DESIGNING ADHESIVELY-BONDED JOINTS FOR INFINITE LIFETIME WHEN SUBJECTED TO CREEP AND (OR) FATIGUE LOADINGS

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Abstract A methodology for designing structural adhesively-bonded joints made with metallic, composite or glass adherends and structural elasto-plastic adhesives subjected to fatigue and (or) creep loadings is described in this paper.
This methodology is based on analytical methods [1], [2], [3], [4] for simple configurations or the finite element method for complex structures enabling the designer to calculate the stress distribution in the adhesive layer.
In previous studies [5], [6],[7], it was shown that the intrinsic mechanical characteristics of the adhesive could be determined on "bulk" specimens in tension or on thick-adherend shear test (TAST)specimen (NF-EN 14869-2) and that the Von-Mises strength criterion could be used within the linear elastic behaviour of the adhesive.
In this present study, the TAST is used to characterise two structural adhesives at room temperature under static and fatigue loadings.
SN curves up to 10^7 cycles (frequency: 30 cps) are given and the fatigue limits (maximum shear stress) are derived from these curves for both adhesives. The non-failed specimens (after 10^7 fatigue cycles) were tested in static shear and no damage was observed.
It was shown also that the fatigue limit was slightly higher than the static elastic limit of the adhesive in "pure" shear.
Fatigue tests were also monitored on single-lap shear specimens (NF-EN 1465) with these two adhesives in the same conditions (frequency, room temperature). SN curves and fatigue limit (maximum load) were obtained. Stress distributions in the single-lap shear specimens bonded with these two adhesives were calculated using Hart-Smith analytical method [1].
A good correlation was observed between the experimental fatigue limit (maximum load) at 10^7 cycles obtained on single-lap joints (SLJ) and the predicted one determined by stress distribution computation using the Von-Mises criterion and the “static” elastic limit of the adhesives obtained on TAST specimens.

1 INTRODUCTION

Adhesives are more and more used for structural assemblies in many industries (aerospace, automotive, mechanical parts in different applications…).
Users have to design safe adhesively bonded structures for such applications.
A simple methodology is given in this paper allowing users to design adhesively-bonded joints for infinite lifetime when subjected to creep and (or) fatigue loadings.

2 INTRINSIC MECHANICAL CHARACTERISATION OF STRUCTURAL ADHESIVES (STATIC)

It was shown previously [5,6] that this characteristics can be obtained :
- on bulk specimens in uniaxial tension and compression (see figure 1),

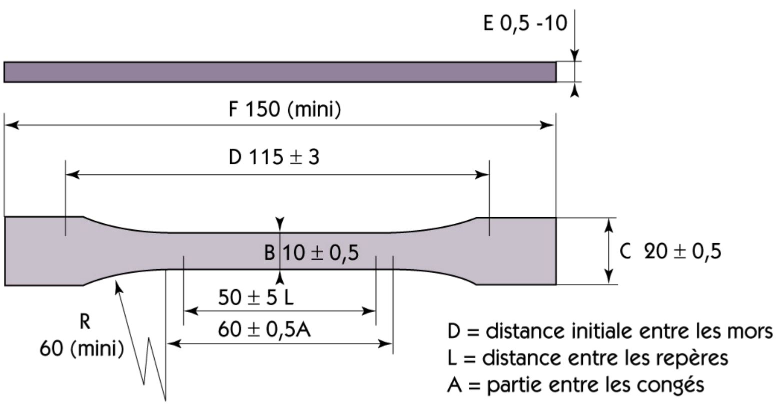


Figure 1. Tensile "bulk" specimen according to NF-EN-ISO 527-1.

- on thick adherend bonded specimens according to EN 14869-2 (see figure 2).

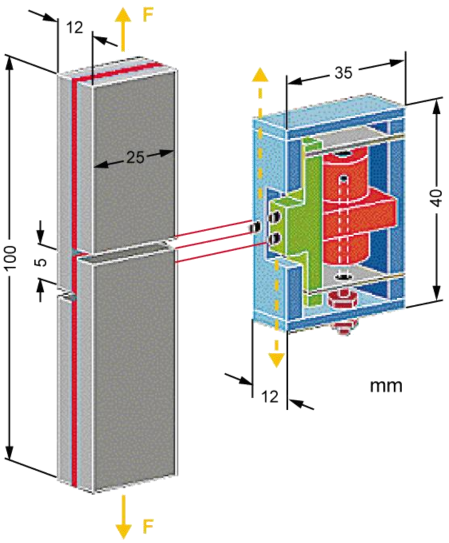


Figure 2. Thick-adherend-shear-test according to NF-EN 14869-2.

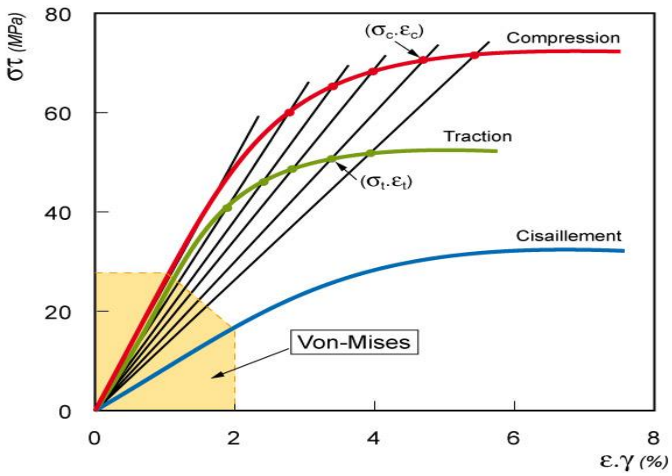
For elastoplastic adhesives, it was shown that the the elastic properties in the thin film form and in bulk specimens are similar (see table 1).

Adhesive	Young's Modulus E_c (MPa)	Shear Modulus G_c (MPa)	Poisson's Ratio (ν_c)
Redux 322-epoxy film (cure: 1h at 175°C)	4570 [a]	1650[b] 1630[c] 1660[d]	0.38[a]
Eccobond 45 LV-2-part epoxy paste (cure: 30 min at 70°C)	4760 [a]	1800[b] 1760[c] 1800[d]	0.324[a]
3M SW 9323 B/A-2-part epoxy paste (cure: 24 h at RT + 1 h at 80°C)	2150[a]	940[b] 650[c]	ND
Araldite AV 119 -1-part epoxy paste (cure: 1 h at 150°C)	3400[a]	1180[b] 1100[c]	ND
EVODE DP 70 -1part epoxy paste (cure 30 min at 190°C)	3300[a]	1320[b] 1050[c]	ND

[a] Tensile test on bulk specimens (NF-EN-ISO 527-1)
[b] Torsion Pendulum on bulk specimens
[c] Shear test on bonded thick adherend specimens (NF-EN 14869-1)
[d] Derived from the relationship $Gc = Ec/2\ (1+ \nu_c)$

Table 1. Comparison of the elestic properties of two adhesives determined on bulk specimens and bonded specimens.

Dolev *et al* [7] have found that the properties derived from uniaxial testing of a bulk adhesive (tension, compression, torsion) where related to those of an *"in-situ"* adhesive layer loaded in pure shear (napkin-ring specimen according to NF-EN 14869-1 test) by a combined stress law which follows a modified Von-Mises criterion (see fig 3) also called Raghava criterion.



$\sigma eq = Cs\,(J_{2D})1/2 + CvJ_1$
$J_{2D} = 1/6\,[(\sigma_1 - \sigma_2)2 + (\sigma_2 - \sigma_3)\,2 + (\sigma_3 - \sigma_1)2]$
$J_1 = \sigma_1 + \sigma_2 + \sigma_3$
$C_S = \sqrt{3}\,(\lambda+1)/2\lambda$
$C_V = \lambda-1/2\lambda$
$\lambda = \sigma_C/\sigma_T$
If the volumetric component is negligible:
$\sigma_C = \sigma_T\ (\lambda = 1)$
$C_S = \sqrt{3}$
$C_V = 0$
$\sigma eq = Cs\,(J_{2D})1/2$ *(Von Mises)*

Figure 3. Raghava strength criterion used for "elasto-plastic" structural adhesives.

This strength criterion gives a function which relates the tensorial components of stress and strain to their respective effective values. This function is valid throughout the entire range of stress/strain relationships up to failure and under all combinations of compound stresses.
When the effect of the volumetric component of the stress is negligible, this function is reduced to the common Von-Mises criterion.
For the five adhesives given in table 1, we have shown that the Von-Mises strength criterion holds within their linear elastic range.

3 FATIGUE AND CREEP TESTS ON THICK ADHEREND SHER TESTS (SHEAR CHARACTERIZATION)

3.1 Creep tests

A single-part epoxy adhesive cured at 180°C during 30 min was used for this study.
The thick-adherend shear test was used to characterize this adhesive in static "pure" shear as shown in § 2 above.
The following results were obtained:
-shear modulus : $G_c = 1270$ MPa
-"elastic" or "reversibility" limit : $\tau_E = 18$ MPa
Thick-adherend shear specimens were used for creep tests. Bonded specimens were loaded at different constant stress levels from 16 to 32 MPa (five specimens for each level) for times up to 8 months.
Table 2 gives the creep results obtained on this adhesive at room temperature.

Applied stress level $\tau_{applied}$ in MPa	Failure time (days)	remarks
32	30 minutes to 3 days	
28	10 days to 32 days	
24	71 days to 164 days	
20	No failure after 8 months	No damage of the adhesive*
16	No failure after 8 months	No damage of the adhesive*

*non–failed specimens were tested in static shear after the removal of the applied stress and the shear stress/strain curves obtained were identical to the initial (static) ones.
Table 2. Creep test results obtained on thick-adherend shear specimens.

These results show that the adhesive can be loaded at a constant shear stress level up to 20 MPa (slightly above the "reversibility" limit (τ_E = 18 MPa) for a long (infinite) time with no failure and no damage of the adhesive layer.

3.2 Fatigue tests

The same specimens (thick-adherend shear test according to NF-EN 14869-2) were used for testing two adhesives at room temperature (static and fatigue loadings).
Fatigue tests were preformed with the following conditions :

- sinusoïdal signal,
- frequency: 30 Hz (cps),
- sress ratio: 0,1
- maximum number of cycles : 10^7

Table 3 gives the results obtained on the two adhesives tested.

Adhesive / Supplier Curing conditions	Shear modulus G_c (quasi-static)	"reversibility limit" τ_E (quasi-static)	Fatigue limit * τ_D
SW 9323 B/A-2 part epoxy paste / 3M Cured 2 hours at 65°C	770 MPa	20 MPa	22 MPa
ARALDITE 2021-2 part epoxy paste / HUNTSMAN Cured 12 hours at RT	610 MPa	13 MPa	15 MPa

*no failure after 10^7 cycles, no damage of the adhesive layer (the non-failed specimens were tested up to failure (quasi-static tests) and the stress/strain curves were identical to those of non stressed specimens (initial state).
Table 3. Fatigue test results obtained on thick-adherend shear specimens.
The S/N curve (Wöhler curve) for the adhesive 3M SW 9323 B/A is given on figure 4.

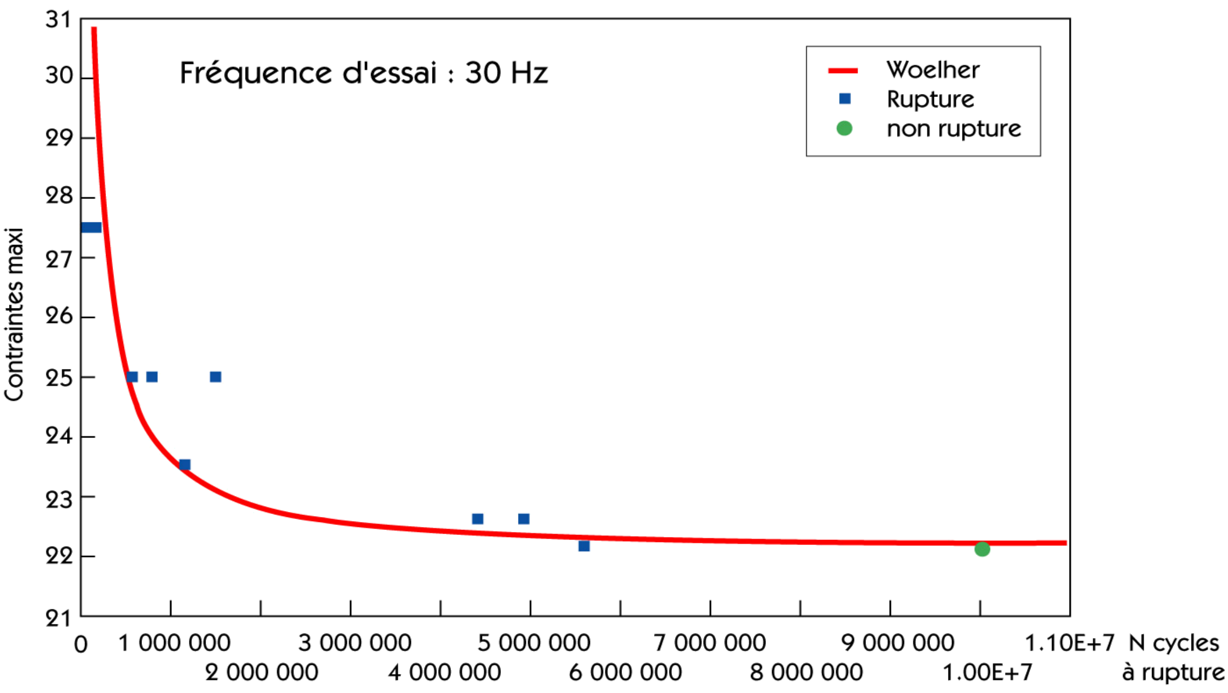


Figure 4. Wöhler curve obtained on adhesive 3M SW 9323 B/A.

These results show that these two adhesives can be cycled in fatigue at a maximum shear stress level slightly above their "reversibility" limit τ_E for an infinite number of cycles (10^7) with no failure and no damage of the adhesive layer.

4 FATIGUE TESTS ON SINGLE LAP SHEAR SPECIMENS (NF-EN 1465)

The specimen is shown on figure 5.

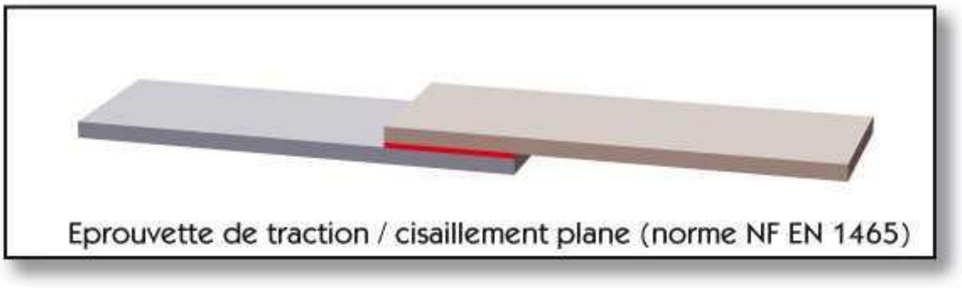


Figure 5. Single lap shear specimen (NF-EN 1465)-dimensions given below.
Adherend length : 112,5 mm
Overlap length : 12,5 mm
ADherend width : 25 mm
Steel adherends (E = 210 000 MPa, ν = 0,3, e = 1,5 mm), degreased/sand-blasted/degreased.
Adhesive thickness : 0,2 mm

The experimental fatigue tests results (same conditions as those used on thick-adherend shear specimens, see § 3.2) are given in table 4.

Adhesive / Supplier Curing Conditions	Experimental fatigue limit (no failure after 10^7 cycles, no damage)
SW 9323 B/A (3M) : 2 part-epoxyde at 65°C for 2 hours	3020 N
Araldite 2021 (HUNTSMAN) : 2 part- epoxyde cured at RT (12hours)	2125 N

Table 4. Fatigue test results obtained on single lap shear specimens (NF-EN 1465).

The stress distribution in this single lap joint is a well known triaxial state of stress.
The Hart-Smith analytical method [1] has been used to analyse the stress distribution in the single lap joint shown on figure 5 with the adhesives characteristics given in table 3 (determined on thick-adherend shear specimens). The stress distributions along the overlap are given on figures 6 and 7 respectively for adhesive 3M 9323 B/A and ARALDITE 2021.

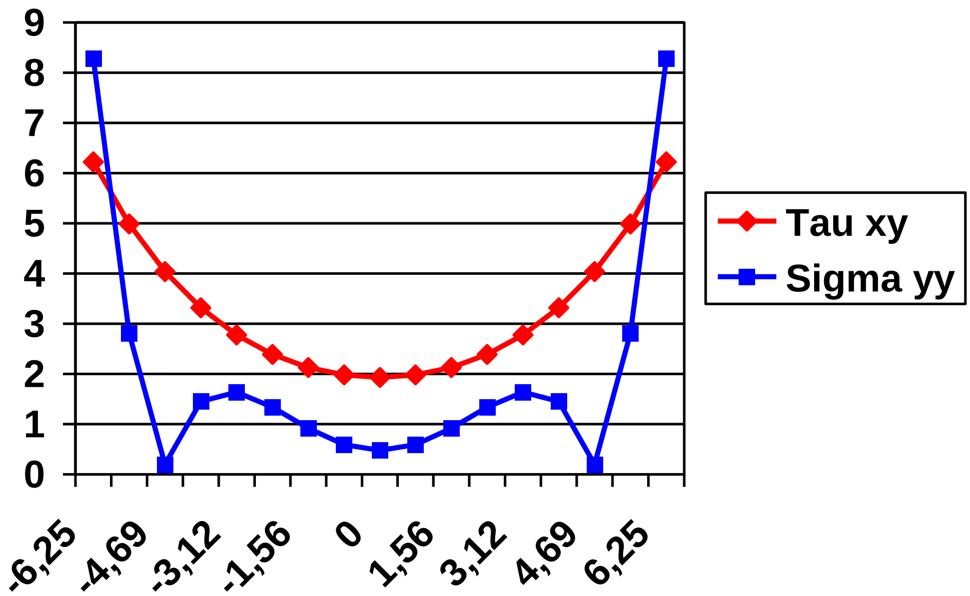


Figure 6. Stress distribution along the overlap of the single lap joint (3M SW 9323 B/A).

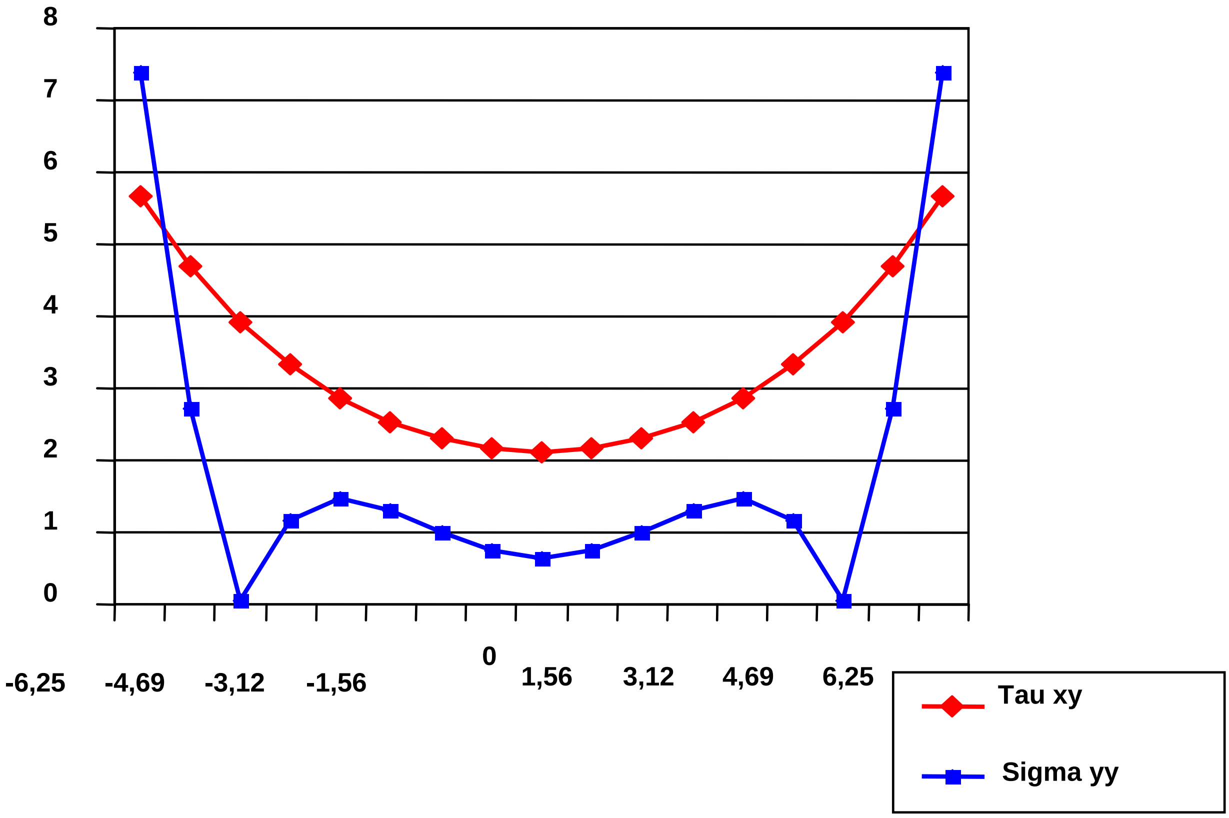


Figure 7. Stress distribution along the overlap of the single lap joint (ARALDITE 2021).

These stress distributions enable us to calculate the maximum Von-Mises stresses located at the end of the overlap for each adhesive (using the Von-Mises strength criterion).
The load at which the maximum Von-Mises stress is reached can then be deduced using the "reversibility limit" or the fatigue limit determined in § 3.2, table 3.
These calculated loads are given in table 5 for each adhesive and compared to the experimental ones given in table 4.
We can see the excellent correlation between the predicted results and experimental results for both adhesives when using the fatigue limit determined on the thick-adherent shear specimens.
A good correlation is also observed when using the static "reversibility limit".

Adhesive / Supplier Curing Conditions	Calculated reversibility limit (using τ_E –see table 3)	Calculated fatigue limit (using τ_D-see table 3) (no failure after 10^7 cycles, no damage)	Experimental fatigue limit (see table 4) (no failure after 10^7 cycles, no damage)
SW 9323 B/A (3M) : 2 part-epoxyde at 65°C for 2 hours	2680 N	2960 N	3020 N
Araldite 2021 (HUNTSMAN) : 2 part- epoxyde cured at RT (12hours)	1880 N	2190 N	2125 N

Table 5. Comparison of calculated and experimental fatigue results on single lap joints bonded with two structural adhesives SW 9323 B/A and ARALDITE 2021.

5 CONCLUSIONS – FUTURE WORK

The thick-adherend shear test method (according to NF-EN 14869-2) enables to determine the shear modulus and the "elastic" or "reversibility" limit of structural elasto-plastic adhesives. These characteristics can be used to used to determine the stress distribution in any adhesively bonded structure (with analytical methods or the finite

element method for more complex structures), and the load at which the adhesive layer (at the highest stressed point) will begin to yield (using the Von-Mises criterion which was validated in previous work within the linear "elastic" range).
In this study, this test method was used to characterize the creep and fatigue behaviours of 3 adhesives.
It was shown that the creep and fatigue limits of these adhesives, using the TAST specimens, were slightly higher than the "reversibility" limit determined in quasi-static shear.
Fatigue tests were also monitored on single-lap shear specimens (NF-EN 1465) with two of these adhesives (one two-part epoxy paste and one two-part methacrylate) in the same conditions (frequency, stress ratio, room temperature..) as those used for characterization on TAST specimens.
S/N curves and fatigue limits (maximum loads for running 10^7 cycles without any damage of the bonded joint) were obtained.
A good correlation was observed between these experimental fatigue limits and the predicted ones determined by stress distribution computation using the Von-Mises strength criterion and the static "reversibility" limits obtained on thick-adherend shear specimens for both adhesives.
Further work will be carried out on adhesives with more complex stress/strain behaviours (elasto-visco-plastic, hyper-elastic...) and using more complex strength criterions.

6 REFERENCES

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