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A methodology for the experimental characterization of energy release rate-controlled creep crack growth under mode I loading

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ABSTRACT

Understanding the performance of a bonded joint over time is essential for the design of durable bonded joints and maintenance protocols. Viscoelastic creep crack growth and how it affects the mechanical behaviours of an adhesive is relevant information for a durable design. For this purpose, a method to obtain the average crack growth rate (da/dt) as a function of the energy release rate (G) was developed. The proposed roller wedge driven (RWD) creep crack growth methodology can provide creep crack growth rate curves for a constant applied energy release rate. The RWD test setup was designed by the authors to test mode I DCB-like specimens by using a roller wedge. An advantage of using a moving wedge is that, on average, the crack growth rate equals the displacement rate of the wedge. By changing G for different specimens, a G vs da/dt curve can be obtained for the methacrylate adhesive Araldite 2021–1. The power law regression line of the G vs da/dt curve provides a Pariś law-like equation. Data have shown that applying an energy release rate that is relatively low compared to the fracture toughness of Araldite 2021–1, found by quasi-static testing, will result in creep crack growth. Furthermore, a transition from cohesive to adhesive failure has been observed when the applied energy release rate is lowered. For durability design of bonded joints it must be considered that only using data from quasi-static testing will very likely overestimate the durability of the bonded joint.

1. Introduction

Structural adhesive bonds are an interesting alternative to mechanical joints from a design point of view [2]. Using a structural adhesive instead of mechanical fasteners to bond a joint makes the structure lighter, smoother and stress concentrations are reduced. However, using structural adhesives has some limitations, like difficult visual inspection, surface preparation prior bonding, influence of process parameters on the mechanical properties and environmental sensitivity [3]. Understanding the mechanical behaviour of a structural adhesive for different service load cases and environmental conditions is essential to design a durable adhesively bonded joint.

Creep behaviour of polymeric adhesives could be considered as a mechanism that negatively affects the durability of an adhesively bonded joint. Creep is a time and temperature dependent deformation of a stressed material. The level of applied stress and the

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Nomenclature

a_0	initial crack length
B	width of specimen
E_x	longitudinal Younǵs modulus
d	distance from the initial location of the bonded section
da/dt	crack growth rate
$F_{Push\|s}$	force to push the wedge simplified data reduction method
G	energy release rate
G_c	fracture toughness
h	thickness of the adherend
L	specimen length
r_w	radius of the wedge
t_a	bondline thickness
T_g	glass transition temperature
w	wedge displacement
δ_y	opening displacement
χ	crack length correction factor
DCB	Double Cantilever Beam
LVDT	Linear Variable Displacement Transducer
MMA	Methyl Methacrylate
RWD	Roller Wedge Driven

temperature related to the glass transition temperature of the adhesive influence the creep behaviour [4,5]. The analysis of the creep behaviour is relevant because it can occur with an applied stress that is below the yield strength of the material and, in case of polymers, creep can already occur at room temperature. Typically creep deformation passes through three stages. In the primary stage there is relative rapid creep deformation. In the secondary stage a linear increase in deformation relating to time can be observed. And in the tertiary phase the deformation increases exponentially which, could follow by sudden creep rupture [4,6].

The situation is different if a crack is already present in the adhesive of a bonded joint. For a constant level of load over time, creep behaviour at the crack tip could cause the crack to propagate, referred to as viscoelastic creep crack growth [7]. Polymer adhesives behave like a fluid (viscous) at low deformation rates and as an (elastic) solid at high deformation rates, therefore referring to viscoelastic behaviour of the material [8]. It is the viscoelastic deformation in the fracture process zone that provides the possibility for a crack to growth over time [7]. Thus, understanding the viscoelastic creep crack growth and how it affects the performance of the bonded joint over time is essential for the design of durable bonded joints and maintenance protocols.

For design purposes, it would be useful to have a creep crack growth curve for a certain adhesive system to predict creep crack growth behaviour, similar like the Pariś law-based expression [9]. Indeed, similar approaches have been developed to predict creep crack growth rate (da/dt) for a certain applied energy release rate [4,10,11]. For mode I it has been tried to obtain crack growth rates from the Boeing wedge test (ASTM D-3762) [12]. A wedge remains stationary in a DCB-like specimen and crack increment is measured over time [10,13]. However, with increasing crack length, the energy release rate decreases, resulting in a reduced crack growth rate. Also it has been tried to obtain crack growth rate from displacement controlled DCB and TDCB test where very slow displacement rates are applied, trying to keep the same load over time [14,15].

Considering creep crack growth, ideally the specimen should be loaded under a constant energy release rate, so crack growth rate predictions can be made based on the sustained applied load or stress state that is expected in a bonded joint during its service life. In this direction, there are standards for creep testing on polymers and bonded joints like, ASTM D1780 – 99, ASTM D2294 – 96 and ISO 15109:1998. In these standards a single lap joint is loaded in tension, so effectively testing the bonded joint in mode II. However, as far as the authors know, there is no standard for testing a bonded joint for creep crack growth in mode I. In this paper we propose a methodology for creep crack growth testing which, is based on the roller wedge driven (RWD) test methodology [1]. The idea of this method is that the roller wedge follows the crack tip during crack propagation. Following that when applying a constant load to the wedge, the energy release rate remains constant at the crack tip. It is assumed that on average the roller wedge displacement equals the crack length increase. Combining these two properties of the RWD result in a proposal for a new RWD creep crack growth methodology that can provide creep crack growth rate curves, useful for durability design purposes.

In section 2, we present the RWD creep crack growth test method, how the creep crack growth rate is determined and the experimental test campaign we carried out to prove the validity of the method. In section 3, we describe the RWD creep crack growth test results, which we discuss in section 4. In section 5 we conclude the work done for this manuscript.

2. Methodology

2.1. The roller wedge Driven (RWD) creep crack growth test

The RWD test setup (Fig. 1, left) was designed to test mode I DCB-like specimens by using a roller wedge. The roller wedge consists out of three rollers (Fig. 1, right) [1]. The specimen was clamped in vertical position. Bearings in the wedge support rod and a carriage system made sure unwanted loads on the specimen were avoided (mode II & III). The RWD test setup was also used for creep crack growth testing, where on top of the wedge a weight was placed (Fig. 1, left). When crack growth takes place, the wedge will follow that crack tip, while the applied load remains constant during the test.

The applied load to the wedge was measured with a load cell (HBM U9C-500) that has a precision of 0.2 %. The displacement of the wedge was measured with a HBM WA-T-50 linear variable displacement transducer (LVDT, 1 % precision) that was connected to the horizontal loading beam of the roller wedge. The displacement was also visually tracked by a camera (Logitech C920). The camera took pictures of two reference points every 120 min (see Fig. 1, left). The images were analysed with the ImageJ software to measure the displacement of the roller wedge. The software was used to measure pixels, which was done by user input, and transformed into distances. Two reference dots were used to calibrate the pixel measurement in the photos. In the rest of this manuscript the visual measurement method refers to the wedge displacement data obtained by the camera, and the LVDT measurement method refers to the data obtained by the LVDT. A second camera (Canon 550D and macro lens EF100) was used to take images from the adhesive to capture the propagation of the crack through the adhesive. For the quasi-static pre-cracking of the specimens, a picture was taken every-two seconds and for the creep crack growth test every 8 min. The RWD manual test method was used to pre-crack the specimen for about 10 to 15 mm of crack length before the creep crack growth test was initiated. For a more detailed description of the RWD manual test method, as well as the RWD test setup design, the reader is referred to the work of Meulman et al. [1].

In that same manuscript, the equation to determine the energy release rate (G) for the RWD test reads [1]:

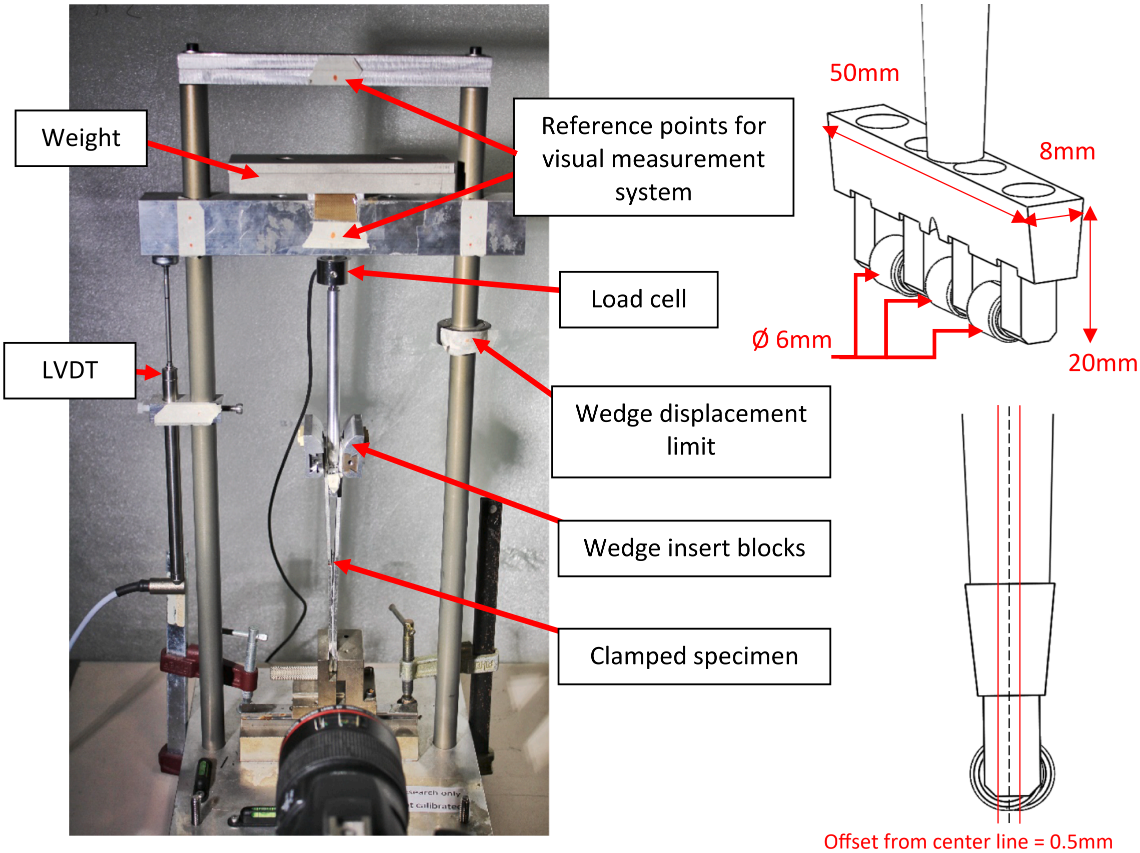

Fig. 1. Left: RWD creep crack growth test where the roller wedge was loaded with a weight. (The Logitech C920 camera for visual measurement is behind Canon 550D camera and not visible in the picture). Right: Sketch of the roller wedge design with three rollers and the offset of the rollers indicated [1].

$$G = \frac{3}{4}\frac{E_x h^3 \delta_y^2}{\left(\sqrt[4]{\frac{3}{4}\frac{E_x B h^3 r_w{}^2}{F_{Push|s}}} + \chi h\right)^4} \tag{1}$$

where E_x is the longitudinal Younǵs modulus of the adherend, h is the thickness of the adherend, δ_y is the opening displacement at the contact point between the roller and the adherend, B is the width of the specimen, r_w is the wedge tip radius (i.e., the roller radius), χ is the crack length correction factor [16], $F_{Push|s}$ is the applied force to the roller wedge measured with the load cell. It must be mentioned that the RWD force data reduction assumes zero friction in the system because of to the use of the roller wedge. The bondline thickness is indirectly considered in the equation, which is described in more detail in the RWD test methodology [1]. During the creep crack growth test the applied force provided by the weight remains constant, this results in a constant energy release rate during the test, since the other parameters of equation (1) are constants.

2.2. Crack growth rate

From the creep crack growth test, we want to obtain the average crack growth rate (da/dt) as a function of the energy release rate (G). An advantage of using a moving wedge is that, on average, the crack growth rate equals the displacement rate of the wedge, which will be discussed in more detail in section 4.1. When a given level of G is applied to a specimen so that it results in creep cracking of the adhesive, then the crack length can be measured over time and average da/dt can be determined. By changing G for different specimens a log–log linear regression G vs da/dt curve can be obtained, which governs the damage evolution over time in constant load tests.

2.3. Experimental testing campaign

To demonstrate the feasibility of the methodology, an experimental testing campaign was carried out with bonded joints between metallic adherends. Specimens were in-house manufactured by bonding aluminium Al 7075-T6 adherends with Araldite 2021–1. The same type of specimens were used in the RWD test design testing campaign [1]. Araldite 2021–1 is a methacrylate-based rigid structural adhesive with a glass transition temperature of 80 °C. The aluminium adherends were 200 mm long, 25 mm wide and 3 mm thick and had a Young's modulus of 71 GPa, shear modulus of 27GPa and a yield strength of 550 MPa [1,17]. The bondline thickness t_a was between 0.4 and 0.7 mm (Fig. 2, Table 1).

We used a sandblaster with brown fused aluminium oxide of 60 μm for surface treatment of the adherends. Afterwards, the adherends were cleaned with acetone and they were degreased with high grade alcohol just before applying the adhesive. Teflon spacers were used to achieve the desired bondline thickness. The Teflon spacer was placed in such a way that an initial crack length (a_0) of 100 mm was created. The adhesive was cured in an oven at 60 °C for 16 h. The specimens were manufactured and tested in the ISO17025 and NADCAP certified AMADE research group testing laboratory at the University of Girona. In the laboratory, there was an ambient temperature and relative humidity $(23 \pm 2)^{\circ}C$ and (50 ± 5) % RH, respectively. A variety of weight levels was applied to different specimens. The weights were selected based on the data obtained during the previous RWD experimental test campaign and are shown in Table 1.

3. Results

In this section, we present the results of the RWD creep crack growth test performed on adhesively bonded joints. First, the obtained crack growth versus time data is described. From this data, the average crack growth rate can be obtained, which is then plotted against the normalised applied energy release rate to be able to plot a log–log linear curve.

3.1. RWD creep crack growth test

The wedge displacement against time for specimen RWD-C_03 is shown in Fig. 3, which is representative for a specimen where the

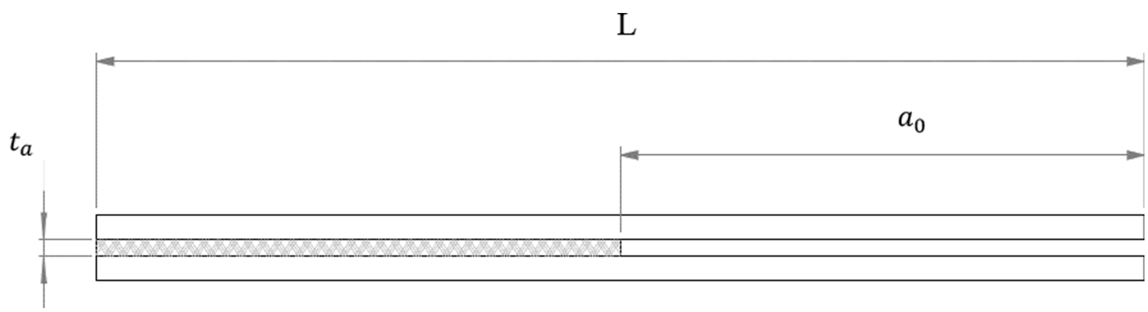

Fig. 2. DCB-like specimen geometry for the RWD creep crack growth test with L the specimen length, a_0 the initial crack length and t_a the bondline thickness [1].

Table 1
Overview table of tested specimens.

Specimen	Weight applied (N)	t_a (mm)	Measurement method
RWD-C_01	31	0.55 ± 0.02	Visual + LVDT
RWD-C_02	48	0.49 ± 0.03	Visual + LVDT
RWD-C_03	57	0.43 ± 0.04	Visual
RWD-C_04	70	0.51 ± 0.11	Visual + LVDT
RWD-C_05	80	0.51 ± 0.02	Visual
RWD-C_06	22	0.62 ± 0.06	Visual + LVDT
RWD-C_07	28	0.62 ± 0.06	Visual + LVDT
RWD-C_08	21	0.59 ± 0.06	Visual + LVDT
RWD-C_09	26	0.68 ± 0.03	Visual + LVDT

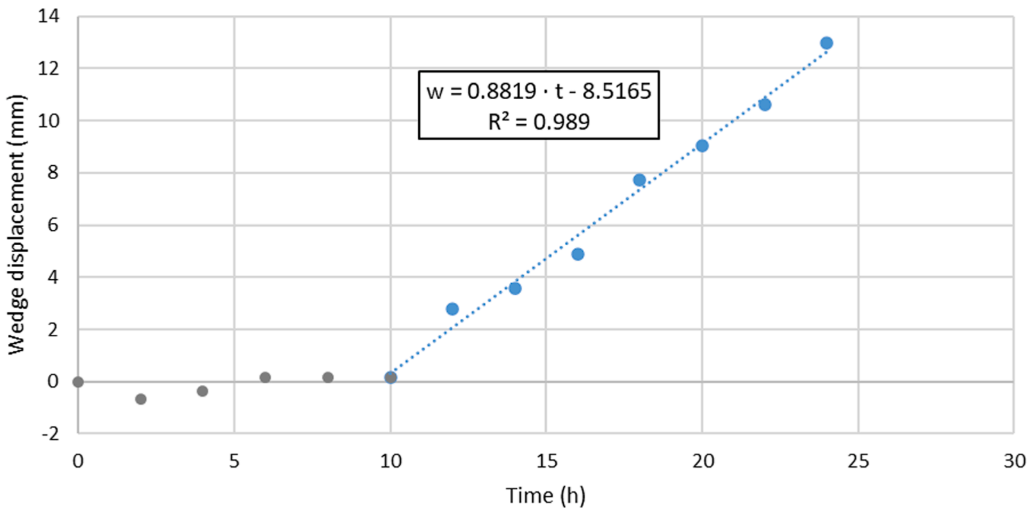

Fig. 3. Wedge displacement (w) in millimeters against time (t) in hours of specimen RWD-C_03 measured with the visual measurement method.

wedge displacement was only measured with the visual measurement method. It can be seen in Fig. 3 that there was first a transitory period where no displacement of the wedge was observed. After the transitory period, a linear trend line shows that, on average, the crack growths with a constant rate. The slope of the linear trend line can be considered as the average crack growth rate related to the

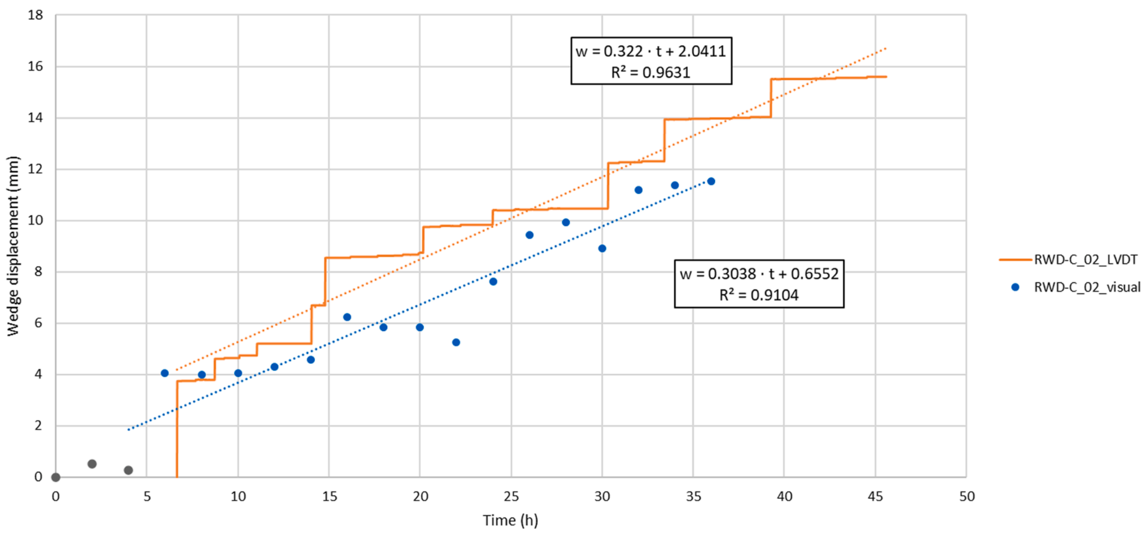

Fig. 4. Wedge displacement (w) in millimeters against time (t) in hours of specimen RWD-C_02 measured with the visual measurement method and the LVDT.

specific weight that was applied to the specimen (Table 1).

For specimen RWD-C_02 also the wedge displacement was measured with the LVDT (Fig. 4). The LVDT measurement is continuously, contrary to the visual measurement method. The LVDT measurement shows that the crack in this type of adhesive is not growing in a constant manner but rather in small jumps. If again a linear trendline is plotted it can be seen that the discontinue crack increments over a longer period follow on average a linear increase. In both the visual and LVDT measurement the transitory phase was not considered in determining the average crack growth rate, since no visible cracking took place during that phase. Comparing the wedge displacement data from the visual measurement method and the LVDT, it can be noticed that there is some off-set in the absolute wedge displacement measurement but that the slope obtained from both measurement methods are similar, resulting into close values of the average *da/dt*.

Table 2 shows an overview of the average crack growth rate obtained for each specimen and the corresponding energy release rate applied. The energy release rate is directly related to applied weight and is calculated with RWD data reduction method (equation (1). There is no visual measurement data available for specimen RWD-C_06 to RWD-C_09 because the displacements are too small to be able to measure it with the visual measurement method.

Plotting the average crack growth rate against the energy release rate for both measurement methods on a log–log scale produces Fig. 5. For the x-axis G is normalised with fracture toughness (G_c) that was found with the RWD test method in the previous test campaign and is 3.016 N/mm [1]. The specimens fit well on a power trend line which is presented as a straight line on a log–log scale. Close to $G/G_c = 0.3$ there is a sharp drop in the average crack growth rate and the power trend line is no longer being applicable for the specimens (RWD-C_06 to RWD-C_09) loaded below this threshold energy release rate. The specimens tested below this threshold had so low wedge displacement values that cracking of the adhesive could not be determined with certainty, therefore it is assumed that da/dt is equal to 0 mm/h. The standard error found for the power law coefficients are 0.319 and 0.465 for the LVDT method. For the visual method the standard error is 0.217 and 0.384.

3.2. Fracture surface and transition

After the tests were run, we opened the specimens and took pictures of the fractured surfaces. In each specimen, three different regions could be observed and are shown in Fig. 6. First, the pre-crack created with the RWD manual test method (region 1). A fracture surface with a cohesive failure was created. After the pre-cracking, the weight was placed on top of the wedge (Fig. 1, left) to initiate the RWD creep crack growth test (region 2). A transition was visible from cohesive to mostly adhesive failure. The specimen was completely opened with lab tools to inspect the fracture surfaces (region 3). Here a transition to cohesive failure was observed again, however this part was not intended to be part of the test and was solely to open the specimen for inspection. On both ends of the specimens, unbonded section (region 0), a Teflon spacer was located during manufacturing to control the bondline thickness. The spacer on the left side was removed before testing because that is the side of the specimen where the roller wedge was inserted. In region 0, the scratches on the aluminium adherends were caused by the lab tools during completely opening of the specimen, after the test was already finished.

In Fig. 7, fracture surfaces of specimens RWD-C_01 to 05 are presented where the specimens from left to right were tested with increasing load levels. Increasing load levels, and therefore increasing energy release rates as can be seen in Table 2. Fig. 5 shows that, when the energy release is increased also the average crack growth rate increases. It appears that, when the average crack growth rate increases, the fracture surface transitions from mostly adhesive to cohesive failure. It can be seen that specimens RWD-C_02 to 04 start to show an increasing cohesive part at the centre line of the specimen. Specimen RWD-C_05 shows for about 5 mm of crack propagation a clear cohesive failure and then transitions at the centre line to what seems to be more adhesive failure. However, specimen RWD-C_05 became unstable after about 5 mm of stable creep crack growth and the specimen failed completely until the wedge displacement limit. Therefore, this part of the fracture surface is not considered in the results.

4. Discussion

In this section, the results of the RWD creep crack growth tests are discussed. First, the crazing zone that was observed during

Table 2
Overview of specimen test data.

Specimen	*G*– RWD (N/mm)	da/dt**_visual**(mm/h)	St. Error (mm/h)	da/dt**_LVDT**(mm/h)	St. Error (mm/h)
RWD-C_01	1.09	0.05*	0.0073	0.09	0.0004
RWD-C_02	1.67	0.30	0.0246	0.32	0.0013
RWD-C_03	1.97	0.88	0.0379	–	–
RWD-C_04	2.38	1.07	0.1286	1.62	0.0396
RWD-C_05	2.71	3.04	0.1676	–	–
RWD-C_06	0.79	+	+	0.00017	–
RWD-C_07	1.01	+	+	0.00019	–
RWD-C_08	0.77	+	+	0.0001	–
RWD-C_09	0.93	+	+	0.0003	–

*Only data available of last part of the test, + displacement not measurable with visual measurement method.

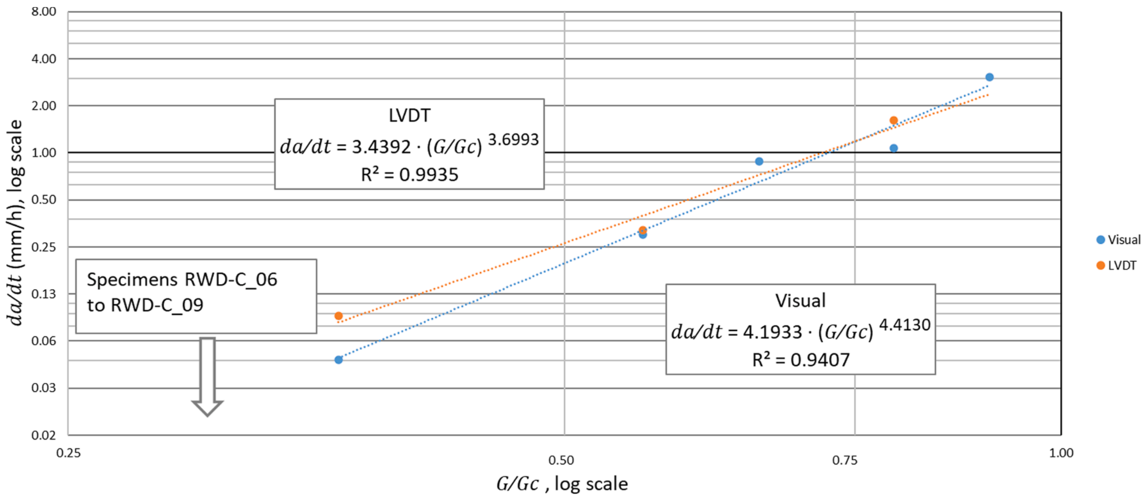

Fig. 5. Average crack growth rate (da/dt) against normalised energy release rate (G/G_c) on a log–log scale of the visual and LVDT measurement method. Specimens RWD-C_06 to RWD-C_09 are considered to have a da/dt of 0 mm/h and cannot be plotted on the log scale.

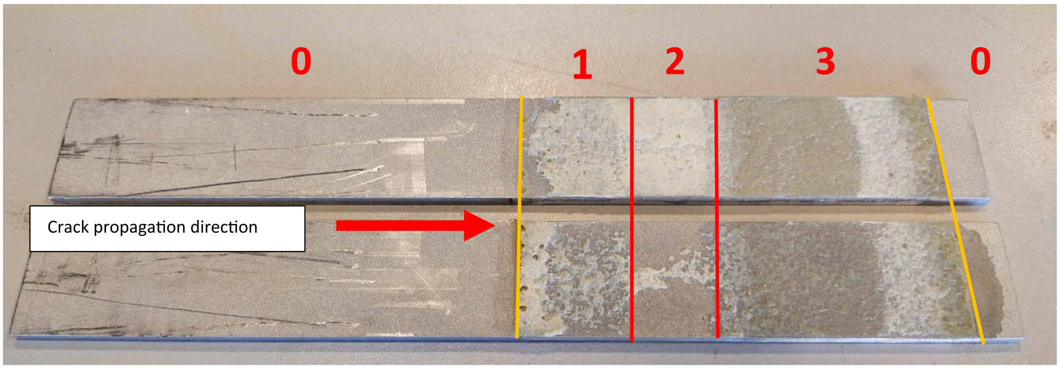

Fig. 6. Specimen RWD-C_03, 0: Teflon insert region, 1: Pre-crack region, 2: Creep crack propagation region, 3: Lab tool specimen opening region.

testing and the transitory phase before crack growth are discussed. Secondly, the rate sensitivity and fracture surfaces of the used adhesive system. Finally, the obtained average crack growth rates and the resulting log–log linear creep crack growth rate against normalised energy release rate curves.

4.1. Crazing zone

The two-component adhesive (Araldite 2021–1) that bonds the two aluminium adherends is a with rubber particles toughened methyl methacrylate (MMA)-based adhesive. When the adhesive was mixed during manufacturing it had a yellow colour, after curing and forming the bondline between the adherends it appeared to be greyish. It was noticed during testing that before a crack visual appeared the adhesive became whiter. When the crack tip became visible, the white area seemed to continue to increase with the same rate as the crack tip was going through the adhesive (Fig. 8).

By using the visual measurement (same method as the wedge displacement measurement described in section 2.1), the increase in the whitened area in the adhesive and the distance crack tip has moved through the adhesive was measured during the test and plotted in Fig. 9, which are the results of pre-cracking specimen RWD-C_05. In the first part of the pre-cracking the wedge was pressed into the specimen where the load on the adhesive was still too low to form a visual whiting zone. Then the adhesive started to turn white, and the area grew while there was no crack visible. After the crack became visible and grew, it followed a linear trendline. The white area in front of the crack grew with a similar linear trend. In literature, the same whiting of these type of materials have been reported and is very likely caused by micro voids forming in the adhesive in the zone in front of the crack tip [18]. As mentioned, Araldite 2021–1 is a rubber toughened adhesive, the rubber particles can enhance the forming of voids and result in a random multiplication of void initiation. The adhesive in between the voids starts to locally stretch and aligning the polymer chains forming so called fibrils [19–22]. The aligning of the chains and the forming of voids change the refractive index of the material, which changes the colour of the adhesive. This effect has been reported as stress whiting or craze forming [18,22]. Thus, the whiting zone observed for this specific type

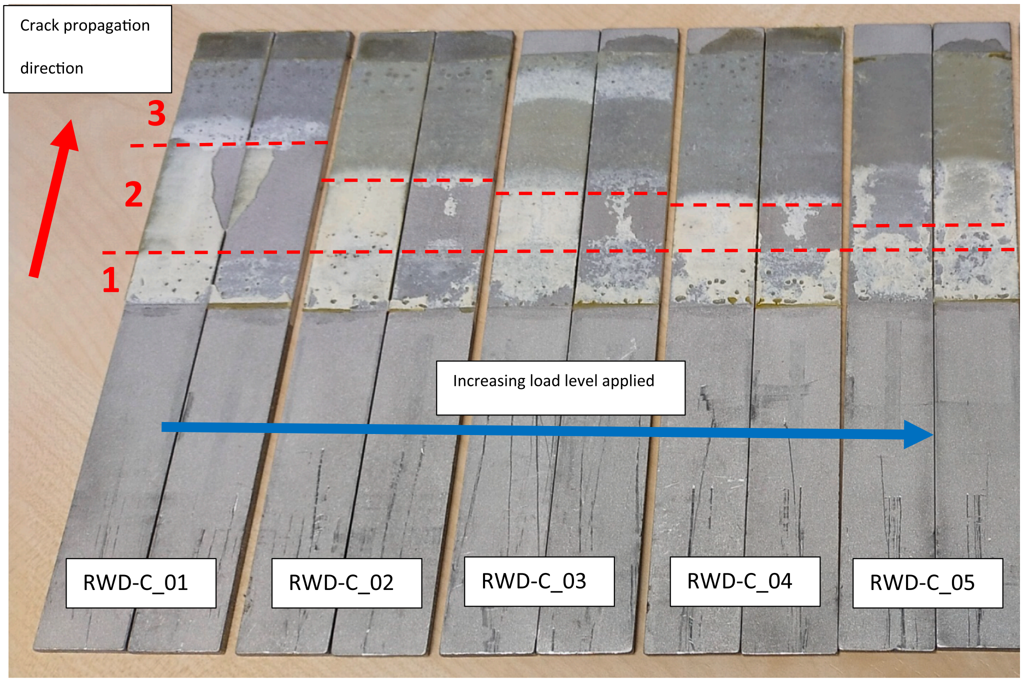

Fig. 7. Fracture surface of specimens RWD-C_01 to 05. With region 1 indicating the fracture surface created with the pre-crack, region 2 the RWD creep crack growth test and region 3 opening the specimen with lab tools to be able to inspect the fracture surface of the specimen. Scratches on the adherends are caused by the lab tools, after the tests were already finished.

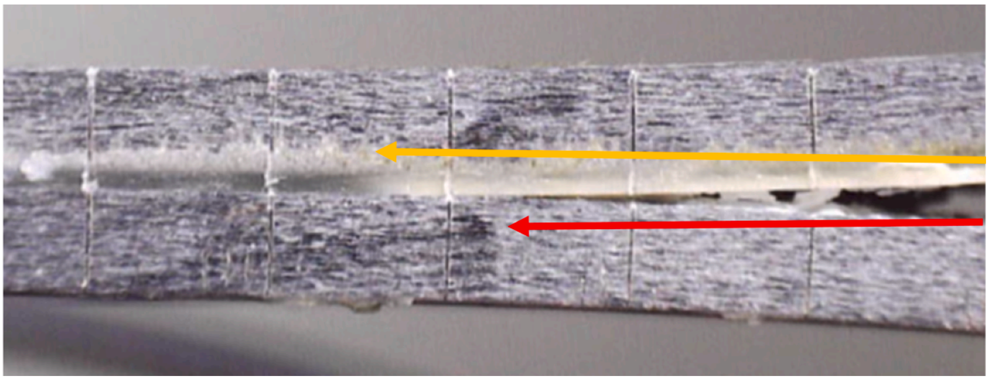

Fig. 8. Specimen RWD-C_05 with whitened adhesive ahead of the crack tip. The yellow arrow indicates the distance the whitened area had passed through the adhesive and the red arrow the crack tip.

of adhesive, could be considered as the crazing zone.

Fig. 10 shows the RWD creep crack growth test of specimen RWD-C_05, where both the crack tip and craze front were measured in the same way as in Fig. 9. Since the crazing zone was already formed in front of the crack tip during the pre-cracking phase there is not a clear difference between the crazing zone growth rate and average crack growth rate through the adhesive and thus a similar trendline for both is found. The average distance found between the craze front and the crack tip is 2.8 mm.

Specimen RWD-C_05 had a relatively high applied G compared to the fracture toughness. The crack tip and craze front progress immediately after the load was applied. This was not the case when a lower G was applied. For instance, the specimens that are shown in Fig. 3 and Fig. 4 first show a transitory phase before linear crack propagation occurred. Fig. 11 shows for specimens RWD-C_01 to RWD-C_05 the applied load against the transitory phase in hours. Although, a clear trendline cannot be found it seems that when G/G_c is increasing the transitory time is decreasing. More tests are required to find a plausible trendline describing the relationship between G and the transitory time before creep crack growth initiates. When the duration of the transitory phase is dependent on G, the question arises on how fast the energy release rate changes while it is still leading to the creep crack growth. In for example, the Boeing wedge test, one might be able to measure the instantaneous crack growth rate, but it is difficult to know if the measured crack growth rate

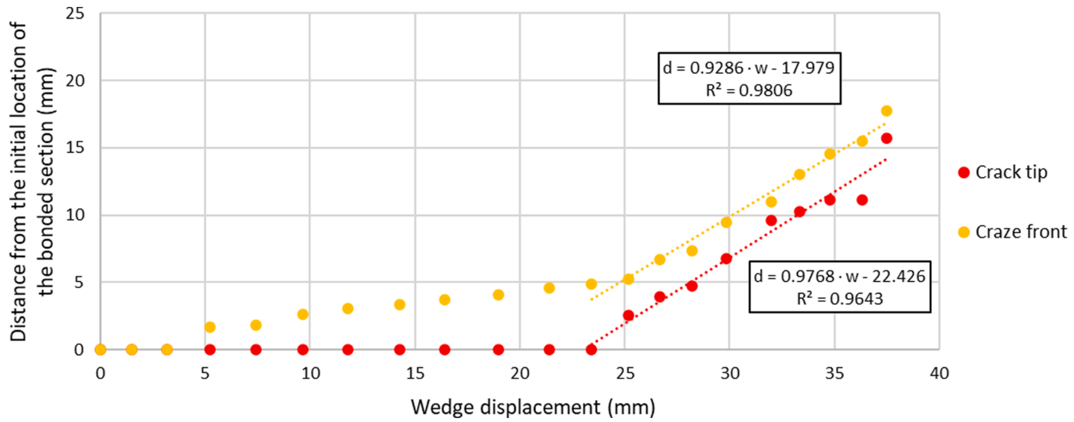

Fig. 9. Specimen RWD-C_05 pre-cracked visual measurement data of the craze front and the crack tip distance from the initial location of the bonded section (d).

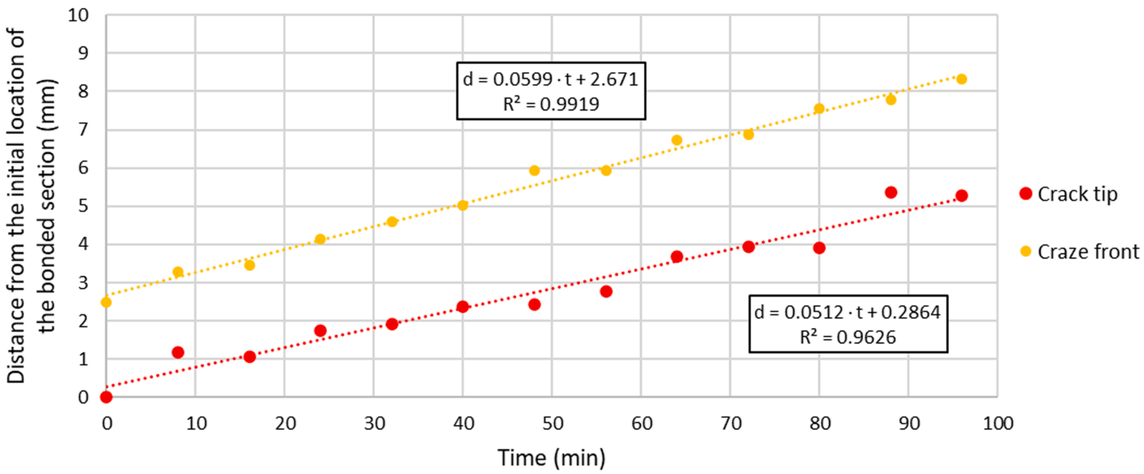

Fig. 10. Specimen RWD-C_05 creep crack growth phase with progressing craze front and crack tip in the adhesive, data normalized with the crack tip distance from the initial location of the bonded section (d).

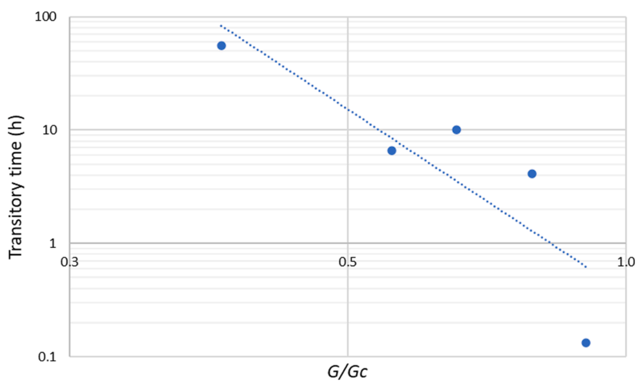

Fig. 11. Applied normalised energy release rate against the transitory time in hours found for specimens RWD-C_01 to RWD-C_05.

corresponds to the transitory or steady state propagation phase due to the decrease in energy release rate. Employing a constant energy release rate testing strategy is likely the most accurate approach when testing materials with expected relatively large FPZ, as in the case of adhesive joints, to prevent a too fast shedding rate that would lead to a different crack growth rate than observed in constant energy release tests.

When the pre-cracking is performed, the wedge is forced into the specimen with a certain rate. Therefore, also the forming of the craze zone and crack growth are forced to progress with a similar rate. It was demonstrated that, for this specific adhesive system, there is creep crack growth over time (Fig. 5). For the creep crack growth test, Fig. 4 shows that when considering the continuous measuring of the LVDT, the crack growths in a step like way for this specific adhesive. The step-like crack propagation indicates there are moments of crack arrest followed by sudden increase of the crack length. Slow crack growth in polymers could show this behaviour because part of the fibrillar zone at the crack tip ruptures, followed by a certain incubation time in which the fibrillar zone stabilizes before fibril rupture takes place again [22]. This effect could be considered as local and over a relatively short time compared to the total duration of the creep crack growth test. It was demonstrated that, over the whole creep crack growth test, a linear trendline can be found that describes the average crack growth rate for a specific specimen for a certain applied level of energy release rate. Since the fibrils are formed by the stress concentration at the crack tip, it could explain why at higher levels of applied energy release rate, and thus a higher stress at the crack tip, the fibrillar zone incubation time is shorter resulting in a shorter transitory time (Fig. 11) and higher obtained average crack growth rates. Another time dependent mechanism might be active in the graze zone which relates to the cohesive to adhesive fracture surface transition that was observed (Fig. 7). For all specimens the crack tip zone conditions were similar after the pre-crack was formed, like sharp crack tip, craze zone and cohesive failure. For lower applied G, besides the lower stress at the fibrils also the transition from cohesive to adhesive failure could result in the observed increase in the transitory time.

4.2. Rate sensitivity and effect on the fracture surface

The process of crazing in the fracture process is influenced by the strain rate during fracture of polymers. Polymeric materials are known for their strain rate sensitivity [23]. More specific the work Kozłowski et al. [24,25] shows for tensile tests of a MMA adhesive, that the test speed ranging from 1 to 100 mm/min, clearly influences the strength and stiffness of the adhesive which, confirms the viscoelasticity behaviour expected with this type of polymeric adhesive. Besides rate sensitivity it is also well known that temperature has a significant influence on the mechanical properties of a polymer. Low temperatures result in more brittle fracture behaviour of a polymer like MMA, and high temperatures relative to the glass transition temperature (T_g) result in more ductile fracture behaviour. Because of the viscoelastic nature of the polymer the change in fracture behaviour due to temperature can also be observed if the strain rate is changed. Where a high strain rate results in more brittle fracture behaviour and a low strain a more ductile fracture behaviour [26,27]. Arnott et al. [28] demonstrate with constant displacement mode I tests on adhesively bonded joints the influence of the displacement rate on the energy release rate and the fracture behaviour. In that work it is clearly visible that for higher rates the fracture surface shifts from primarily cohesive failure to complete adhesive failure. This is the same type of behaviour that was observed for the specimens tested with the creep crack growth test (Fig. 7). It must be noted that, the tests in the work of Arnott et al. were performed at an elevated temperature of 50 °C where in this work all the tests have been performed at $(23 \pm 2)^{\circ} C$. However, it was stated before that an increased temperature makes the fracture behaviour shift to a more ductile fracture behaviour. It can be assumed that if the tests were performed at a higher temperature likely more adhesive failure would have been observed if the same average crack growth rates would have been applied. Compared to quasi-static testing, creep crack growth tests below 50 % of G_c can be considered as relatively slow rate testing (Fig. 5), hence the pure adhesive fracture surface of specimen RWD-C_01 (Fig. 7). For bonded joint design purposes, characterizing the mechanical properties of a bonded joint only with quasi-static testing likely overestimates the load bearing capabilities of the bonded joint. Especially when durability of the bonded joint is an important design criterion.

4.3. Average crack growth rate

What we are looking for in the RWD creep crack growth tests is obtaining the average crack growth rate. Since the RWD test method makes use of a roller wedge, it is assumed that the wedge follows the crack tip and therefore the distance between the roller wedge and the crack tip remain constant, on average, during the crack propagation phase. This assumption can be demonstrated in Fig. 9, where the crack length is plotted against the wedge displacement. During the crack propagation it follows a linear trend with a ratio close to one and has a good correlation between the crack length measurement and the wedge displacement. As shown in section 3.1, there is a difference between measuring the wedge displacement with an LVDT and using the visual measurement method. Since the latter is discrete the data points can show linear crack propagation (Fig. 3), while the continues measurement of the LVDT shows that this specific adhesive system accommodates a step-like crack propagation during a creep crack growth test (Fig. 4). The step-like crack propagation could be considered as a local and short time behaviour of the adhesive. For durability and creep crack growth predictions it is more interesting to know the behaviour of the adhesive system over a longer time period. In that case both measurement systems show a linear trendline with a similar slope which equals the average crack growth rate of that specific specimen. The test can be repeated with different specimens of the same type with every time applying a different load or in other words, a different energy release rate. The RWD force equation (1) was used to translate the applied force to energy release rate. It must be mentioned that this data reduction method overestimates the applied G slightly. This is because the friction of the roller is assumed to be zero, as mentioned in section 2.1. Fig. 5 shows there is more scatter in the results for the visual measurement method compared to the LVDT method, which is likely caused by the lower accuracy of the visual measurement method compared to the LVDT. However, the order of magnitude found for the coefficients of the power-law are similar.

5. Conclusions

This manuscript proposes a methodology for the experimental characterization of energy release rate-controlled creep crack growth under mode I loading. The proposed methodology makes use of the Roller Wedge Driven (RWD) test setup. The design of the RWD test setup makes it possible to obtain a creep crack growth rate curve by applying a constant load to the roller wedge. During the RWD creep crack growth test the energy release rate remains constant. Different average crack growth rates can be obtained when testing multiple specimens at different G (load) levels, resulting in a single log–log linear plot that shows energy release rate against average crack growth rate. The power law regression line provides a París law-like equation. The specimens are required to be pre-cracked before performing the creep crack growth tests which, can be done inside the RWD test setup by forcing the wedge manually in the specimen with a threaded bar and a spanner, described in more detail in previous work [1]. Directly after pre-cracking a certain load can be applied to the roller wedge to initiate the RWD creep crack growth test.

Comparing the two measurement methods, visual and LVDT, it seems that using an LVDT provides more accurate results and gives better insight in the creep cracking behaviour of the adhesive, since it is a continues measurement. Thus, it was observed that this specific adhesive shows a step-like creep crack growth behaviour, but over a long time period the trendline was linear. Therefore, the average crack growth rates obtained from both measurement methods provided similar results, resulting in similar coefficients found for the power law regression.

Inspection of the fracture surfaces after testing showed a different response to the different average crack growth rates measured. It was observed that going from relatively high average crack growth rates to relatively low average crack growth rates it shifted the fracture surface from predominantly cohesive failure to adhesive failure.

For this specific adhesive system, data have shown that applying an energy release rate that is relatively low compared to the fracture toughness found by quasi-static testing, will likely result in creep crack growth. For durability design of bonded joints this behaviour must be taken into account and only using data from quasi-static testing will very likely overestimate the durability of the bonded joint. The power law coefficients found in the París law-like equation could potentially be used for models in a similar way as the Paris law is used for modelling of fatigue. This could provide a valuable tool for engineers to make better predictions for creep crack growth in adhesively bonded joints. However, more tests and different tests are required to validate if the limited results in this work indeed follow a París law-like equation.

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CRediT authorship contribution statement

E. Meulman: Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Visualization, Investigation, Validation, Formal analysis, Methodology, Software. **J. Renart:** Conceptualization, Funding acquisition, Writing – review & editing, Visualization, Investigation, Validation, Formal analysis, Methodology, Supervision, Resources, Project administration. **L. Carreras:** Conceptualization, Writing – review & editing, Visualization, Investigation, Validation, Formal analysis, Methodology, Supervision. **J. Zurbitu:** Conceptualization, Writing – review & editing, Visualization, Investigation, Validation, Formal analysis, Methodology, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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