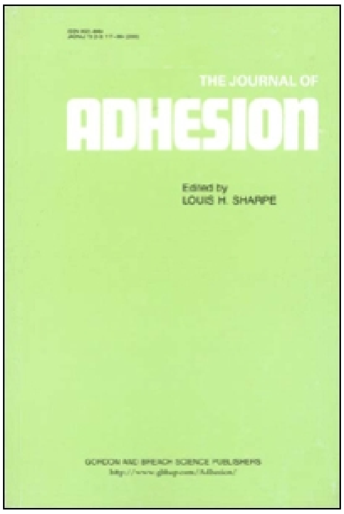

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Comparison of the Mechanical Behaviour Between Stiff and Flexible Adhesive Joints for the Automotive Industry

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Comparison of the Mechanical Behaviour Between Stiff and Flexible Adhesive Joints for the Automotive Industry

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Adhesive bonding is increasingly being used in structural applications such as in automotive joints. The theoretical analyses and experimental data are generally for rigid and strong epoxy adhesives. Elastomeric adhesives such as polyurethanes are used in structural applications such as windshield bonding because they present important advantages in terms of damping, impact, fatigue, and safety which are critical factors in the automotive industry. However, there are other structural applications in the main body where polyurethanes may also be used. The main objective of the present project is to compare the behaviour of structural joints used in the automotive industry, such as single lap joints and T-joints made of rigid adhesives, and those made of elastic adhesives in terms of stiffness, strength, impact, damping, and fatigue. The elastomeric adhesive selected was a polyurethane from Sika (Sikaflex® 256) and the structural adhesive selected was an epoxy from Huntsman (Araldite® AV138/HV998). The shear strength of the polyurethane is approximately four times lower than that of the epoxy. However, the polyurethane shear failure strain is 330%, whereas that of the epoxy is only 6%. The benefits of using elastomeric adhesives in structural adhesive joints used in the automotive industry are described, especially in terms of ductility, impact, and fatigue.

Keywords: Damping; Epoxy adhesive; Fatigue; Impact; Polyurethane adhesive; Single lap joint; Steel; T-joint

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1. INTRODUCTION

Structural adhesive bonding was initially used in the aerospace industry, especially from the 1950's [1]. The automotive industry has recently been implementing what the aerospace industry has been using for decades, namely, adhesives for joining load-bearing components. As the designers of road vehicles try to produce cheaper and lighter products, more ways are needed for joining new and dissimilar materials. The main method of joining in the automotive industry has been by means of spotwelds. This has required large investments in the appropriate technology, such as highly automated production lines and many years experience of designing. However, there are disadvantages with spotwelds because they require access to both sides of the joint, they cannot join aluminium effectively, or composites at all, and they generally destroy any coatings used to improve the corrosion resistance of steels. A good, cheap method, which can solve these problems, is to use adhesive bonding [2]. Adhesives are used today in a variety of places in the vehicle [3]. High-strength adhesives are used where the adhesive plays the primary role in the joining and strength of a structure. Generally, toughened, single-part paste epoxies are used for structural bonding of car bodyshells [4–7]. These adhesives have an improved impact and peel strength in relation to the previous generation of brittle epoxy adhesives [8,9]. However, their high stiffness and low ductility create stress concentrations that give rise to sudden and catastrophic joint failures [10].

Elastomeric bonding is a relatively new fastening technique [11–13]. These joints offer high peel strength, impact resistance, and flexibility. Interest in this class of adhesive is on the rise because elastomeric bonding is more forgiving than other adhesive techniques. The low modulus gives a more uniform stress distribution and a more uniform stress transfer. Consequently, stresses within the bonded materials are relatively low, which is fundamental for improved fatigue behaviour [14]. The high tear propagation strength of elastomers, even where the adhesive layer has started to tear, prevents sudden catastrophic joint failure. This forgiving behaviour means damaged adhesive joints can be identified and repaired before total failure. This is a critical point in terms of safety. In contrast to rigid adhesive joints, elastomeric adhesive layers deform under applied loads. This property is extremely useful for damping vibrations [15,16] and absorbing impact loads [17,18]. These attributes can be very interesting in vehicles where dynamic loads are very frequent. Exposure to heat may result in differential thermal expansion, causing adhesively bonded components to move relative to each other [19]. Elastomeric adhesives are well suited to join materials with different coefficients of linear expansion, which can be an advantage in the ever-increasing use of multi-material structures in the automotive industry.

Most theoretical analyses and experimental data in the literature are generally for rigid and strong epoxy adhesives. Elastomeric adhesives such as polyurethanes have been used in structural applications such as windshield bonding for more than 20 years. They present important advantages in terms of damping, impact, fatigue, and safety which are critical factors in the automotive industry. On the other hand, epoxy adhesives are increasingly being used in structural joints of the main car body due their strength and stiffness. However, there might be situations where the polyurethane, despite its low strength and stiffness, might be able to substitute for the epoxy adhesive. The main objective of the present project is to compare the behaviour of structural joints used in the manufacture of the car bodyshells, such as single lap joints and T-joints made of rigid adhesives, and those made of elastomeric adhesives in terms of stiffness, strength, impact, damping, and fatigue.

2. EXPERIMENTAL DETAILS

2.1. Materials

Two adhesives were selected: a two-component paste epoxy adhesive, Araldite® AV138/HV998, from Huntsman (Salt Lake City, UT, USA) and a very ductile, one-component, polyurethane (Sikaflex® 256) supplied by Sika Portugal S.A. (Porto, Portugal). In practice, one-component epoxies are used for manufacturing reasons. The adhesive used here might not be adequate for production use but its mechanical properties are similar to high modulus adhesives used in the structural bonding of car bodyshells. Therefore, the epoxy used in the present study is adequate for comparison purposes and will serve as the reference. Adhesive AV138/HV998 cures at 100°C for 10 min, whereas the polyurethane needs 6 days curing at room temperature. This is a serious drawback in practical terms, but the cure time conditions may be reduced by using a two-component polyurethane. The glass transition temperature (Tg) of AV138/HV998 is 66°C and that of Sikaflex 256 is −45°C (manufacturer's information). Table 1 shows the shear properties of the adhesives used in this work. The properties were determined using the thick adherend shear test [20]. The adherends were mild steel such as used in the manufacture of bodyshells which are typically 1-mm thick, with a yield strength of 184 MPa.

TABLE 1 Adhesive Shear Properties Using the Thick Adherend Shear Test Method ISO 11003-2 [20]

	Araldite AV138M/HV998	Sikaflex-256 FC
Shear modulus G (MPa)	1559 ± 11	1.351 ± 0.04
Shear yield strength τ_{ya} (MPa)	25.0 ± 0.55	8.26 ± 0.30
Shear strength τ_r (MPa)	30.2 ± 0.40	8.26 ± 0.30
Shear failure strain γ_f (%)	5.50 ± 0.44	330 ± 27

2.2. Specimens

The single lap joints (SLJ) had an overlap of 15 mm and a width of 25 mm; see geometry in Fig. 1. The SLJs were manufactured individually in a mould and the adhesive thickness (0.2 mm) was controlled by shims.

The geometry chosen for T-joints is shown in Fig. 2. The adherend radius (4 mm) was formed in a manual bending machine and controlled with radius gauges. A flush fillet was used in conjunction with a 15-mm overlap. This type of geometry is the one most commonly found in vans, where the fillet is flush for cosmetic appearance and the overlap is the minimum required. The bondline thickness was 0.2 mm. The T-joints were produced using a metal jig to hold the joint in place, as shown in Fig. 3. Before the application of the adhesive, the bonding area was sand-blasted (corundum) and degreased with acetone. For Sikaflex 256, a primer was also applied at least 10 min before the adhesive application. In the automotive industry, the adherends may be bonded without surface preparation, but this will lead to a higher scatter in the failure, as shown in [5].

2.3. Static Tests

The SLJs and the T-joints were tested in tension as shown in Figs. 1 and 2. In order to determine the influence of the test rate on the joint strength, two different crosshead rates were used: 1 and 100 mm/min.

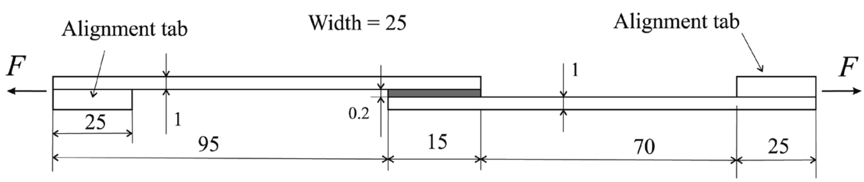

FIGURE 1 Single lap joint geometry (not to scale, dimensions in mm).

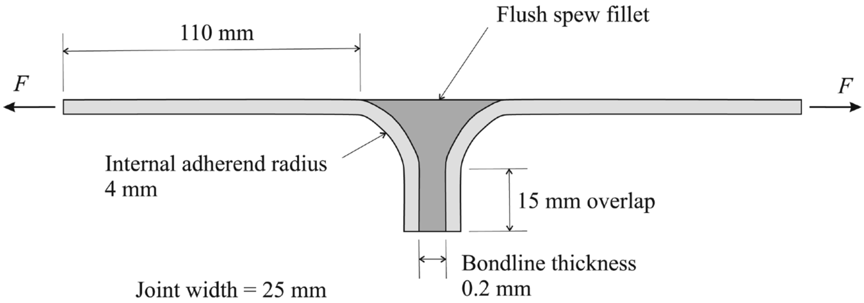

FIGURE 2 T-peel joint geometry.

Six specimens were tested in an MTS servo-hydraulic machine 312.31 (Eden Prairie, MN, USA) for each case studied. Testing was conducted at typical laboratory conditions (approximately $25 \pm 3°C$ and $60 \pm 5\%$ relative humidity).

2.4. Damping Tests

The natural frequency of a system can be used to determine experimentally the damping properties of a system. This was done by means of the bandwidth method, which determines the damping ratio by measuring the frequency bandwidth between points on a response curve where the response is some fraction of the resonance of the system, as shown schematically in Fig. 4. The usual convention is to consider points located at frequencies on the response curve where the amplitude of response at these points is $1/\sqrt{2}$ times the maximum

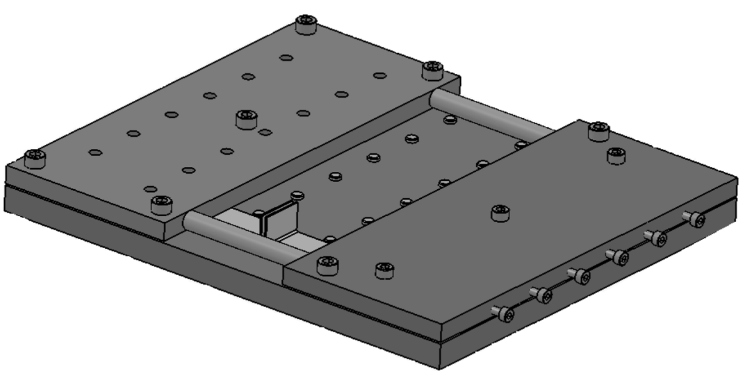

FIGURE 3 Diagram of the jig to produce T-joints.

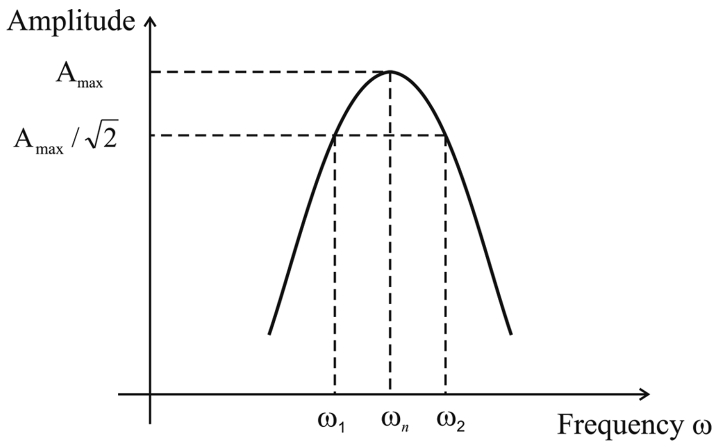

FIGURE 4 Half-power bandwidth method (half-power points occur at ω_1 and ω_2, bandwidth $\Delta\omega = \omega_2 - \omega_1$).

amplitude. The bandwidth at these points is frequently referred to as the "half-power bandwidth." The specimen was clamped at one end and left free to vibrate at the other. A transverse (out-of-plane) load was applied at the free end of the specimen with an impact hammer (see Fig. 5). A laser beam focused on the free end of the specimen, in the direction of the applied force, was used to measure the specimen displacement. The damping ratio, ζ, was determined using the amplitude spectrum of the free vibration decay record as:

$$\zeta = \frac{\omega_2 - \omega_1}{2\omega_n}, \tag{1}$$

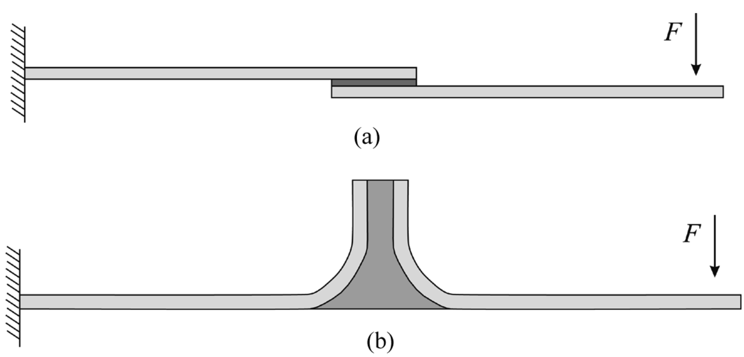

FIGURE 5 Damping load applied (a) in the SLJ and (b) in the T-joint.

where ω_1 and ω_2 are frequencies at an amplitude corresponding to $(1/\sqrt{2})$ times the maximum amplitude, and ω_n is the frequency at the maximum amplitude.

2.5. Fatigue Tests

The testing program used load control with a sinusoidal waveform, a load ratio, R, of 0.1 and a frequency of 10 Hz. The specimens were tested at different load values (40, 50, 60, and 80) of the average static failure load obtained in the SLJ at a displacement rate of 1 mm/min. The specimens were tested in an MTS servo-hydraulic machine 312.31 (Eden Prairie, MN, USA). Three specimens were tested for each load level. The stopping criterion established was a maximum of 1 million load cycles.

2.6. Impact Tests

Impact tests of the specimens were carried out using an impact test machine similar to the inertia wheel machine developed by Cayssials and Lataillade [21]. As shown in Fig. 6, the machine has a steel inertia wheel 600-mm in diameter and 100-mm in thickness, driven with an electric motor. Impact loads are caused by the collision of an impactor, at the circumference of the wheel, and an anvil connected to the end of a specimen. The anvil and specimen are swung by a pneumatic actuator. The applied load is measured with a quartz load transducer

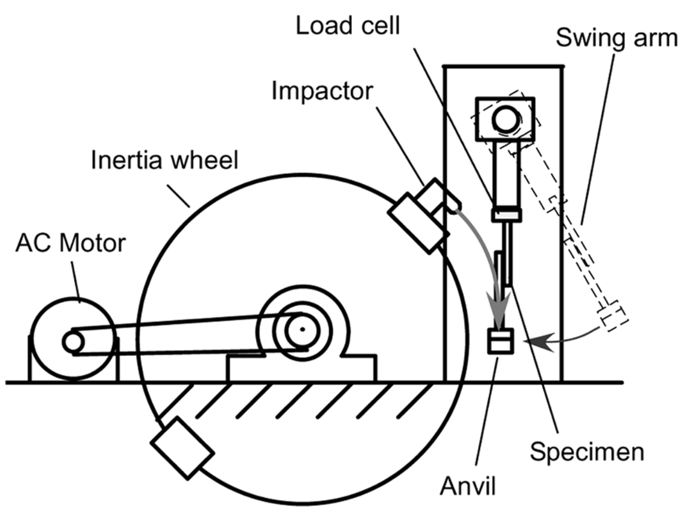

FIGURE 6 Inertial wheel impact testing equipment.

(Type 9041A, Kistler, Ostfildern, Germany). The impact velocity in these tests was 3 m/s, which is equivalent to a test rate of 1.8×10^5 mm/min.

3. RESULTS

3.1. Static Tests

All the joints failed cohesively, leaving a clear adhesive layer on both adherends after failure.

The failure loads obtained with each adhesive for SLJs and T-joints are presented in Fig. 7. For the same adhesive, the failure load of the SLJs is twice as high as that of the T-joints. In order to understand the joint mechanics and better interpret the results, a two-dimensional (plane strain) linear elastic finite element analysis was carried out to study the stress distribution in the SLJ and in the T-joint for the two adhesives. In a SLJ, the major stress component is shear, whereas, in a T-joint, the loading is directly through the adhesive layer, as shown by Grant *et al.* [5]. In the T-joints (see Fig. 8), there is a rotation of the overlap region, as well as direct tension across it. There is a direct longitudinal tensile load across the overlap and fillet region, and also a bending moment created by the offset of the tensile load. Therefore, the adhesive shear stress is plotted in Fig. 9 for the

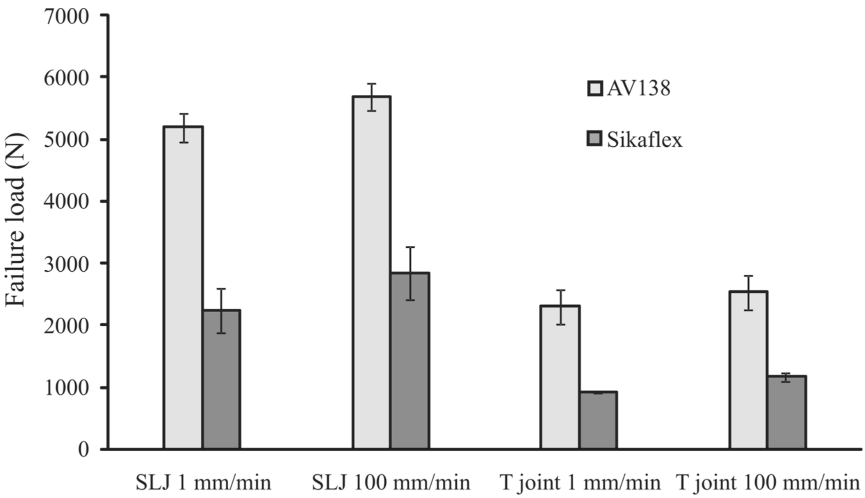

FIGURE 7 Failure loads for the epoxy adhesive (AV138) and the polyurethane (Sikaflex) in SLJs and T-joints tested in quasi-static conditions under 1 and 100 mm/min.

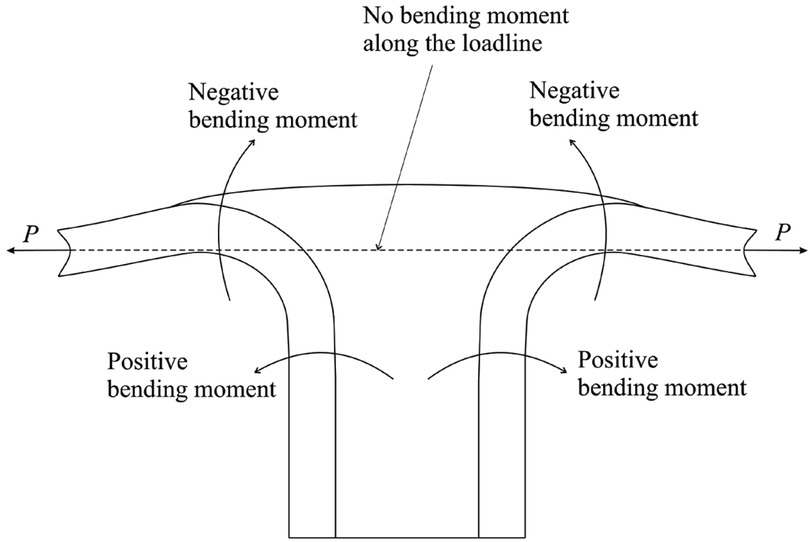

FIGURE 8 T-joint loading.

SLJ and the adhesive tensile stress (in the load direction) is shown in Fig. 10 for the T-joint. Figures 9 and 10 show that in SLJ specimens, the effective loaded area is significantly larger than the loaded area

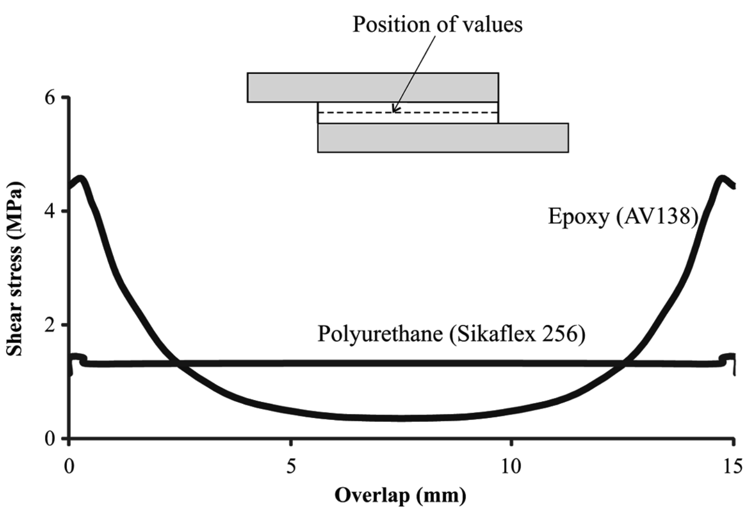

FIGURE 9 Adhesive shear stress distribution in the single lap joint for a tensile load of 500 N.

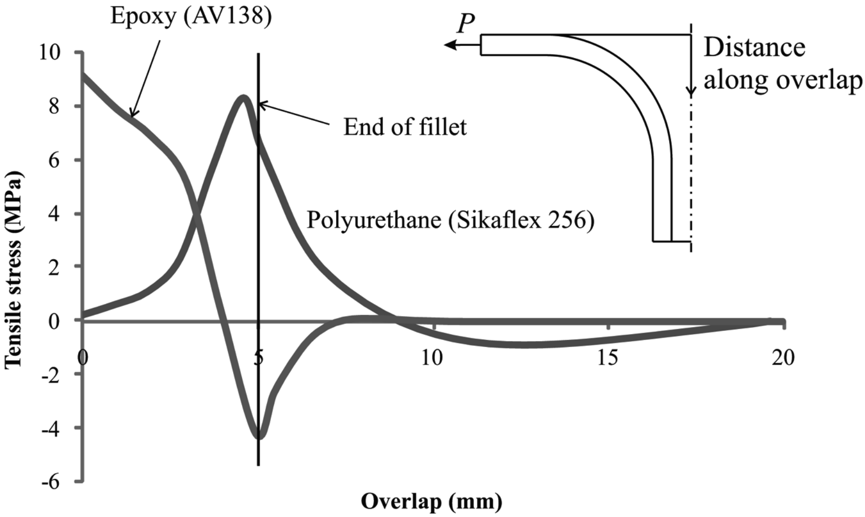

FIGURE 10 Adhesive tensile stress distribution in the T-joint for a tensile load of 500 N.

found in T-joints specimens. This enables the SLJ to handle higher loads. In SLJ specimens, the shear stresses are spread more evenly along the adhesive layer, especially for the low modulus of the polyurethane. In the case of the polyurethane T-joint, there is little load transfer through the adhesive fillet due to the adhesive's low stiffness. Most of the load is transferred underneath the fillet which means that the fillet is not so beneficial for elastomeric adhesives. On the contrary, for the epoxy adhesive, the fillet transfers most of the load and improves the load transfer greatly [5].

The joint strength with the epoxy adhesive is approximately two times that of the polyurethane, whether it is a SLJ or a T-joint. However, Table 1 shows that the epoxy strength (pure shear) is four times as high as that of the polyurethane. This illustrates well the fact that joint strength and adhesive strength are two completely different things. The joint strength depends not only on the adhesive strength but also on the adhesive ductility. The polyurethane adhesive is much more ductile (330%) than the epoxy adhesive (5.5%). The ductility is very important to redistribute the stresses along the overlap and use the less-stressed parts of the joint.

Figure 11 shows load-displacement curves registered for both adhesives in SLJs for a crosshead speed of 1 mm/min. The curve of the epoxy adhesive presents a linear behaviour for low displacements and becomes non-linear from approximately 4 kN. The polyurethane

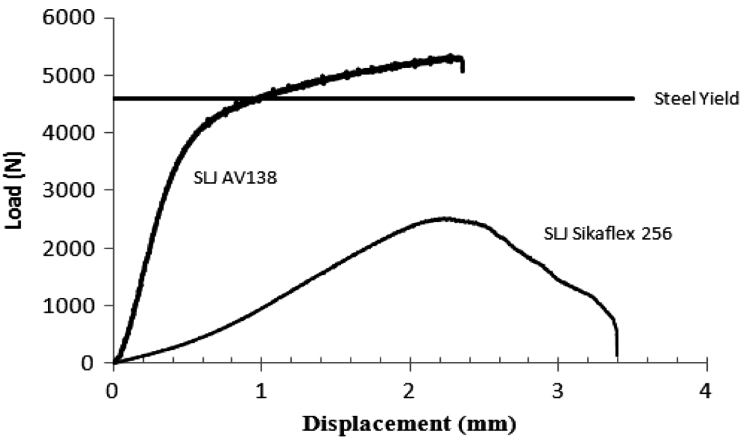

FIGURE 11 Load-displacement curves for SLJs of Sikaflex 256 and AV138 tested at 1 mm/min.

SLJ is non-linear from the start and presents a much lower stiffness that that of the epoxy adhesive. Adams *et al.* [9] proposed a simple methodology for designing single lap joints under tension. The upper limit is given by the load corresponding to the total plastic deformation of the adhesive (global yielding) which is:

$$P_{GY} = \tau_y \cdot b \cdot l, \tag{2}$$

where P_{GY} is the failure load of the adhesive due to global yielding, τ_y is the yield strength of the adhesive, b is the joint width, and l is the overlap length. Applying this equation to the present case, P_{GY} gives an approximate value of 9375 N for the epoxy adhesive and 3098 N for the polyurethane. This value is well above the experimental failure load for the epoxy and proves that the adhesive was far from being plastic along the whole overlap. However, for the polyurethane, the global yielding criterion is close to the experimental failure load, which was expected due to the high ductility of the polyurethane. A lower limit is given when the adherends yield plastically. The direct tensile stress (σ_t) acting in the adherend due to the applied load, P, is

$$\sigma_t = P/bt, \tag{3}$$

where t is the adherend thickness. The stress at the inner adherend surface (σ_s) due to the bending moment, M, is

$$\sigma_s = 6M/bt^2, \tag{4}$$

where $M = kPt/2$, according to Goland and Reissner [22]. The variable k is the bending moment factor which reduces (from unity) as the lap joint rotates under load. The stress acting in the adherend is the sum of the direct stress and the bending stress. Thus, the maximum load that can be carried by the joint is just that which causes the adherend to yield (P_{Y}) and is given by the expression:

$$P_{\mathrm{Y}} = \sigma_y bt/(1 + 3k), \tag{5}$$

where σ_y is the yield strength of the adherend. For low loads and short overlaps, k is approximately 1. Therefore, for such a case,

$$P_{\mathrm{Y}} = \sigma_y bt/4. \tag{6}$$

However, for joints that are long compared with the adherend thickness, which is the case here ($l = 15$ mm and $t = 1$ mm), the value of k decreases and it is assumed here that it tends to zero. In this case, the whole of the cross-section yields and

$$P_{\mathrm{Y}} = \sigma_y \cdot b \cdot t. \tag{7}$$

Equation (7) gives a failure load of 4.6 kN, which is in accordance with the non-linear behaviour seen in Fig. 11 for the epoxy adhesive. As the load imposed on the joint increases, the bending moment imposed at the edge of the overlap increases, which in turn increases the stress at the edge of the adhesive. When the stress reaches the yield point of the steel, large plastic strains result. Because the maximum adhesive strain is limited (5.5%), it, therefore, fails when the maximum adhesive strain is exceeded. In terms of strain energy (area under the load-displacement curve), the SLJs with the epoxy adhesive are more advantageous than SLJs with the polyurethane adhesive due to the adherend yielding. However, if high strength adherends were used, there would not be adherend yielding, and, in that case, a SLJ with a polyurethane adhesive would give a larger strain energy. Figure 12 shows a picture of the failed specimens tested statically where it is possible to see the adherend yielding in the case of the SLJs with the epoxy adhesive AV138. In the case of the T-joints, it is surprising to see that despite the fact that the joint strength of the T-joints with AV138 is higher than that of T-joints with the Sikaflex, there is adherend yielding only in the case of the T-joints with Sikaflex. The epoxy adhesive AV138 is stronger than Sikaflex 256 but it is brittle. The fracture of AV138 T-joints happened suddenly after the initial crack generation. The initial crack generation of T-joints with AV138 needed a much higher load than for Sikaflex

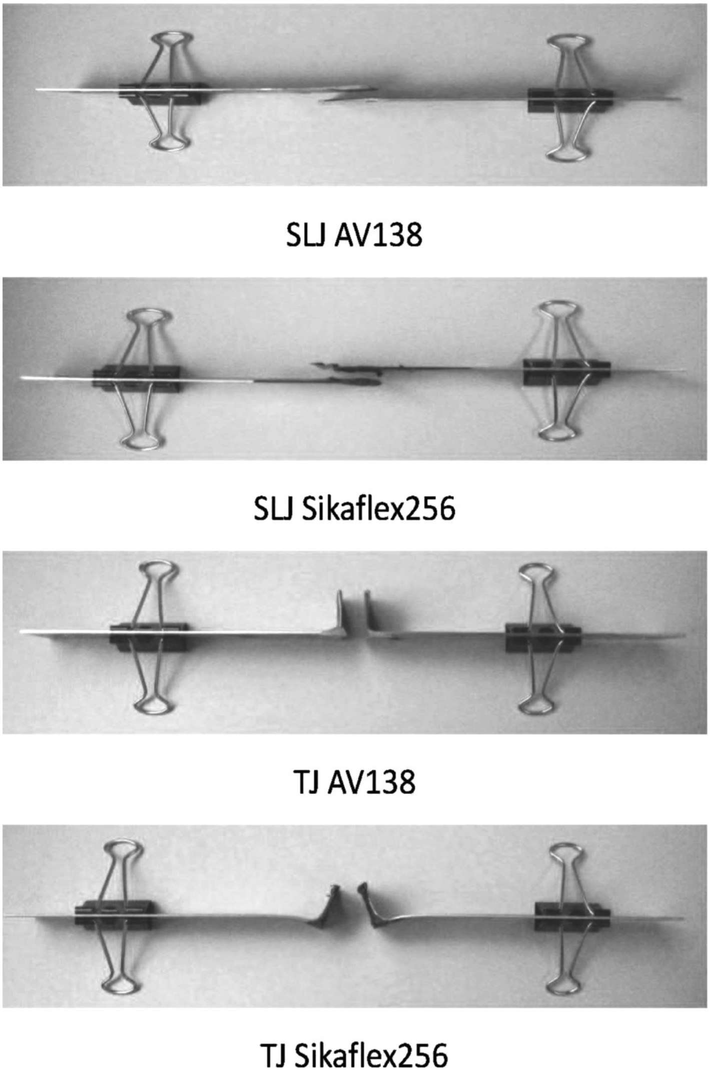

FIGURE 12 Failed specimens tested statically under 1 mm/min.

256. However, once the crack was initiated, it propagated along the whole overlap causing instantaneous failure. The load to cause crack initiation was not sufficient to cause yielding of the T part of the AV138 joint. On the contrary, Sikaflex 256 polyurethane adhesive is weak but ductile. Therefore, the load to initiate a crack is smaller than for the T-joint with AV138. Once a crack has initiated in the T-joint

with the polyurethane, the load to cause its propagation bends the adherend increasingly and is sufficient to cause adherend yielding. Figure 13 shows the load-displacement curves for both adhesives in T-joints at a crosshead speed of 1 mm/min. The curve for the epoxy adhesive is practically linear. The load-displacement curve of the polyurethane is highly non-linear, corresponding to adhesive plastic deformation and adherend yielding. As in the case of the SLJ, the stiffness of the T-joint with the polyurethane is much lower than that of the epoxy. However, when high deformations or high strain energy (area under the load-displacement curve) are required, the T-joint with the polyurethane adhesive is clearly better. Note also that the T-joint with the polyurethane adhesive exhibits a much lower scatter in the failure load than the T-joint with the epoxy adhesive (see Fig. 7). As explained above, the T-joint is mostly loaded in tension which will give more dispersion in the results if the adhesive is brittle (such as the epoxy adhesive) and, therefore, more sensitive to defects that bonded joints always contain.

Looking back at Fig. 10, the load corresponding to crack initiation can be easily determined, bearing in mind the ultimate tensile strength of both adhesives, which is 41 MPa for the epoxy adhesive AV138 and 12 MPa for the polyurethane Sikaflex 256 [23]. For a load of 500 N, the maximum tensile stress in the adhesive is 9 MPa for

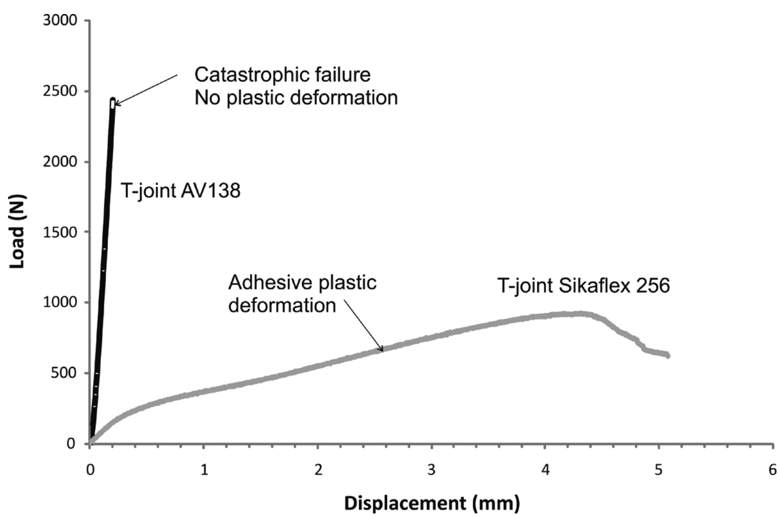

FIGURE 13 Load-displacement curves for T-joints of Sikaflex 256 and AV138 tested at 1 mm/min.

AV138 (at the left edge of Fig. 10) and 8.2 MPa for Sikaflex 256 (at the end of the fillet). Supposing that the failure load occurs when the tensile stress in the adhesive reaches its tensile failure strength, failure loads of 2554 and 914 N are obtained for the epoxy adhesive and for the polyurethane, respectively. These values compare very well with the failure loads presented in Figs. 7 and 13. In the case of the T-joint with the epoxy adhesive AV138, this analysis is sufficient because the failure is instantaneous. However, for the T-joint with the polyurethane, the failure is progressive and leads, after a crack has formed in the fillet, to the steel adherend's plastic deformation. To capture the debonding failure of the T-joints with the polyurethane along the overlap, the interfacial cohesive elements of ABAQUS were used, as illustrated in Fig. 14. The traction *versus* separation approach was employed as the constitutive response of cohesive elements since the thickness of the interface is negligibly small. This constitutive relation relates cohesive tractions to the displacement discontinuities for modelling the behaviour of the material in the process zone that is located ahead of a crack tip. The elastic properties of the interface material were defined using uncoupled traction-separation behaviour, with a tensile stiffness of 4 MPa and shear stiffness of 4 MPa. The quadratic traction-interaction failure criterion was chosen for damage initiation in the cohesive elements; a mixed-mode, energy-based damage evolution law based on the power law (coefficient of 2) criterion was used for damage propagation. The relevant material data are as follows: tensile strength = 4 MPa, shear strength = 4 MPa, tensile toughness = 3 N/mm, and shear toughness = 15 N/mm. These values were obtained by the inverse method using the load displacement curve of a double cantilever beam specimen [20]. The steel's plasticity was included in the analysis with a tensile yield strength of 180 MPa and an ultimate tensile strength of 465 MPa for 35% of failure strain. Figure 14 shows four stages of the crack propagation until complete failure. Two important features are worth commenting. The first is related to the progressive adherend yielding ahead of the crack tip which corroborates the initial interpretation of the experimental results. The second is the final shape of the adherends that is very similar to the experimental deformation presented in Fig. 12.

Through the observation of Fig. 7, it is possible to verify that the joint strength increases with the test speed for both adhesives. The joint strength increase is much higher for joints with the polyurethane adhesive (~27%) than for those with the epoxy adhesive (~10%). The polyurethane adhesive is more dependent on the test speed than the epoxy. For high strain rates, the polyurethane stiffness and strength increase but its ductility is still very high, as can be seen

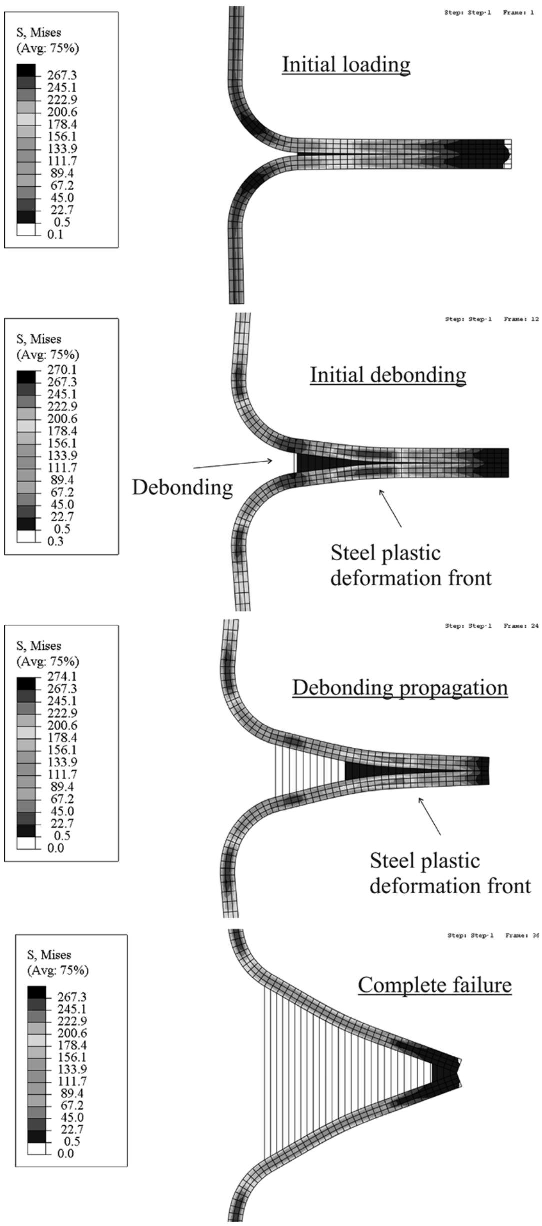

FIGURE 14 Modelling of the crack propagation in T-joints with the polyurethane adhesive (Sikaflex 256).

the load-displacement curves shown in Fig. 15. As the test speed increases, the difference in joint strength between joints with the epoxy and the polyurethane decreases.

3.2. Damping Tests

The damping ratio values for each type of joint and adhesive are presented in Table 2. The results show that there is little difference between the two adhesives, even though, as expected, the Sikaflex adhesive gives a slightly higher damping. A thicker adhesive might have produced a larger damping difference. Note that the transverse load applied to the specimen for the damping measurements causes shear loading in the case of the T-joint and peel loads in the SLJ (see Fig. 5). Therefore, the larger adhesive area under shear in the T-joint can damper the structure more than in the case of the SLJ.

3.3. Fatigue Tests

As in the static tests, all specimens failed cohesively in the adhesive. The fatigue curve (load *vs*. number of cycles to failure in logarithmic scale) is shown in Fig. 16 for SLJs and in Fig. 17 for T-joints. Fatigue data were normalised with respect to the average static failure load. Load is used rather than stress amplitude because an average shear

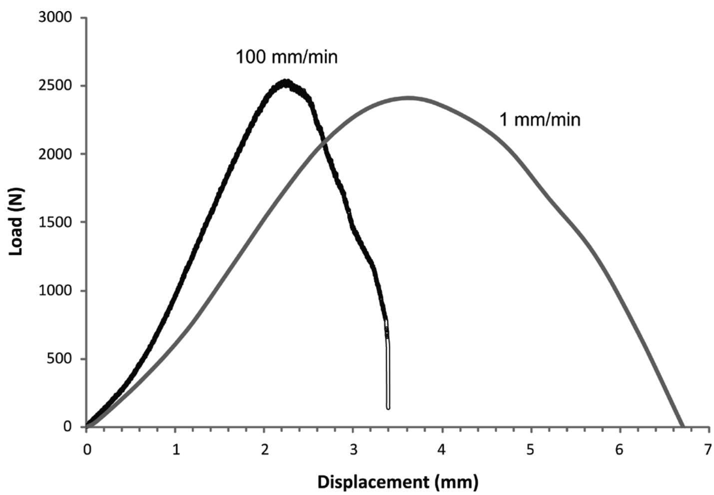

FIGURE 15 Load-displacement curves of SLJs with the polyurethane adhesive (Sikaflex) at 1 and 100 mm/min.

TABLE 2 Summary of Damping Ratio Results

Adhesive	Joint geometry	Damping ratio (%)
AV138	SLJ	0.248
	T-joint	0.303
Sikaflex 256	SLJ	0.251
	T-joint	0.306

stress may be misleading, considering the non-uniform nature of the shear stresses and the existence of significant peel stresses, which most likely contributes to failure. A straight line was fitted to the measured values (a logarithmic approximation was made). A comparison of the fatigue results between the joints with the epoxy and those with the polyurethane shows that the slope of the fatigue curves and the scatter are approximately the same. This result is rather surprising since elastomeric materials are known for their improved fatigue resistance. A possible cause for this result is the adhesive heating during fatigue testing that would have more influence on the elastomeric adhesive (decreasing its strength) than on the epoxy.

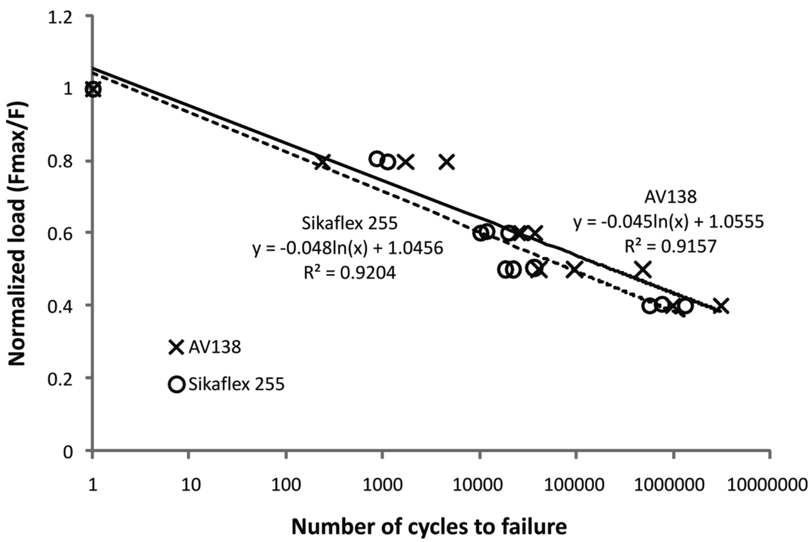

FIGURE 16 Fatigue life curve of SLJs with epoxy (AV138) and polyurethane (Sikaflex).

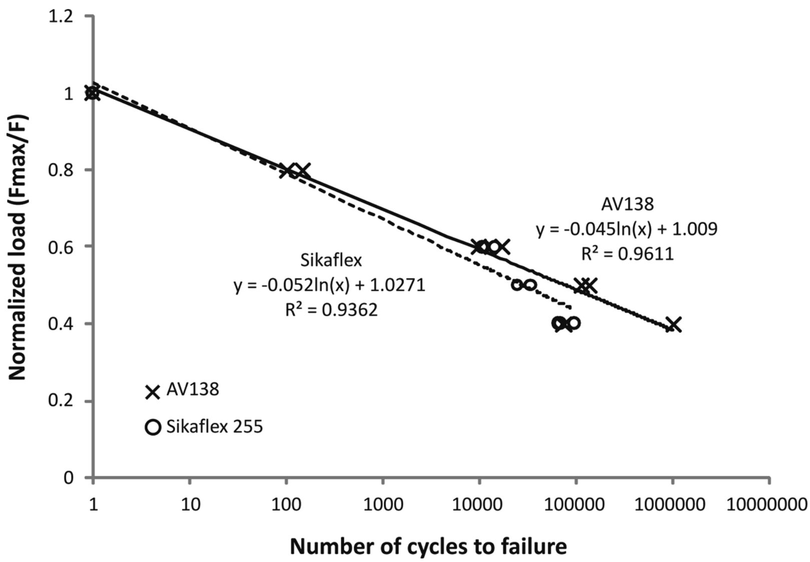

FIGURE 17 Fatigue life curve of T-joints with epoxy (AV138) and polyurethane (Sikaflex).

3.4. Impact Tests

All the specimens failed cohesively in the adhesive. Figure 18 shows typical load variations of the impact tests using SLJs and T-joints bonded with AV138 epoxy adhesive and Sikaflex 256 polyurethane adhesive. The load registered in the impact tests presented variations due to the inertia effects of the specimen and the test setup. However, at the initial stage of loading, every specimen showed a stable increase of load. Therefore, the maximum value in this stage, *i.e.*, the maximum value before drastic decrease in Fig. 18, can be considered as the failure load of the specimens. The displacement of the anvil, which is equivalent to the total elongation of the specimens, can be calculated from the loading time, *i.e.*, 1 ms = 3 mm. Note that the total elongation includes the plastic deformation of the steel adherends, especially around the bolt holes used for fixing the specimen in the test machine.

Figure 19 shows the failure loads obtained in the impact tests, along with the static failure loads at 1 mm/min for comparison purposes. In this figure, the error bars represent the standard deviation of the failure loads. As in the case of the static tests, adhesive joints under impact with the epoxy adhesive (AV138) are still stronger than those with the polyurethane adhesive (Sikaflex). There is a clear increase in

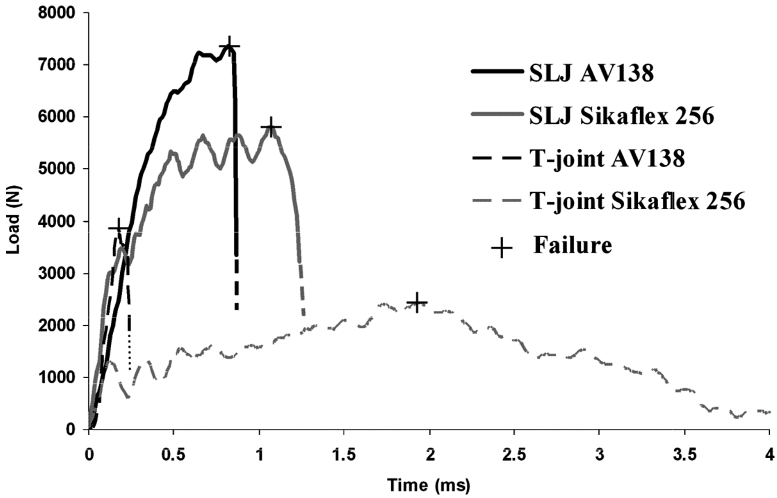

FIGURE 18 Load variation of impact tests with respect to time.

joint strength from static to impact tests, especially for Sikaflex 256. This phenomenon may be attributed to the elastomeric nature of the Sikaflex 256 polyurethane adhesive. The difference in joint strength between the two adhesives is much lower under impact conditions

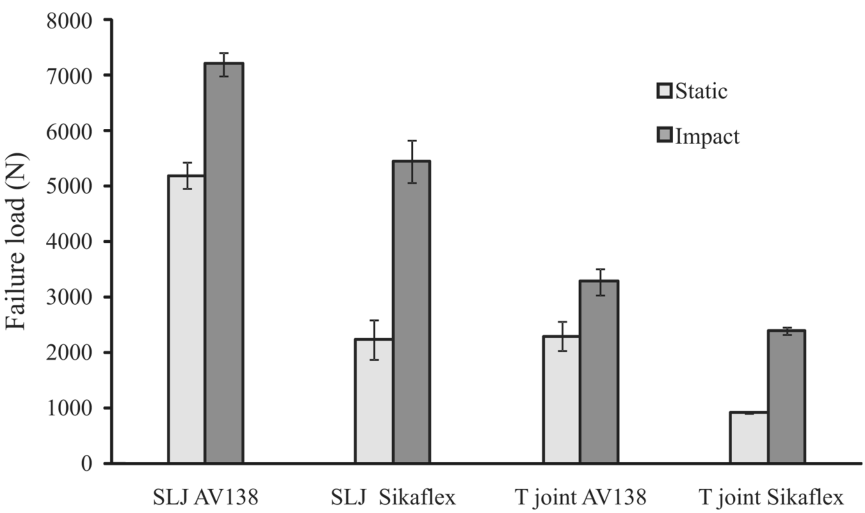

FIGURE 19 Failure loads of specimens under impact loads, along with the static failure loads at 1 mm/min for comparison purposes.

than under static conditions. This is an important result, bearing in mind that the major type of loading in cars is impact loading.

A photo of the failed specimens for each case is shown in Fig. 20. There is plastic deformation of the adherends in the case of SLJs with the epoxy adhesive AV138 and T-joints with the polyurethane adhesive Sikaflex 256. In the case of the SLJs with the epoxy adhesive AV138, the failure under impact is dictated by the adherend yielding as in the case of the static results. The increase in failure load is due to an increase of the yielding strength of the steel under impact. In the case of the T-joints, there is adherend yielding only in the case of the T-joints with Sikaflex, as for the static tests.

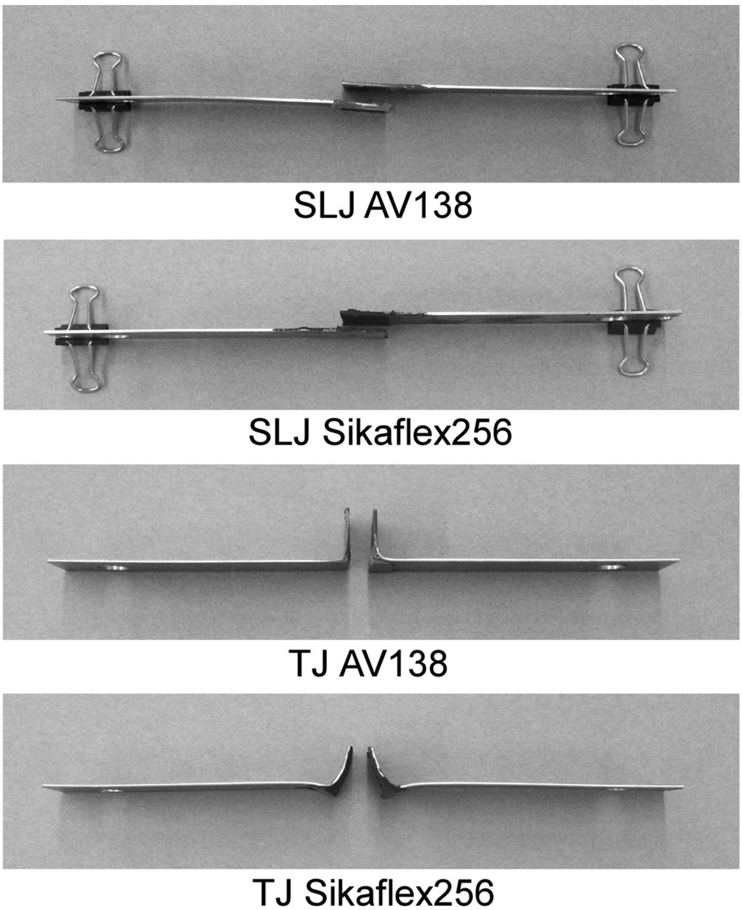

FIGURE 20 Failed specimens subjected to impact loading.

4. CONCLUSIONS

The behaviour of structural joints used in the automotive industry such as single lap joints and T-joints made of a rigid adhesive (epoxy AV138) and made of an elastomeric adhesive (polyurethane Sikaflex 256) was compared in terms of stiffness, strength, impact, damping, and fatigue. The following conclusions can be drawn.

1. The load-displacement curve of SLJs with the epoxy adhesive presents a linear behaviour for low displacements and becomes non-linear from approximately 4 kN, corresponding to the steel yielding. The polyurethane SLJ is non-linear from the start and presents a much lower stiffness than that of the epoxy adhesive.
2. The load to cause crack initiation was not sufficient to cause yielding of the T part of the AV138 joint. The load to initiate a crack is smaller for the polyurethane. However, once a crack has initiated in the T-joint with the polyurethane, the load to cause its propagation bends the adherend increasingly and is sufficient to cause adherend yielding.
3. A predictive analysis is done for each geometry and adhesive. For SLJs, the global yielding is used for the polyurethane and the adherend yielding for the epoxy. For T-joints, the crack initiation is determined by an elastic finite element analysis. The crack propagation in the case of the T-joint is modelled with cohesive elements to explain the adherend progressive yielding.
4. The stiffness of the T-joint with the polyurethane is much lower than that with the epoxy. However, when high deformations or high strain energy (area under the load-displacement curve) are required, the T-joint with the polyurethane adhesive is clearly better.
5. The polyurethane adhesive joints give a slightly higher damping than those with the rigid epoxy. Thicker bondlines should be studied in order to differentiate this behaviour more clearly.
6. A comparison of the fatigue results between the joints with the epoxy and those with the polyurethane shows that the slope of the fatigue curves and the scatter are approximately the same.
7. The joint strengths under impact were much higher than under static loading, especially for the polyurethane adhesive. The joint strength under impact conditions for the two adhesives is comparable. This is an important result, bearing in mind that the major type of loading in cars is impact loading.

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