. Force-time response for the impacted tube 1 with reinforcement

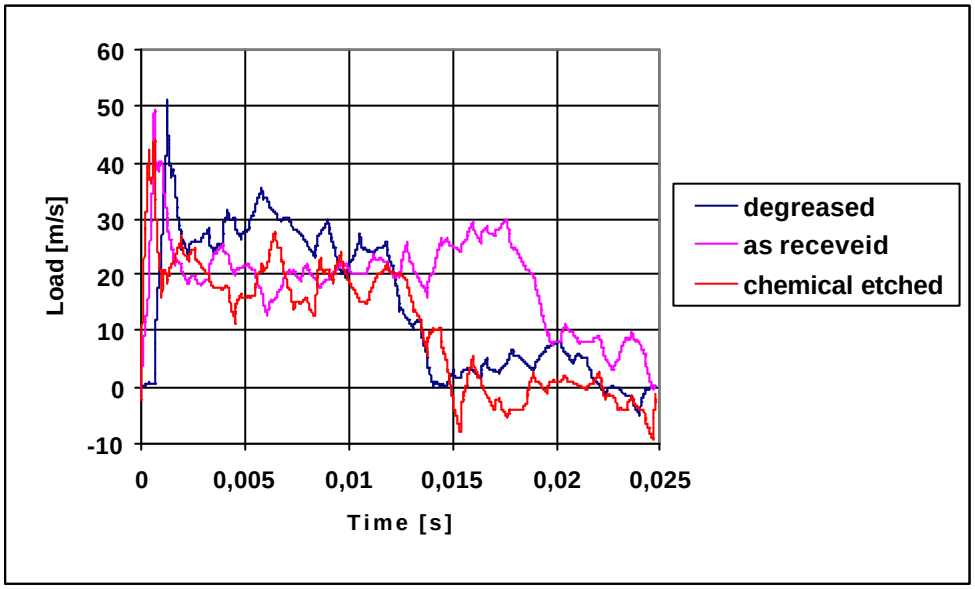

Fig. 5. Force-time response of impacted tube 2 with reinforcement

Table 3 lists the experimental results of reinforced tubes.

Table 3. Results of tubes with reinforcement

Tube	Surface treatment	P_{max} (kN)	P_{moy} (kN)	Crush time (ms)	E_s (kJ/kg)
1	degreased	74.5	35	10	18.6

2	degreased	51.5	25	14	24.2
1	chemical etched	81.5	28	8	14.6
2	chemical etched	45	21	15.5	20.5
1	as received	71	22	8.5	11.5
2	as received	51.5	20	20	19.1

The comparison of dynamic results shows no significant influence of the energy absorption with surface treatments applied onto aluminium. Which means that adherence level is not of prime importance to increase the capacity of energy absorption. We noticed, by wrapping aluminium tube with 2 mm thickness that Es values were lower with the reinforcement that the aluminium tube only. The reinforcement decreases the energy absorption capacity. This is due to the fact that the failure mode changes from axisymmetric to diamond mode whatever the surface treatment is (fig.6). Moreover, this mode improves the deceleration by decreasing the crush time. The same failure mode compared to the aluminium tube is observed for the tube 2 with reinforcement (fig 6).

Tube 1 degreased with reinforcement Tube 2 degreased with reinforcement

Fig. 6. Example of multimaterials failure mode

CONCLUSION

The influence of surface treatments of aluminium on the energy absorption capacity of multi-material tubular elements was determined under dynamical compression conditions. No significant differences were observed on the energy absorption value with surface treatments. The 2 mm thickness tube with reinforcement changed of failure mode from axisymmetric to diamond mode, this mode decreases the crush time and the favorable levels of deceleration are obtained. The role of the composite reinforcement is to guide and to constrain the aluminium tube to deform in a favorable manner for dissipating energy with a better deceleration level for vehicle occupants.

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