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Comparison of three different adhesive joints using static and dynamic impact tests: development of a new drop weight impact test rig incorporating a modified Arcan fixture

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Abstract

The paper proposes to compare static and dynamic properties of three structural adhesives selected for the integration of optical space systems. These comparisons are based on an original methodology using static test and drop weight impact test to determine the best shock-strength candidate. In a first section, the design of the drop weight impact rig integrating a modified Arcan fixture is described. Then validity of the impact test rig is discussed on a simplified case thanks to an analytical model of "soft impact" available in literature. In a second section, static tests results are presented and the adhesive's critical stresses are identified with a point stress criterion. Finally, impact tests results are used to discuss the dynamic tensile and shear behaviour of each adhesive with different stress concentrations. Static critical stresses and impact strengths of the adhesives are reported. In conclusion a strategy of adhesive choice is discussed.

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Keywords: Adhesive joint, Impact tensile load, Impact shear load, Arcan fixture, Free edge effect

1. Introduction

Over the last 20 years, structural adhesives have been increasingly integrated into complex structures in order to reduce mass, particularly in the field of transport and civil engineering. Choosing the optimal adhesive forces us to make a decision on a multi-factorial trade-off. Indeed, weight must be reduced but neither sacrificing structural performance and nor creating new zones of vulnerability.

It is essential to carry out experimental tests to characterise the mechanical performance of adhesives. Static tests are well documented in the literature. In the last few years, the interest for the dynamic behaviour characterisation has been growing. Recently, a review of adhesives and adhesive joints under impact loading was published by Machado et al. [1]. Authors described that the adhesive joints behaviour under impact is complex and influenced by the properties of the adhesive, the joint geometry and the loading modes. You et al. [2] proposed a review of experimental techniques to determine impact properties of adhesive bonds.

To characterize impact strength, a dynamic loading have to be imposed on the specimen. Two main types of dynamic loading are considered: the first one is an "high speed loading" of the specimen in a tensile test machine at a high strain rate driven by a servo hydraulic systems as in Blackman [3]; the second one is a "shock elastic wave type": the impact on the sample can be direct or indirect, and corresponds to Izod and Charpy pendulums,

23 drop weight tower as in Beevers and Ellis [4], powder and gas gun, and split
24 Hopkinson bar (SHPB) techniques. These experimental methods are detailed
25 in Goglio [5], and da Silva [6].

26 Within framework of work carried out on direct bonding process for op-
27 tical space systems design [7, 8, 9], we need to characterize three adhesives
28 via both static and dynamic tests in order to compare the identified prop-
29 erties and to find the best candidate. The chosen adhesive will be finally
30 to integrate direct bonded optical space systems that are subjected to high
31 dynamic loading in the launcher and static loading during preparation on
32 the ground.

33 The paper describes the development of a drop weight impact rig inte-
34 grating a modified Arcan fixture to compare mechanical properties of three
35 selected structural adhesives. These comparisons are based on static and
36 drop weight impact test results obtained for different loading modes and
37 stress concentrations. As discussed by Adams and Harris in [10] about the
38 critical assessment of the ASTM D950, we propose a new "energy" oriented
39 methodology interesting for comparative studies.

40 In a preliminary section, the static test design based on a new modified
41 Arcan fixture (cylindrical samples) and a new impact test rig are described.
42 Then the validity (i.e good physical behaviour) of the impact test rig is
43 discussed on a simplified case (an elementary sample whithout adhesive)
44 thanks to an analytical model of "soft impact" available in the literature.
45 As proposed by Vales et al. in [11, 12], we have developed a test rig based
46 on the drop weight system of Beevers and Ellis [4] coupled with a modified
47 Arcan fixture. Based on the work of Arcan et al. [13], the geometry of Arcan

48 fixture allows us to test adhesive joints in a tensile machine with different
49 loading directions. Moreover, based on the work of Cognard et al. [14], a set
50 of different specimen geometries allows us to investigate stress singularities
51 (well known as "edge effects") in the adhesive.

52 In a first section a short introduction describe the three selected adhesives
53 and the adhesively-bonded specimens. In a second section, static test results
54 are presented and adhesive's critical stresses are identified with a point stress
55 criterion. Finally, the impact tests results are the starting point to discuss
56 the dynamic behaviour of the three adhesives in traction and shear with
57 different stress concentrations. The adhesive's mechanical strengths in static
58 and dynamic are compared using two characteristic experimental values: the
59 static critical stress and the impact strength. In conclusion a strategy of
60 adhesive choice is discussed.

61 **2. Preliminary work: design and validation of static and impact**
62 **test rigs**

63 *2.1. Static test with a modified Arcan fixture*

64 Static tests are performed using a modified Arcan fixture [14]. This de-
65 vice consists in loading an adhesively-bonded assembly along a controlled
66 axis which forms an angle with the axis sample between 0° and 90° . It allows
67 to apply a load in various orientations which results in a combined tension-
68 shear load mode of the bonded joint. It is constituted of two half discs with
69 several attachment points along the perimeter. These attachment points al-
70 low setting up the device on a standard tensile testing machine. For these
71 investigations, the Arcan system is adapted to use cylindrical specimens. Po-
72 sitioning and holding of the test sample are carried out using flanges. These
73 flanges fix the sample with screws uniformly distributed on its periphery
74 (Fig.1). The flanges are made in 7075 Aluminum. The half-discs are made
75 in 40CMD8S Steel in order to increase the system stiffness without adding
76 too much mass. The flanges and interface with half-discs are pre-tensioned
77 with M4 screws of class 12.9 with a controlled tightening torque of 4 *N.m*.
78 The torque is controlled in order to ensure the same clamping condition dur-
79 ing the experiments. Static tests are carried out on a tensile test machine,
80 an electro-magnetic Instron (Fig.2(a)). The Arcan device is connected to
81 the machine with a ball joint that guarantees isostatism and auto-alignment
82 of the applied force. Tests were performed at a quasi-static speed of 0.5
83 *mm.min*⁻¹. The load is measured with a sensor with a capacity of 50 *kN*.
84 Fig.2(b) describes the load displacement curves tested in traction and ob-
85 tained for five rounded edge samples bonded with Cyanoacrylate adhesive.

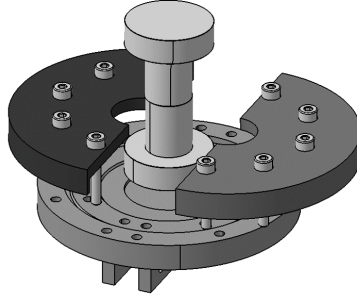
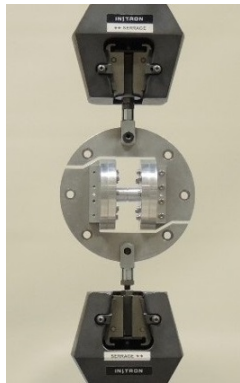
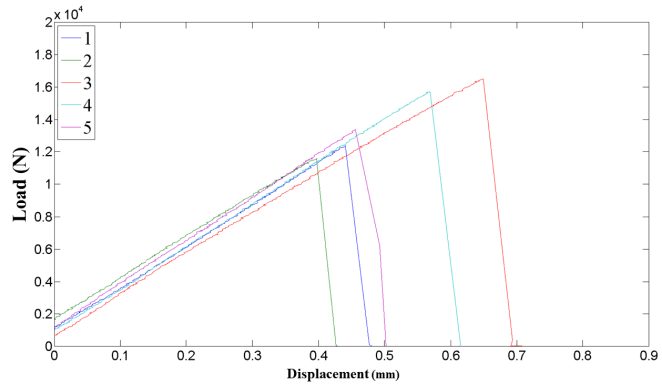


Figure 1: Homogeneous clamping device for the test samples.

86 We are able to identify the critical load at fracture (i.e first load drop on the
 curve).



(a) Static test



(b) load-displacement curves

Figure 2: (a) Description of the Arcan fixture mounted in the Instron tensile machine.
 (b) The load displacement curves tested in traction and obtained for five rounded edge
 samples bonded with Cyanoacrylate adhesive.

87

88 *2.2. Impact test machine with Arcan fixture*

89 The impact test machine is designed to generate a shock for different
 90 loading modes (traction, shear and mixed-mode) on the specimen. In order

91 to respect these requirements, as described in Fig.3, the impact test rig is
92 based on two principles the Beevers and Ellis drop weight test machine [4]
93 and the modified Arcan fixture proposed. Beevers and Ellis machine imposes
94 a tension load on a specimen by falling a weight along a tube connected to
95 the specimen. They performed single lap shear tests on an adhesive joint.
96 We propose to adapt their drop weight system and to integrate our modified
97 Arcan fixture in order to be able to impact adhesively-bonded assemblies
98 with different loading mode.

99 *2.2.1. Test machine design*

100 The new impact test bench including the Arcan fixture is detailed in Fig.3.
101 The drop weight system is chosen to generate shocks. The steel impactor
102 (noted (10) in Fig.3) is maintained through two electromagnets (9). When
103 experimental test begins, the impactor slides along the bar until to its stop
104 position against the impact zone (2). The specimen (7) is loaded in traction
105 through the bar and the Arcan device. In order to ensure isostatism and
106 to avoid plastic strain in the holes, the Arcan system is mounted between
107 two pivot links (6) using pins and steel inserts placed on the half-discs. On
108 the upper part, a ball joint (4) is added between the load sensor (3) and
109 the pivot link (6) to ensure the alignment of the system in the direction
110 of loading. A guidance system using calibrated bars and ball bushings (8)
111 is used to avoid any rotation of the system during impact. The removable
112 profile (1) allows to adjust the height of fall of the impactor up to 1 *m*. The
113 mass of the impactor is also a controlled parameter: steel impactors from
114 0.1 *kg* to 1.6 *kg* are used. In shear, we choose to limit the drop height to
115 0.5 *m* in order to not exceed a load threshold that could damage the Arcan

116 fixture (plastic strain in the radius of the angle). The system is equipped
 117 with a load sensor U9C/50kN from HBM, with a maximal capacity of 50kN
 118 and two accelerometers of Brüel Kjaer with a maximal capacity of 20,000 g.
 119 A PCI Express card with a sampling at 1 MHz is used for high frequency
 data acquisition.

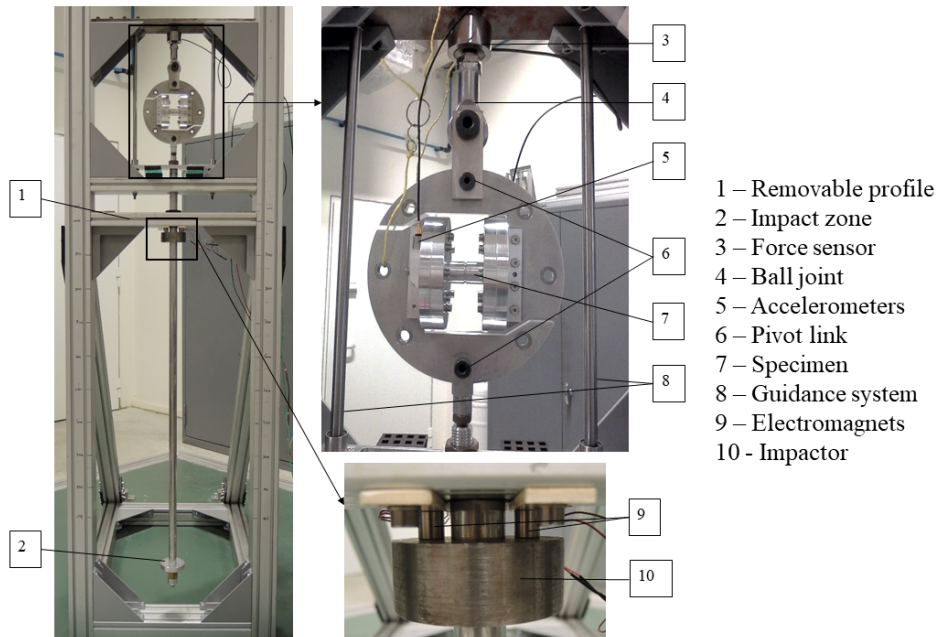


Figure 3: Drop weigh test machine incorporating a modified Arcan device

120

121 We used unidirectional accelerometers specifically chosen for impact tests.
 122 For the mounting of the accelerometers, two aluminum supports have been
 123 manufactured, they are screwed on the sample support of each half-disc
 124 (Fig.4(a)). These supports allow the accelerometer to be screwed in direction
 125 of solicitation. Fig.4(b) illustrates the mounting for the mode I (pure tensile
 126 testing), Fig. 4(c) for the mode II (pure shear testing) and Fig. 4(d) for
 127 the mixed mode. Accelerometers measurements allow us to validate that the

128 tests are carried out under the same conditions (i.e dynamic response of the
test bench does not change throughout the experimental campaign).

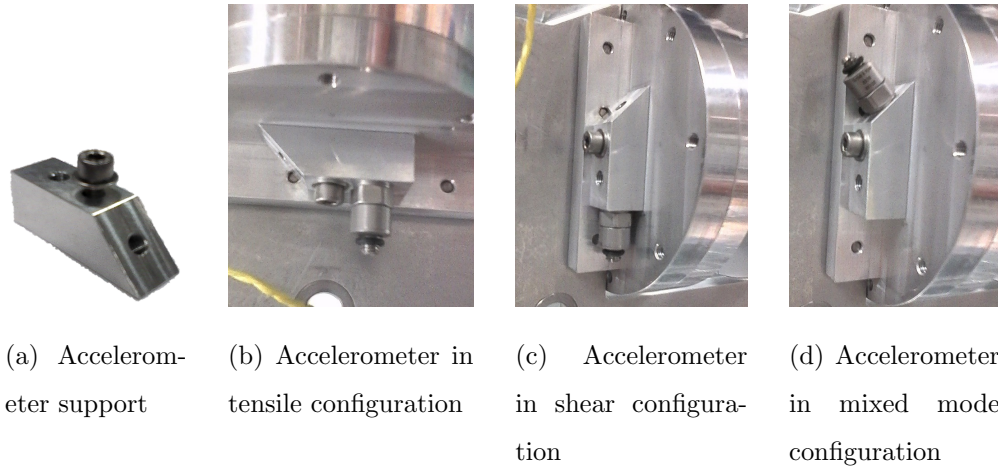


Figure 4: Aluminum parts to support accelerometers in different configuration.

129

130 2.2.2. Validation tests in a simplified case: one-piece specimens

131 In order to validate the behaviour of our impact test machine, we decided
132 to test a one piece specimen in traction and shearing. The protocol consists
133 in checking the response of the impact test rig on a simplified case (i.e. an
134 elastic material without the interface and interphase of the adhesive joint).
135 The evolution of the maximal load seen by the specimen at different shock
136 levels is experimentally observed by varying the drop height and mass of the
137 impactor.

138 Our modified Arcan device is composed of different parts placed between
139 the impactor and the load cell. We have controlled the successive assembly
140 procedures to be sure to have a good reproducibility in experimental results.
141 For instance, the tightening torque are controlled to not disturb the shock
142 wave travel in the system. In traction, ten masses from 0.1 *kg* to 1 *kg* are



Figure 5: One-piece specimen without the adhesive joint.

143 released from 10 different heights from 0.1 m to 1 m . In shearing, ten masses
144 are tested but only up to a height of 0.5 m in order to avoid damage to the
145 Arcan fixture. For each condition (mass, height), the impact is performed 3
146 times in order to validate its reproductibility and to quantify its dispersion.
147 The maximal load underwent by the sample is recorded using the load cell
148 acquisition during impact with a sampling at 1 MHz . Fig.6 describes the
149 load curves measured for three impact tests performed for a drop of 0.9 m
150 and a mass of 0.9 kg in traction. Considering these three tests, the tensile
151 force curves are very similar. Finally the maximal positive value of forces are
152 identified and compared with a theoretical shock model available in literature.
153

154 *2.2.3. Comparison with Brossard model*

155 We propose to confront our experimental results with the model proposed
156 by Brossard [15]. Within the framework of this model, a soft impact is
157 considered (i.e. where the materials deform elastically during the impact).

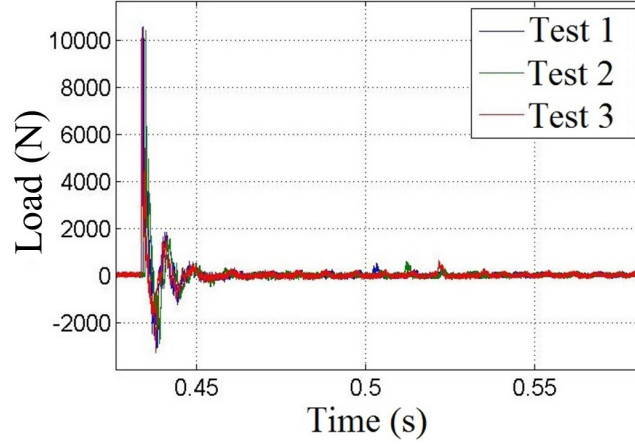


Figure 6: Load curves measured for three impact tests performed for a drop of 0.9 m and a mass of 0.9 kg in traction.

158 This model is used to calculate the value of the maximum load applied when
 159 a mass falls along a bar as can be seen in Fig.7. A spring is added along
 160 the bar in order to simulate a system of a different stiffness connected in
 161 series with the bar. In our impact test machine, this system is the Arcan
 162 fixture. Brossard proposes three steps during the impact test to determine
 163 the maximum load underwent by the one-piece specimen. The first step
 164 considers the movement before the impact where the speeds of each solid is
 165 defined. Then the second step is the impact itself where the conservation of
 166 the momentum is written and resolved in assuming that during the impact
 167 there is no variation in the position. The last step consists in writing and in
 168 solving the equations of motion after the impact. Finally the maximum load
 169 F_{max} is given by the following expression:

$$F_{max} = g(M + \eta m) \quad (1)$$

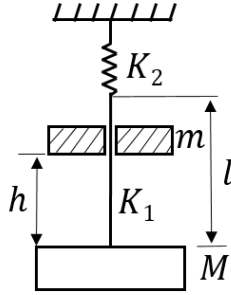


Figure 7: Modeling of the drop weight test in traction proposed in Brossard model [15].

170 with g the gravitational acceleration, M the impact platform mass equal to
 171 250 g , m the impactor mass and η a test rig parameter written with the
 172 following expression:

$$\eta = 1 + \sqrt{1 + 2 \frac{h}{f_s} \frac{1}{1 + \frac{M}{m}}} \quad (2)$$

173 with f_s the static deflection defined by:

$$f_s = \frac{mg}{K} \quad (3)$$

174 with K the stiffness of the system depending on the stiffness of the bar K_1 and
 175 on the global stiffness K_2 of the Arcan fixture equipped with the one-piece
 176 specimen connected in series as described in Fig.7. K can be written:

$$K = \frac{K_1 K_2}{K_1 + K_2} \quad (4)$$

177 where K_1 is defined by:

$$K_1 = \frac{E_b S}{l} = 2.62 \cdot 10^7 \text{ N.m}^{-1} \quad (5)$$

178 where $E_b = 70 \text{ GPa}$ is the Young's modulus of the bar, $S = 0.00049 \text{ m}^2$
 179 the bar section and $l = 1.31 \text{ m}$ the length of the bar. To measure the global
 180 stiffness K_2 of the Arcan fixture equipped with one-piece specimen, we choose

181 to test it in a tensile machine. Fig.8 describes the load-displacement curve
 182 measured in tensile and shear configurations. The linear elastic response is
 183 approximated by the best-fit line. The identified stiffness of the Arcan fixture
 with the one-piece specimen are reported in Table 1.

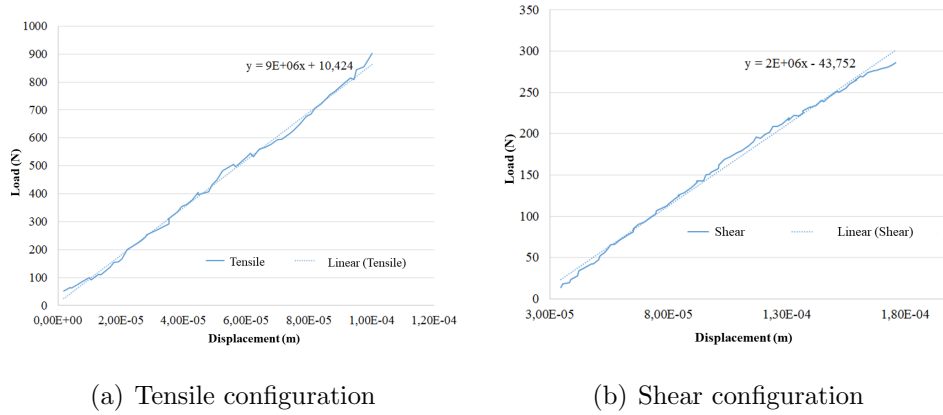


Figure 8: Measurement of the Arcan fixture stiffness equipped with one-piece specimen.

	Tensile	Shear
Rigidity K_2 $N.m^{-1}$	9.10^6	2.10^6

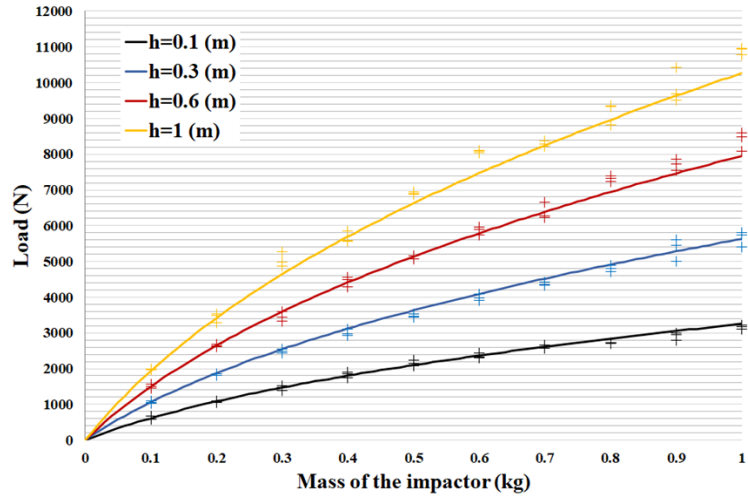
Table 1: Arcan fixture stiffness in tensile and shear configurations.

184

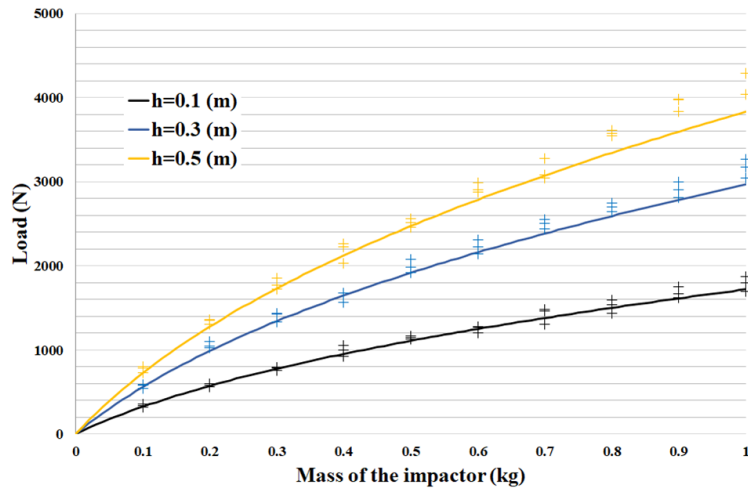
185 Then, the η and f_s parameters can be respectively fully calculated with
 186 Equation (2) and Equation (3). Finally the theoretical maximum load seen
 187 by the one-piece specimen as a function of the drop height and mass can be
 188 calculated with Equation (1). Fig.9 describes values of the maximal load ob-
 189 tained during an impact as a function of the drop height and impactor mass.
 190 The theoretical value obtained with Brossard model (lines) are confronted
 191 with the experimental results (markers) in tensile and shear configuration.

192 The load has the same evolution in traction (Figure 9(a)) and in shearing
193 (Figure 9(b)), it increases at the same time as the mass of the impactor and
194 the drop height. For the same impact conditions (mass, height), the maxi-
195 mum load measured is greater in traction than in shearing. The theoretical
196 load proposed by Brossard [15] is a good approximation of the experimental
197 values measured. The variation coefficient range between the mean experi-
198 mental forces and the theoretical force is between 2 % and 6 % for traction
199 and between 1 % and 9 % for shear. The maximal deviation observed on a
200 measured value is 25 % and the minimal is 3 %. It seems that the deviation
201 increases with the drop height and the mass of the impactor. However, the
202 value of the coefficient of variation remains globally stable over all the exper-
203 imental tests. The rigidity of the Arcan system has been taken into account,
204 but the intermediate elements load sensor and ball joint have been neglected
205 in order to avoid damaging them. Moreover, the sensor used is a strain gauge
206 type. Results could have been better using a piezoelectric sensor. These sen-
207 sors are more accurate for measuring signals with dynamic loading. Both
208 remarks can partially explain the discrepancy observed between theoretical
209 and experimental values.

210 This comparison allows us to validate the dynamic behaviour and to un-
211 derstand the physics of the developed impact test rig in a simplified case (i.e.
212 without the presence of a non linear adhesive in the K_2 spring behaviour).
213 The test rig design is validated. The static and impact properties measure-
214 ments of selected adhesives can be launched.



(a) Traction



(b) Shearing

Figure 9: Maximal load obtained during an impact as a function of the drop height and the impactor mass. Confrontation between the theoretical values of the Brossard model (lines) and experimental results (markers) in tensile and shear configuration.

215 **3. Adhesively-bonded specimens**

216 *3.1. Adhesives*

217 Three different adhesives are tested. We have already studied these ad-
218 hesives to characterize their failure initiation in mode I using the Flexible
219 Initiation Test [9]:

- 220 • The Araldite® AV138M-1/ Hardener HV998 is a brittle epoxy adhe-
221 sive with a thickness of 0.1 *mm*. It is a two-component adhesive with
222 an epoxy resin and a hardener. Its polymerization takes place in 24
223 hours at 23° C.

- 224 • The Permabond 910 is a brittle cyanoacrylate adhesive with a thickness
225 of 0.01 *mm*. As a methyle based adhesive, it has a fast setting at room
226 temperature through the application of an uniform pressure on the
227 bonded assembly. We wait 24-hour at room temperature to leave the
228 adhesive to fully cure before releasing the applied pressure in order to
229 ensure total polymerization.

- 230 • The Scotch-Weld™ 3M 2216 B/A is a flexible epoxy adhesive with a
231 thickness of 0.1 *mm*. It is also a two-component adhesive made of an
232 epoxy resin and an aliphatic diamine hardener. After mixing these
233 two components, polymerization takes place in 7 days at 24° C. It is
234 possible to accelerate the process by performing a heat treatment

235 A priori, these adhesives have different mechanical behaviours, ductile versus
236 brittle behaviour, more or less low thickness, different chemical bases. For
237 each adhesive, the shear strength σ_s and the impact strength I_s given by the
238 manufacturer are related in Table 2.

Adhesive	Type	σ_s (MPa)	I_s (kJ.m ⁻²)
Araldite AV138/HV998	Brittle epoxy	14 (ISO4587)	-
Permabond 910	Brittle cyanoacrylate	14 (ISO4587)	3-5 (ASTM D-950)
3M Scotch-Weld 2216 B/A	Flexible epoxy	27 (EN2243-1)	-

Table 2: Adhesive properties: shear strength (σ_s) and impact strength (I_s)

239 *3.2. Sample geometries*

240 The substrates take the form of cylindrical samples, they are machined in
241 Aluminium 2017 whose mechanical properties are reported in table 3. The
242 total height of the aluminium samples includes the height of two half alu-
243 minium samples and the thickness of the adhesive joint as related in Fig.10.
244 The height is set to a constant value equal to 64 mm. The geometry of these
245 samples, in tensile configuration, ensures an axisymmetrical stress field along
the interface.

E (GPa)	σ_y (MPa)	ν
70	210	0,33

Table 3: Material properties of the Aluminum 2017.

246

247 Four conditions are tested, as illustrated in Fig.10, corresponding to four
248 free edge geometries at the interface. First of all, a straight edge (Fig.10(a))
249 with no defects allows to have an homogeneous stress throughout the inter-
250 face. Then, the Chamfered edge (45°) (Fig.10(b)) allows to obtain an infinite
251 stress concentration at the interface. After the rounded edge (Fig.10(c)) al-
252 lows to have an higher stress concentration at the interface than the straight
253 edge. But, in this case the stress is finite and known. And finally, the beaked

254 edge (Fig.10(d)) allows to have a stress close to zero on the adhesive joint
 255 free edge in order to reduce the edge effects as described in experimental
 256 investigations performed by Cognard et al. [14]. The authors have also lead
 257 on a numerical study to explain how the beaked edge can be useful to reduce
 258 measurement dispersion. It is important to note that the bonding surface
 remains the same for each stress concentration.

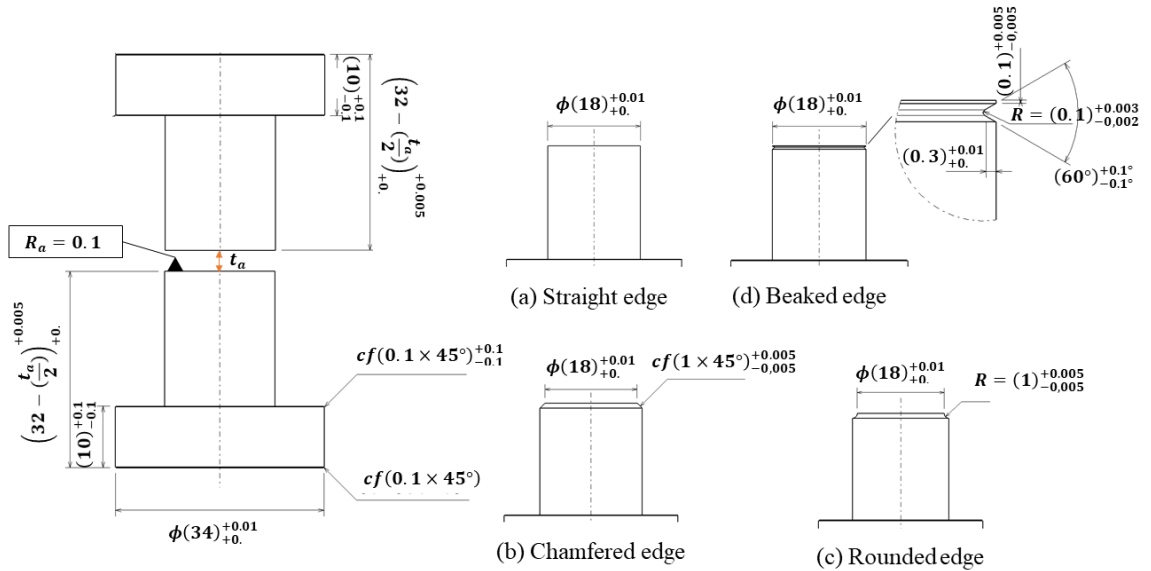


Figure 10: Drawing of aluminium cylinder sample and the half-samples with the four free edge conditions.

259

260 3.3. Surface preparation

261 Before bonding, in order to ensure the effectiveness of the bonding and
 262 to decrease measurement dispersion, we control the bonding area quality in
 263 imposing a surface finish as the last step of sample manufacturing. The

264 roughness specified is chosen with an R_a of $0.1 \mu m$. Then the aluminium
265 surfaces are cleaned with acetone. In the case of the 3M 2216 adhesive, an
266 additional step is added to avoid mixed fracture (adhesive and cohesive as
267 related in Fig. 11). A primer (Primer 3M 3901) is applied to the aluminium
surfaces after acetone cleaning.

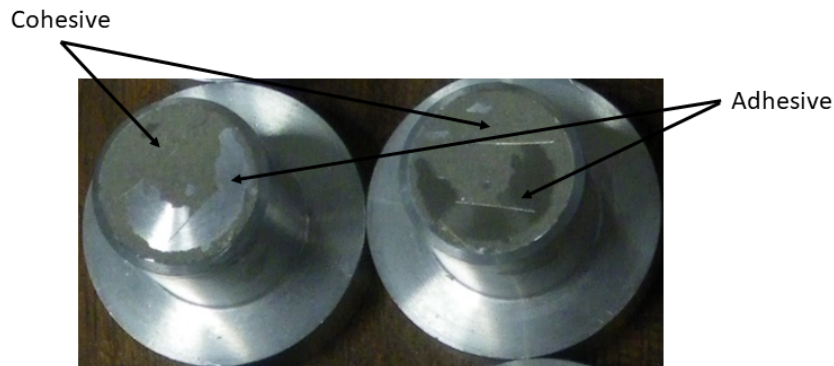


Figure 11: Example of mixed (adhesive and cohesive) fracture of the 3M 2216 interface without using the primer after acetone cleaning.

268

269 3.4. Bonding protocol

270 In these investigations, a bonding protocol is set up in order to mini-
271 mize bonding defects. Thickness recommended by adhesive manufacturers
272 are used. For each test configuration, a minimum of 5 samples are tested
273 to obtain an admissible statistic. In order to position the aluminium sam-
274 ples and the adhesive, a specific set-up is designed as related in Fig.12. It
275 allows to respect the coaxiality between the two aluminium half samples,
276 to stabilise them during the polymerisation process and to be able to bond
277 five adhesively-bonded assemblies at the same time. The operator in charge
278 of the samples process has to respect very high geometrical tolerances (as

279 described in Fig.10) and has to match specimens to each other after mea-
 280 surements in metrology. For Araldite and 3M 2216 adhesives, we bonded five
 281 assemblies at the same time. For cyanoacrylate adhesive, the thickness value
 282 is of the same order of magnitude as the geometric specifications, that's why
 283 we bonded the samples one by one. The first half sample is placed on the
 284 lower base. The adhesive is applied to the bonding surfaces. The second half
 285 sample is placed and flanged in order to be fixed on the upper base. Then,
 286 a guidance system allows the upper base to be positioned on the lower base
 287 and the half samples to be positioned relatively to each other. The upper
 288 base is made in steel in order to increase the weight to press the adhesive
 289 joints with a good pressure distribution along the five samples. Once the
 samples have been bonded, the adhesive joint must be gently cleaned.

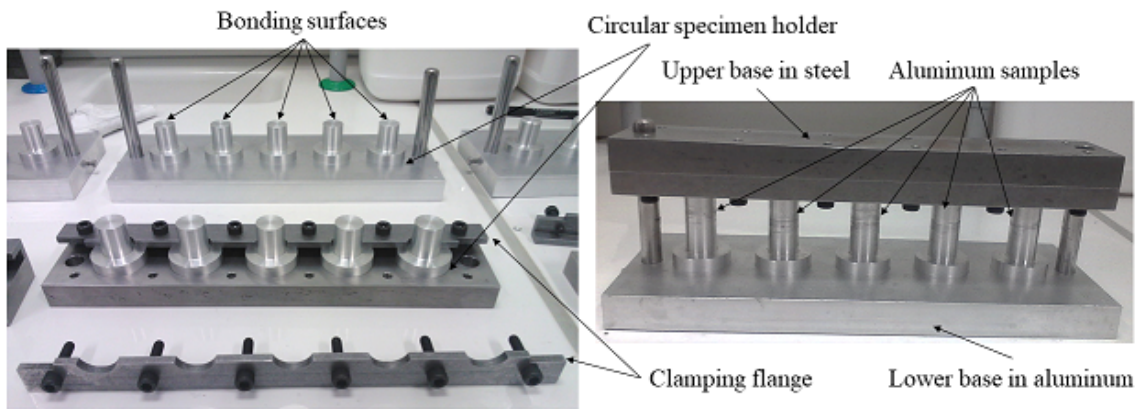


Figure 12: Specific set-up designed to position five adhesively bonded specimens.

290

291 Just after adhesive application, four fluorocarbon calibrated wires are
 292 placed inside the adhesive in order to control the adhesive thickness at 0.1
 293 *mm* as related in Fig.13(a). With the upper part in steel, same weight is used
 294 for each sample to ensure the necessary constant pressure during polymeriza-

295 tion. Except with the Permabond adhesive, for which the recommended joint
 296 thickness is equal to 0.01 mm . Indeed, the cyanoacrylate adhesive polymer-
 297 izes immediately when both bonded surfaces are pressurized, which allows
 298 air to be expelled at the interface and polymerization to be initiated. In all
 299 experimental tests presented in this paper, we keep only samples that have
 exhibited a cohesive failure as related in Fig.13(b).

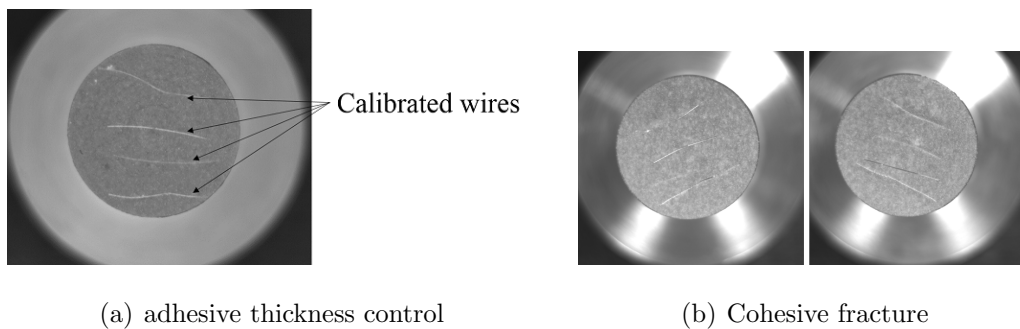


Figure 13: Calibrated wires used to control the adhesive thickness and the cohesive fracture obtained for the adhesive 3M 2216.

300

301 Once the assembly of the sample is performed, it is necessary to wait
 302 for the polymerization of the adhesive. In the case of 3M 2216 and Araldite
 303 adhesives, polymerization is accelerated by heat treatment. A curing at 40°C
 304 for 24 hours for the 3M 2216 adhesive and a curing at 40°C for 16 hours on
 305 the Araldite adhesive are performed. We have chosen this temperature of
 306 40°C because it limits the thermal expansion effects, in order to avoid to
 307 generate high residual stresses in the adhesive joint during polymerization
 308 and cooling.

309 An optic control is performed, with an optical microscope, to check the
 310 alignment between the two substrates especially for cyanoacrylate adhesive.
 311 For other adhesives we controlled the free edge geometry of the adhesive joint

312 and we are able to withdraw samples with a pronounced bulge of adhesive,
313 or a hole in the adhesive joint due to the cleaning procedure. For instance
314 in Fig.14, one of cyanoacrylate samples with a very low thickness (0.01 mm)
315 and in Fig.15, one of 3M 2216 adhesive with a thickness equal to 0.1 mm are
316 presented. Specimens that do not respect the criteria are removed from the
317 experimental set and replaced by new ones. Table 4 sums up the number of
318 each adhesive samples with cohesive fracture used for the static and dynamic
experimental campaigns.

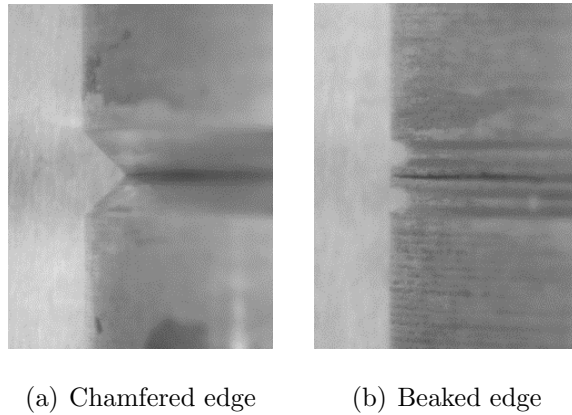
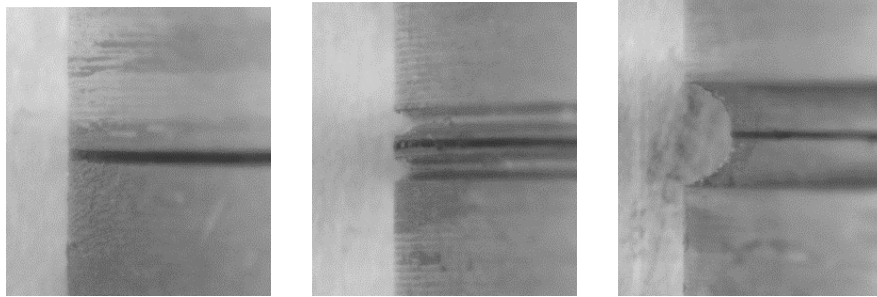


Figure 14: Bonded interface pictures for Cyanoacrylate adhesive specimens made with a microscope for Chamfered (45°) and beaked edges.

319

Loading	Geometries/Adhesive	Araldite		Cyanoacrylate		3M 2216	
		Static	Dynamic	Static	Dynamic	Static	Dynamic
Traction							
	Straight edge	3	45	3	52	3	45
	Beaked edge	3	45	3	57	3	45
	Rounded edge	3	35	3	39	3	55
	Chamfered edge (45°)	3	40	3	37	3	50
Shear							
	Straight edge	3	30	3	45	3	25
	Beaked edge	3	30	3	46	3	25
	Rounded edge	3	30	3	27	3	30
	Chamfered edge (45°)	3	25	3	21	3	30
Total	981 samples	24	280	24	324	24	305

Table 4: Number of samples with cohesive fracture used for the experimental campaign.



(a) Straight edge

(b) Beaked edge

(c) Rounded edge

Figure 15: Bonded interface pictures for 3M 2216 adhesive specimens made with a microscope for straight, beaked and rounded edges.

320 4. Static tests

321 In this section, the mechanical behaviour of the three adhesives is investi-
322 gated in static in mode I and mode II. The average fracture load is measured
323 for the four free edge conditions and a point stress criterion is proposed to
324 determine the critical stress of the adhesives in traction and shearing.

325 The average fracture load is calculated with a variation coefficient CV
326 (Equation 6) which allows to quantify the data dispersion. This coefficient is
327 calculated with the average of the fracture load \bar{F} and the standard deviation
328 s (Equation 7).

$$CV = \frac{s}{\bar{F}} \quad (6)$$

$$s = \sqrt{\frac{\sum_n (F - \bar{F})^2}{n}} \quad (7)$$

329 4.1. Results

330 Fig.16 and Fig.17 describe respectively the static test results in mode I
331 and in mode II in providing the average fracture load measured and the stan-
332 dard deviation for the four edge conditions and the three adhesives. Table 5
333 sums up the fracture load values and the variation coefficient CV allowing to
334 quantify the dispersion of data.

335 The 3M 2216 adhesive has the lowest dispersion across all experimental
336 results. For the majority of configurations its coefficient of variation remains
337 below 10%. It also appears to be non sensitive to the four different stress
338 concentrations tested. These results were expected for an adhesive with a

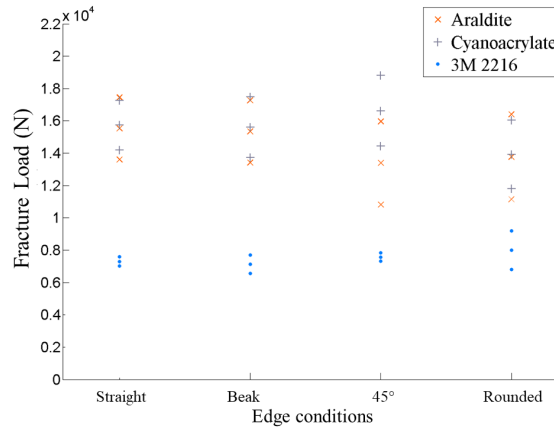


Figure 16: Results of traction static tests (mode I) for the three adhesives: average values and standard deviations of the fracture load.

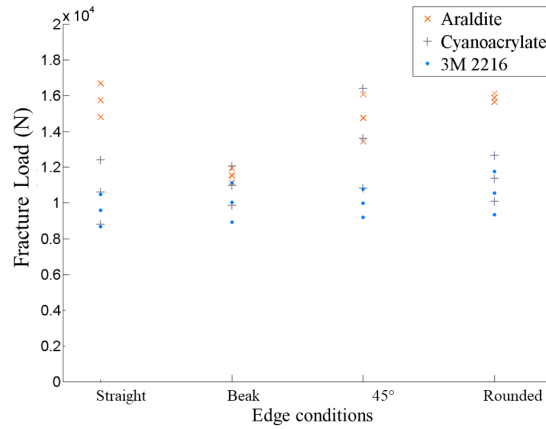


Figure 17: Results of shear static tests (mode II) for the three adhesives: average values and standard deviations of the fracture load.

339 ductile behaviour. However, its mechanical performances in static remain
 340 below the two other adhesives tested.

341 The Araldite adhesive has a higher dispersion in mode I (greater than
 342 10%) but keeps a low dispersion in mode II. In traction, for straight edge
 343 and beak edge results are very close and the dispersion is around 10%. On the

Adhesives	Edge type	\bar{F}_{ModeI} (N)	CV_{ModeI} (%)	\bar{F}_{ModeII} (N)	CV_{ModeII} (%)
Araldite	Straight	15520	11.1	15750	5.3
	Beaked	15340	11.7	11540	3.5
	Chamfered (45°)	13390	17.3	14760	8
	Rounded	13770	17.1	15890	1.3
Cyanoacrylate	Straight	15730	8.8	10610	15.2
	Beaked	15590	10.8	10970	9
	Chamfered (45°)	16610	11.7	13620	18.3
	Rounded	13920	13.6	11370	10.1
3M 2216	Straight	7302	3.5	9586	8.6
	Beaked	7129	7.2	10030	10
	Chamfered (45°)	7576	3	9984	7.3
	Rounded	7989	13.4	10560	10.2

Table 5: Summary of the fracture load values with the corresponding coefficients of variation for the four type edges and the three adhesives.

344 other hand the adhesive is sensitive to higher stress concentration (45° edge
345 and rounded edge). In shearing, dispersion remains very low, this adhesive
346 works better in shear configuration. It also seems that the edge effect is
347 smaller in mode II than in mode I. As expected, the dispersion obtained
348 with this brittle adhesive is higher than with the ductile adhesive. And in
349 shear loading, its thickness allows it to better tolerate stress concentrations.

350 The Cyanoacrylate adhesive has in mode I and mode II a very high dis-
351 persion, indeed, its coefficient of variation is mostly higher than 10%. This
352 result is expected because the adhesive has a brittle behavior and a very low
353 thickness (0.01 mm) which makes it very sensitive to bonding defects. It can
354 be noted that its small thickness allows it to be less sensitive to the most
355 severe stress concentration (45° edge).

356 *4.2. Adhesive's critical stresses*

357 In order to compare the static mechanical strength of the three adhesives,
358 the Point Stress Criterion (PSC) [16] is used. It allows to define the critical
359 stress σ_c (i.e. the stress necessary to initiate a crack). This criterion is
360 applied at a certain distance from the singularity (here the singularity is the
361 free edge of the adhesive joint), this distance being the characteristic length,
362 a_c . The criterion can be written:

$$\sigma(a_c) > \sigma_c \quad (8)$$

363 If the stress σ at the distance a_c from the edge is greater than the critical
364 stress σ_c then the crack will initiate. This length depends on the geometry
365 of the assembly and the thickness of the adhesive joint.

366 We begin by the mode I. The results on specimens with the straight edge
367 (homogeneous stress concentration) and the chamfered (45°) edge (high stress
368 concentration) are used. Both tests are modeled by a finite elements method
369 using the Abaqus commercial software. The model includes the two Arcan
370 half disks and the aluminium specimen which are considered to be elastic.
371 The glue is not modelled (thin adhesives). The lower part of the fixture is
372 embedded and the average fracture load previously measured is imposed on
373 the upper part of the fixture. Before a study of the influence of the mesh
374 along the interface is carried out. The size of 0.1 mm is chosen for all the
375 following simulations (Fig.18).

376 Stress distribution along the interface for both stress concentrations are
377 plotted. The point of curves intersection is used to determine the charac-
378 teristic length and the critical stress. Fig.19 describes the stress distribution

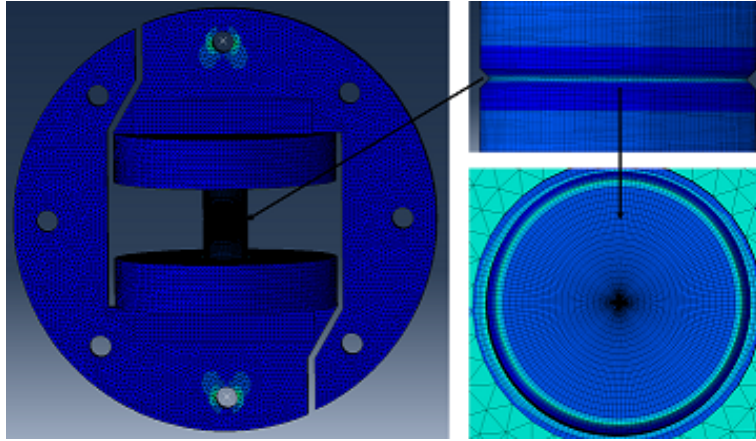


Figure 18: Normal stress distribution for tensile loading of Araldite adhesive with a mesh size of 0.1 mm at the interface.

379 normal to the interface for the straight edge and the chamfered (45°) edge for
 380 the Araldite adhesive. The intersection point gives the values of $a_{c,I} = 0.47$
 381 mm and $\sigma_{c,I} = 62.24 \text{ MPa}$.

382 Then, we investigate the mode II. The results on specimens with the
 383 straight edge and the rounded edge are used. Fig.20 describes the shear
 384 stress distribution at the interface for each stress concentration. Nodes of
 385 the mesh colored in red correspond to the nodes used to plot the shear
 386 stress distribution at the interface. Fig.21 describes the stress distribution
 387 for the araldite adhesive in mode II. The intersection point gives the values
 388 of $a_{c,II} = 2.85 \text{ mm}$ et $\sigma_{c,II} = 47.5 \text{ MPa}$.

389 In the same way, the point stress criterion is applied for the 3M 2216
 390 and cyanoacrylate adhesives in mode I and mode II. Results are summed up
 391 in Table 6.

392 Following the experimental campaign and the application of the stress
 393 point criteria, it became clear that the ductile adhesive (3M 2216) has a

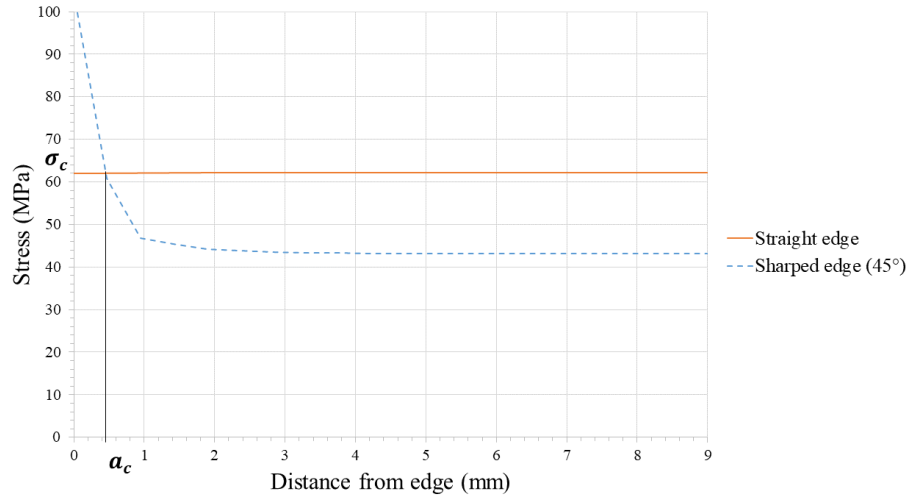


Figure 19: Critical stress identification with normal stress distributions at the interface for tensile loading of Araldite adhesive.

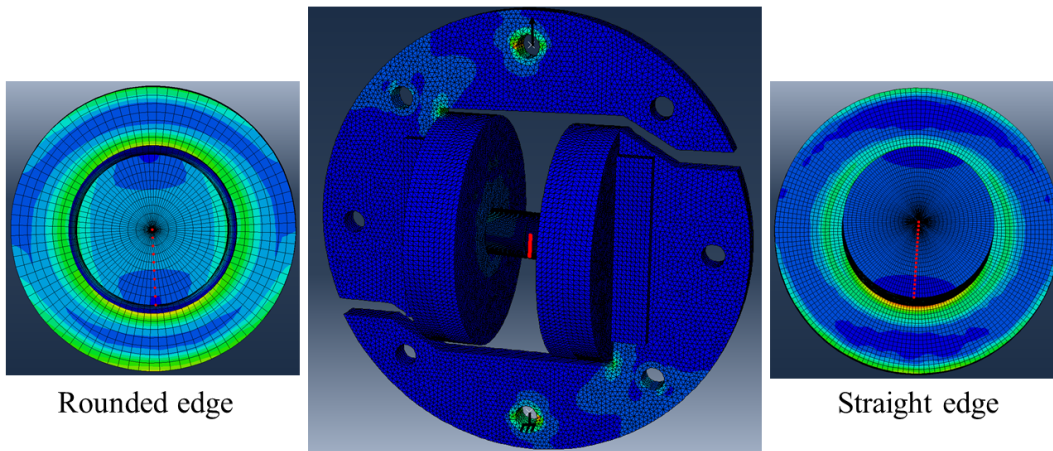


Figure 20: Tangential stress distribution for shear loading of Araldite adhesive at the interface for the rounded edge and the straight edge.

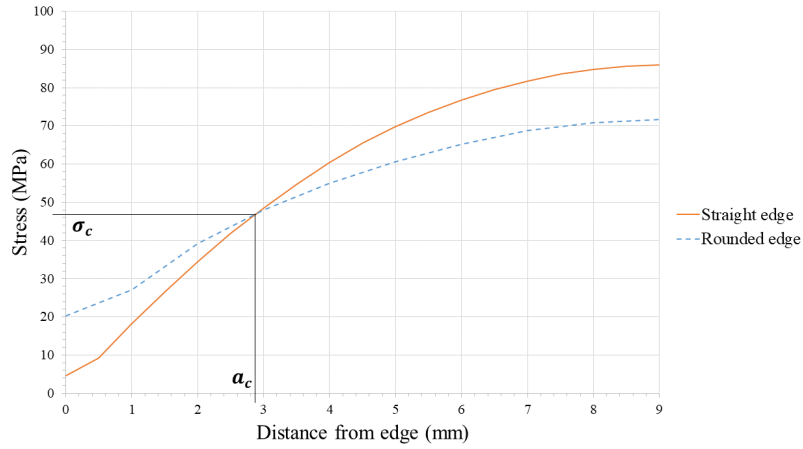


Figure 21: Critical stress identification with tangential stress distributions at the interface for shear loading of Araldite adhesive.

Adhesive	$a_{c,I}$ (mm)	$\sigma_{c,I}$ (MPa)	$a_{c,II}$ (mm)	$\sigma_{c,II}$ (MPa)
Araldite	0.47	62.2	2.85	47.5
Cyanoacrylate	0.78	62	3.4	35.8
3M 2216	0.82	28.7	3.85	36

Table 6: Adhesive's critical stresses identified with the point stress criterion.

394 lower static mechanical strength than the two brittle adhesives. Its critical
395 stress is even half as small in traction. Its mechanical strength is better
396 in shearing than in traction. But experimental results obtained with this
397 adhesive are the least dispersed.

398 For the two brittle adhesives, the mechanical strength is almost the same
399 in mode I. In shear, the Araldite adhesive has a better mechanical strength
400 than the Cyanoacrylate adhesive. They both have better mechanical strength
401 in traction than in shearing. However, these adhesives have a high dispersion
402 which may reduce confidence in their nominal value.

403 After static tests, brittle adhesives seem to have better mechanical prop-
404 erties. It is now interesting in the following section to confront the impact
405 strength of these adhesives.

406 **5. Impact tests**

407 *5.1. Experimental procedure*

408 Impact tests on the three adhesives are performed on the test machine
409 presented in section 3.2. Impact strength of the adhesives are tested, thanks
410 to the integration of the Arcan fixture, in traction (Fig.22(a)) and in shearing
411 (Fig.22(b)) configurations.

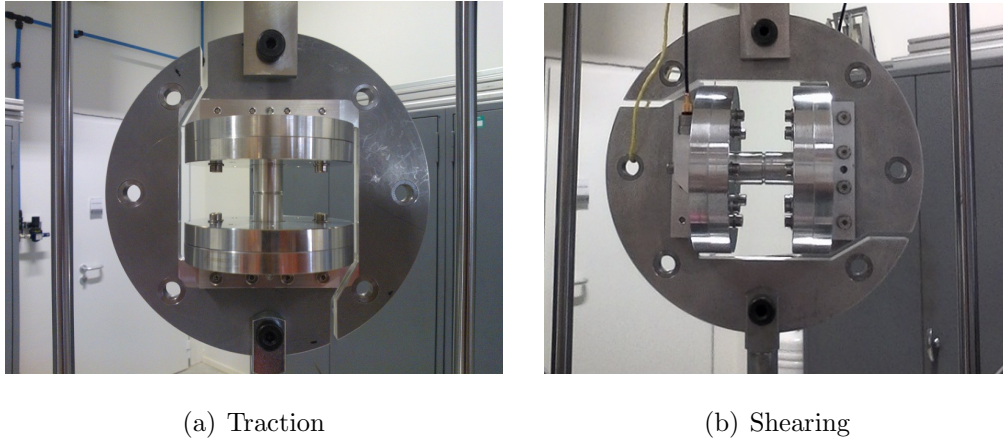


Figure 22: Type of solicitation

412 The height of fall of the impactor h is fixed to 1 m to control the impact
413 speed v as described in Equation 9. Only the mass of the impactor m_i is
414 modified to impose an energy on the specimen. The energy E_i is defined by
415 the expression of Equation 10:

$$v = \sqrt{2gh} = 4.43m.s^{-1} \quad (9)$$

$$E_i = m_i gh \quad (10)$$

416 For each energy level a minimum of five tests are performed. Then the
 417 failure ratio δ_f is calculated, as described in Equation 11, with the ratio of
 418 the number of specimen broken N_b and the total number of specimen tested
 419 N_t :

$$\delta_f = \frac{N_b}{N_t} \quad (11)$$

420 The evolution of the failure ratio δ_f as a function of the impact energy
 421 E_i can be displayed on a graph as described in Figure 23. On this curve, we
 422 choose to define two characteristic energies: an energy E_0 which corresponds
 423 to the limit of the adhesive's impact strength ($\delta = 0\%$) (i.e. below this energy
 424 the integrity of the specimen is guaranteed); and an impact energy E_{100} which
 425 corresponds to the systematical rupture of the adhesive ($\delta = 100\%$).

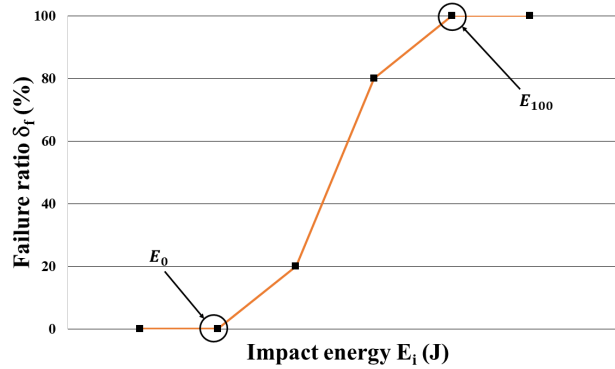


Figure 23: Failure ratio δ_f in function of the impact energy E_i with characteristic energies E_0 and E_{100}

426 The drop tower is approximate but interesting to discriminate selected
 427 adhesives. The notion of high strain rate tests and impact tests are two dif-
 428 ferent physics, one concerns a linear strain imposed at high speed and the

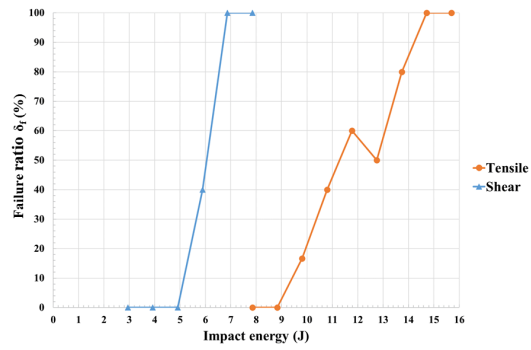
429 other a strain wave (an instantaneous Dirac). Contrary to Vales et al. [12] we
 430 don't try to use the second one to bring us back to the first ones. We choose
 431 here to compare impact failure energies for three adhesives under the same
 432 conditions. If we wanted to be quantitative, we would have chosen a Hopkin-
 433 son type test more suited to controlling the wave and its path as described in
 434 P.Bailly book [17]. We propose to define a relative impact strength I_{S0} , not
 435 describing the intrinsic properties of the adhesive, but allowing to compare
 436 them under the same conditions. I_{S0} is calculated in using the character-
 437 istic energies E_0 and the surface S of the adhesive joint with the following
 438 expression:

$$I_{S0} = \frac{E_0}{S} \quad (12)$$

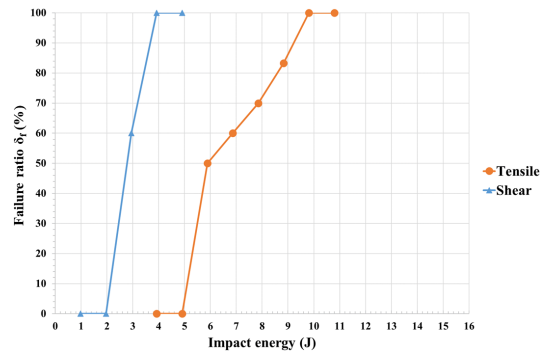
439 5.2. Results

440 5.2.1. Araldite

441 Fig.24 describes impact test results obtained in traction and shearing
 442 configurations for the Araldite adhesive. In these experimental results, we
 443 observe, as expected, three distinct phases : the first one is an impact energy
 444 zone where samples do not break until the impact energy called E_0 ; then a
 445 second phase where the failure ratio evolves quasi linearly between $\delta_f = 0\%$
 446 and $\delta_f = 100\%$; and a last phase beginning at E_{100} where samples break
 447 systematically. The degradation of the impact strength is gradual and linear
 448 for the araldite adhesive. We observe also that the araldite adhesive has a
 449 better impact strength in traction than in shearing in case of straight edge
 450 and 45° edge. Moreover, characteristic energies for the same type of loading
 451 are higher in the case without stress concentration.



(a) Straight edge



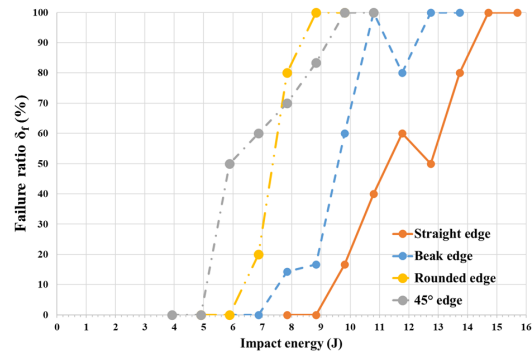
(b) Chamfered edge (45°)

Figure 24: Failure ratio δ_f in function of the impact energy of tensile and shear impact tests for the Araldite adhesive. For the straight edge (a) and the chamfered edge (b).

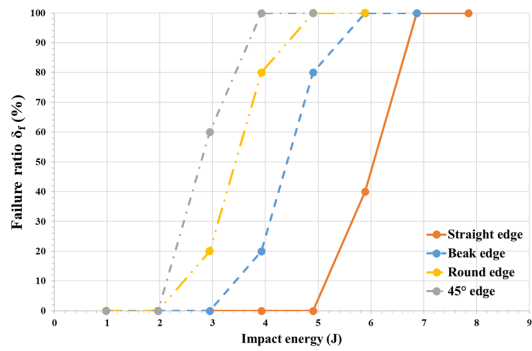
452 Fig.25 describes the impact test results in traction and in shearing of
453 Araldite adhesive for the four different edge geometries. For each stress
454 concentration, the failure ratio as a function of the impact energy evolves
455 in the same way. The transition zone seems more linear in shearing than in
456 traction. A change in impact strength behaviour is observed according to
457 the different edge geometries. Globally, traction and shearing characteristic
458 energies E_0 and E_{100} decrease as the severity of the stress concentration
459 increase.

460 In traction energy E_0 is divided by two between the condition with no
461 stress concentration and the infinite stress concentration. The Araldite im-
462 pact strength is very sensitive to the stress concentration as already observed
463 in static tests. But for a brittle adhesive the value of relative impact strength
464 I_{S0} measured is very high for no stress concentration condition.

465 Table 7 sums up characteristic impact energies and relative impact strengths
466 I_{S0} of araldite adhesive measured for each stress concentration. On the series
467 of tensile tests, the fracture facies showed cohesive fractures, which validates
468 the impact strength measured as described in Fig.26.



(a) Traction



(b) Shearing

Figure 25: Failure ratio δ_f in function of the impact energy for the Araldite adhesive. Confrontation between the different edge geometries (or stress concentrations). In tensile configuration (a) and shear configuration (b).



Figure 26: Fracture facies observed on Araldite joint after an impact test in traction.

Araldite		E_0 (J)	E_{100} (J)	I_{50} (kJ.m ⁻²)
Traction	Straight edge	8.83	14.71	34.7
	Beaked edge	6.87	10.79	27
	Rounded edge	5.89	8.83	23.1
	Chamfered edge (45°)	4.91	9.81	19.3
Shearing	Straight edge	4.91	6.87	19.3
	Beaked edge	2.94	5.89	11.6
	Rounded edge	1.96	4.91	7.7
	Chamfered edge (45°)	1.96	3.92	7.7

Table 7: Impact energies measured and relative impact strengths calculated for the Araldite adhesive.

469 *5.2.2. Cyanoacrylate*

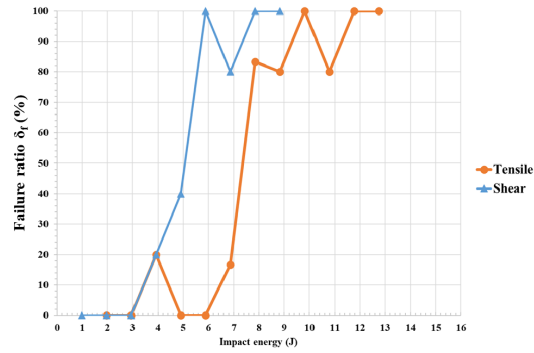
470 Fig.27 describes impact test results obtained in traction and in shearing
471 configurations for the Cyanoacrylate adhesive. As previously, we observe also
472 three distinct phases. The evolution of the failure ratio makes it possible to
473 identify energies E_0 and E_{100} . The degradation of the impact strength is also
474 gradual and linear, but the transition phase here seems more abrupt. We
475 observe also that the Cyanoacrylate adhesive has a better impact strength
476 in traction than in shearing in case of straight edge and 45° edge. On the
477 other hand, Cyanoacrylate seems less sensitive than the araldite face to the
478 different edge conditions.

479 But this behaviour may be due to the bonding process, which is more
480 difficult to control. The very low thickness of the adhesive joint (0.01 mm)
481 which made it very difficult to observe fracture facies (Figure 28). Specimens
482 with adhesive and not cohesive fracture could not be removed. Indeed, during
483 the tests, some specimens which seemed to describe a lack of adhesive on
484 fracture facies has a very good strength while others where adhesive was
485 visible on the complete surface after fracture broke at low energies.

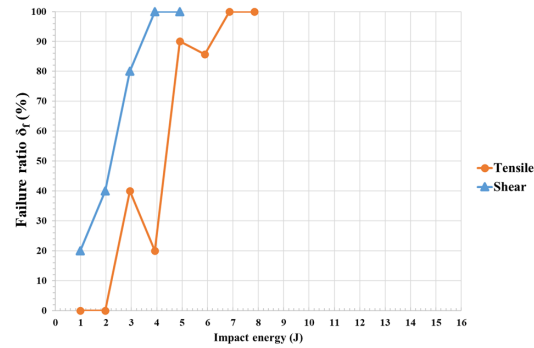
486 Fig.29 describes the impact test results in traction and shearing of Cyanoacry-
487 late adhesive for the four different edge geometries. For each stress concentra-
488 tion, the failure ratio as a function of the impact energy evolves in the same
489 way. A change in impact strength behaviour is observed according to the
490 different edge geometries. The transition zone seems less chaotic in shearing
491 than in traction. In traction, we do not observe a clear difference between
492 the different stress concentrations. For both loading, the beaked edge has
493 the best impact strength. Contrary to static case, the cyanoacrylate seems

494 very sensitive to most severe stress concentrations and the beak edge gives
 495 the best results.

496 Table 8 sums up the characteristic impact energies and the relative impact
 497 strengths I_{S0} of Cyanoacrylate adhesive measured for each stress concentra-
 498 tion.



(a) Straight edge

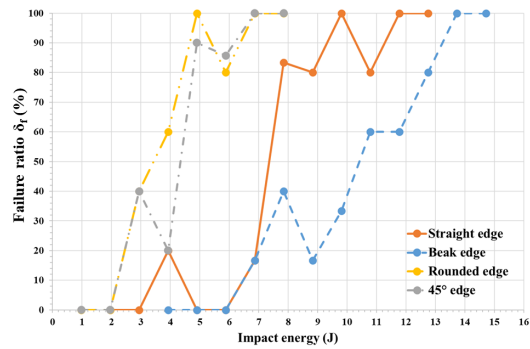


(b) Chamfered edge (45°)

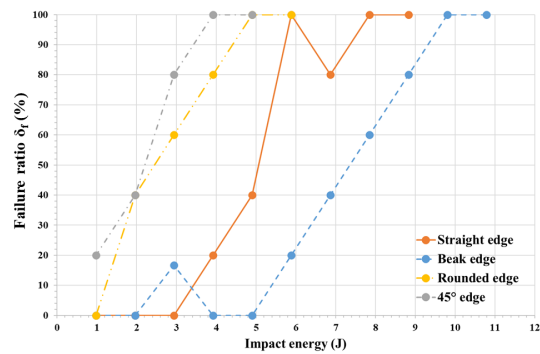
Figure 27: Failure ratio in function of the impact energy measured with tensile and shear impact tests for the Cyanoacrylate adhesive.



Figure 28: Fracture facies observed on Cyanoacrylate joint after an impact test in traction.



(a) Traction



(b) Shearing

Figure 29: Failure ratio δ_f in function of the impact energy for the Cyanoacrylate adhesive. Confrontation between the different edge geometries (or stress concentrations). In tensile configuration (a) and shear configuration (b).

Cyanoacrylate		E_0 (J)	E_{100} (J)	I_{S0} ($kJ.m^{-2}$)
Traction	Straight edge	2.94	11.77	11.6
	Beaked edge	5.89	13.73	23.1
	Rounded edge	1.96	4.91	7.7
	Chamfered edge (45°)	1.96	6.87	7.7
Shearing	Straight edge	2.94	5.89	11.6
	Beaked edge	1.96	9.81	7.7
	Rounded edge	0.98	4.91	3.9
	Chamfered edge (45°)	-	3.92	-

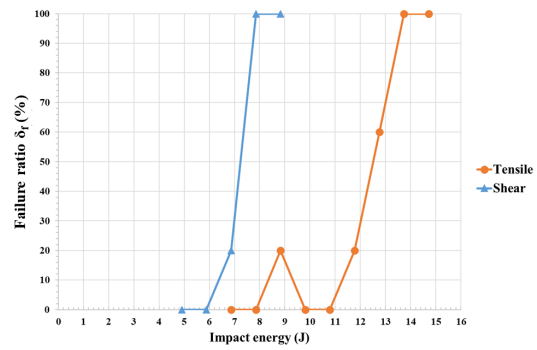
Table 8: Impact energies measured and relative impact strengths calculated for the Cyanoacrylate adhesive.

499 5.2.3. 3M 2216

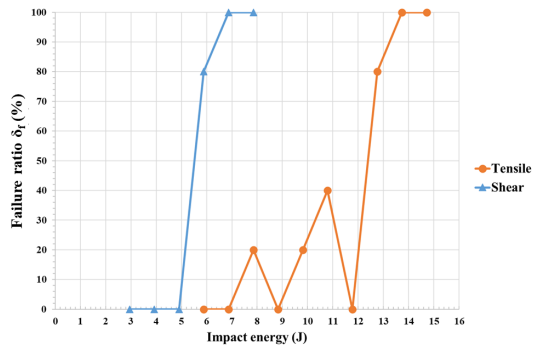
500 Fig.30 describes impact test results obtained in tensile and shearing con-
501 figuration for the 3M 2216 adhesive. As before, the evolution of the failure
502 ratio makes it possible to identify energies E_0 and E_{100} . The degradation
503 of the impact strength is gradual and linear for the 3M 2216 adhesive. 3M
504 2216 has also a better impact strength in traction than in shearing in case
505 of straight edge and 45° edge. Moreover, characteristic energies for the same
506 type of loading are higher in the case without stress concentration. On the
507 other hand, the edge geometries used at the interface seem to have any in-
508 fluence on impact strength results.

509 Fig.31 describes the impact test results in traction and in shearing of 3M
510 2216 adhesive for the four different edge geometries. In traction, we don't
511 observe any difference between the different stress concentrations. Indeed,
512 the characteristic energies E_{100} are identical for the four stress concentrations,
513 only energy E_0 varies. But in this case, the evolution of the failure ratio
514 between characteristic energies E_0 and E_{100} is not linear. This transition
515 zone is chaotic and presents dispersion for 3M 2216 adhesive. In shearing,
516 we don't observe any difference between the different stress concentrations
517 but we find again the linear transition. Contrary to static results, it appears
518 to be sensitive to the different stress concentrations tested.

519 Table 9 sums up the characteristic impact energies and the relative impact
520 strengths I_{S0} of 3M 2216 adhesive measured for each stress concentration.

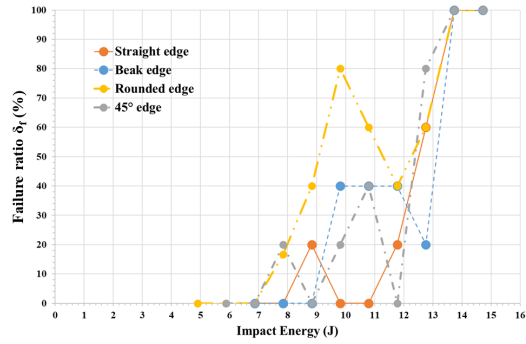


(a) Straight edge

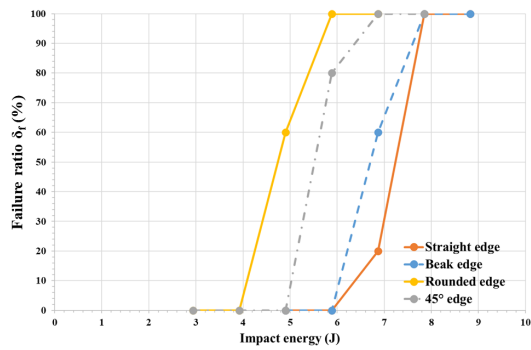


(b) Chamfered edge (45°)

Figure 30: Failure ratio in function of the impact energy measured with tensile and shear impact tests for the 3M 2216 adhesive.



(a) Traction



(b) Shearing

Figure 31: Failure ratio δ_f in function of the impact energy for the 3M 2216 adhesive. Confrontation between the different edge geometries (or stress concentrations). In tensile configuration (a) and shear configuration (b).

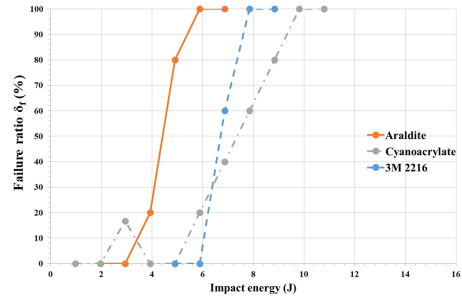
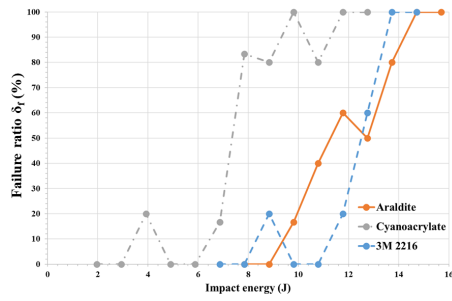
3M 2216		E_0 (J)	E_{100} (J)	I_{S0} ($kJ.m^{-2}$)
Traction	Straight edge	7.85	13.73	30.8
	Beaked edge	8.83	13.73	34.7
	Rounded edge	6.87	13.73	27
	Chamfered edge (45°)	6.87	13.73	27
Shearing	Straight edge	5.89	7.85	23.1
	Beaked edge	5.89	7.85	23.1
	Rounded edge	3.92	5.89	15.4
	Chamfered edge (45°)	4.91	6.87	19.3

Table 9: Impact energies measured and relative impact strengths calculated for the 3M 2216 adhesive.

521 *5.3. Confrontation between adhesives*

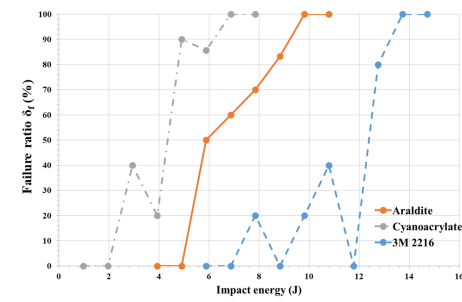
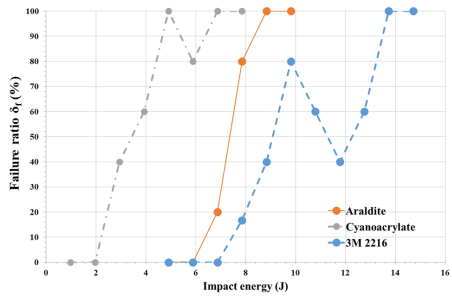
522 Fig.32 et Fig.33 describe the comparison of the three tested adhesives
523 according to the different free edge conditions in traction and in shearing,
524 respectively. In traction, Cyanoacrylate always seems to perform less well
525 than the other two adhesives. Araldite and 3M 2216 seem comparable for
526 the straight edge and the beaked edge. For more severe stress concentrations
527 araldite is much less performing. On the other hand, in shearing the adhesives
528 are better grouped together, but the two brittle adhesives seem to perform
529 in the same way. It seems that thickness does not play a fundamental role
530 in impact strength. Whereas in static tests, it allows to better accommodate
531 the effect of the different stress concentrations.

532 Finally, the flexible adhesive (3M 2216) has the best impact strength. The
533 free edge geometry at the interface has a little influence on its strength. Con-
534 trary to brittle adhesives, which exhibit different impact strength in function
535 of free edge conditions. Cyanoacrylate (very low thickness of 0.01 *mm*) has
536 a better strength with beaked edge and the Araldite has a better strength
537 with straight edge.



(a) Straight edge

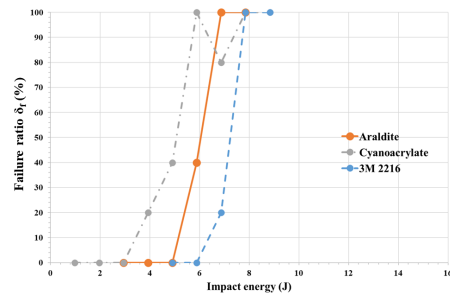
(b) Beaked edge



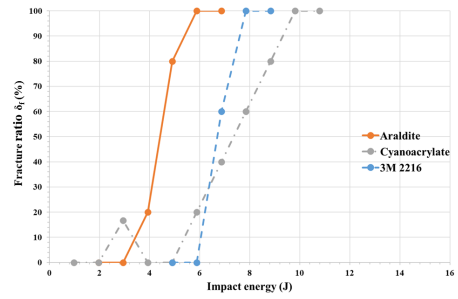
(c) Rounded edge

(d) Chamfered edge (45°)

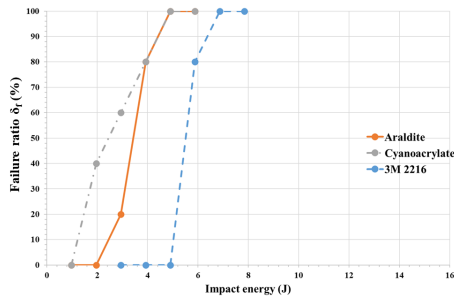
Figure 32: Comparison of the behaviour of adhesives under tensile impact loading for different free edge geometries.



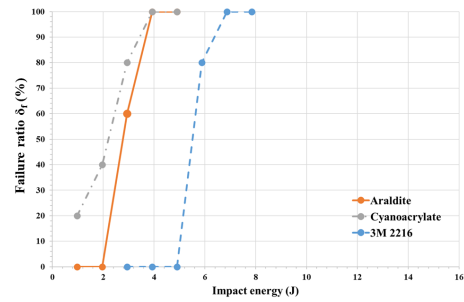
(a) Straight edge



(b) Beaked edge



(c) Rounded edge



(d) Chamfered edge (45°)

Figure 33: Comparison of the behaviour of adhesives under shear impact loading for different free edge geometries.

538 **6. Conclusions**

539 The paper presents the development of an experimental method to char-
540 acterize and to compare the dynamic behaviour of adhesives by coupling a
541 drop tower and a modified Arcan device. The test rig is used to create a soft
542 impact characterised by the transformation of kinetic energy into a dynamic
543 tensile loading thanks to the conservation of the quantity of movement and
544 the minimisation of unwanted phenomena (friction, wave reflection, etc.).

545 A first confrontation with an analytical model made it possible to validate
546 the behaviour of the test bench and to quantify the deviations of the impact
547 system. The introduction of the modified Arcan set-up allows us to carry
548 out our tests in tensile and shear configurations on specimens with different
549 free edge geometries.

550 Then, static tests results were used to determine the critical tensile and
551 shear stresses ($\sigma_{c,I}$ & $\sigma_{c,II}$) of each adhesive using a stress point criterion.
552 These values are plotted on the vertical axis of the graphs described in Fig.34.

553 The second experimental campaign consisted of impacting our adhesive
554 joints in traction and shear for 4 different edge geometries (straight edge,
555 sharp edge, beak edge, rounded edge). These impact tests were used to
556 define the characteristic energies (E_0 and E_{100}) specific to each adhesive.
557 The relative impact strength values I_{S0} are calculated for each adhesive and
558 each edge geometry. Results are plotted on the horizontal axis of the graphs
559 shown in Fig.34.

560 Static tests have demonstrated that the influence of the edge geometry
561 is very small for the ductile adhesive (3M 2216) contrary to the two brittle
562 adhesives (Cyanoacrylate & Araldite). In static, the ductile adhesive showed

563 a lower mechanical strength with little scattered results in comparison to the
 564 two brittle adhesives. This result is more true in traction than in shear.

565 Impact tests have revealed that the geometry of the interface's free edge
 566 has an influence on the impact strength of brittle and ductile adhesives. The
 567 ductile adhesive this time has a slightly higher mechanical strength (20%)
 568 than the brittle adhesives tested.

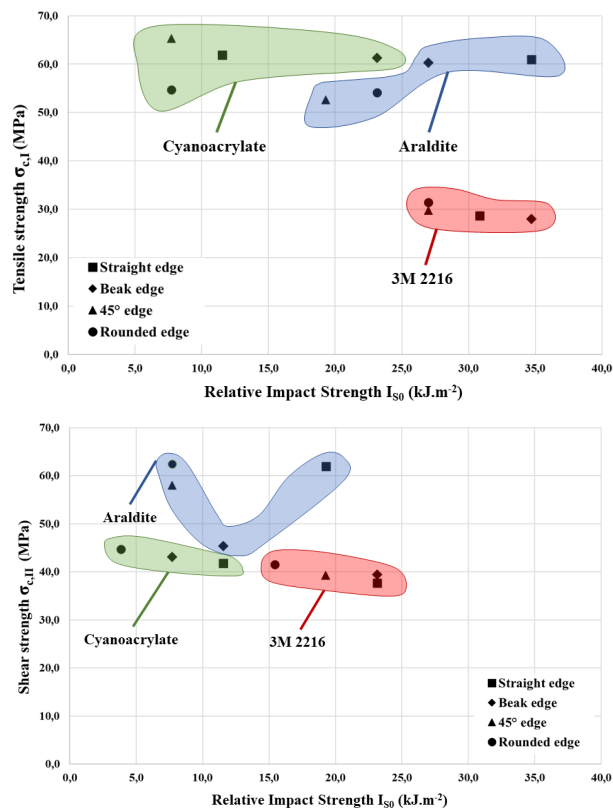


Figure 34: Static ($\sigma_{c,I}$ & $\sigma_{c,II}$) and dynamic (I_{S0}) mechanical properties of the three adhesives in tensile and shear.

569 The two graphs in Fig.34, one for tensile and the other for shear, illustrate
 570 the static and dynamic mechanical properties of the three adhesives. The

571 3M 2216 adhesive is considerably lower in static performance for a relatively
572 low benefit in dynamic performance. If, for example, the Araldite adhesive
573 is chosen and compared with 3M 2216, assuming good control of the edge
574 conditions: the static tensile strength is doubled, the static shear strength is
575 multiplied by 1.5 and the dynamic shear strength is reduced by only 20%.

576 This experimental program has demonstrated that the static and dynamic
577 behaviours of adhesives are different. The best compromise between static
578 and dynamic behaviours is not necessarily easy to find. In our case, the
579 adhesive have to be used to integrate direct bonded optical spatial systems
580 that are subjected to high dynamic loads in the launcher. Our choice here is
581 based on Araldite, with a fine control of the edge conditions and an increase
582 in the bonding surface.

583 Interesting prospects could be investigated: the first concerns the vali-
584 dation of these results on a complex bonded structure undergoing dynamic
585 loading (vibrating pot). The second concerns the effect of the viscoelastic
586 properties of the adhesive on its strength under dynamic loading, which for
587 the moment does not seem very clear to us. And the third, more funda-
588 mental, concerns the discussion of a dynamic experimental criterion that
589 can be used to validate our bonding within a finite element simulation of
590 the dynamic loading of the bonded structure, equivalent to the static failure
591 criterion (stress point, average stress,...).

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