First International Conference on Damage Tolerance of Aircraft Structures
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DAMAGE TOLERANCE OF BONDED AIRCRAFT STRUCTURES

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Abstract. *This paper presents a damage tolerance philosophy for bonded structures and repairs. It is proposed to assess the damage growth in bonded structures loaded mainly in shear with a generic strain elastic energy release rate concept. This concept has been validated on metal-to-metal and metal-to-composite bonding in metallic and hybrid structures.*

1 INTRODUCTION

The current trends in aircraft operations are showing an increasing demand for lower operational and maintenance costs. Practically, this translates into aircraft with longer design lives with longer inspection intervals and shorter inspection downtimes. As a consequence, the damage tolerance aspects of primary aircraft structures are becoming highly important, due to the tighter design requirements for new aircraft on the design table.

The increase of service life by replacing the riveted structure by a bonded structure makes it worthwhile to explore the bonding technology further than the current state-of-the-art. As a result, bonded designs become very attractive as solutions to comply with these requirements. Examples of bonded structures are among others: stringers, clips and frames bonded to the skin, bonded doublers and bonded window frames.

With respect to structural integrity, all damage tolerance concepts have to prove that the occurrence of any damage (fatigue initiated, foreign object induced, etc.) will not impair structural integrity. This is also required for bonded structures.

In the past decades, various methods have been proposed to assess the strength of bonded structures. Analysis methods currently utilized by the industry for designing bonded structures vary from simple two-dimensional methods to software-based analysis tools. Most methods are based on the calculation of local shear and peel stress distributions, which are then used to estimate joint strength based on designed overlap lengths [1,2]. However, methods to assess damage growth, following from a damage tolerance approach are limited.

In general, the discussion on damage tolerance of bonded structures includes metal-to-metal, metal-to-composite and composite-to-composite joint structures. However, the approach proposed in this paper is mainly based on the experience and analysis of the first two categories. Whether or not the approach is suitable for composite-to-composite joining techniques must be verified in a later stage.

2 STRUCTURAL INTEGRITY AND DAMAGE ASSESSMENT

To ensure bonded structural integrity, the following aspects must be considered:

- Type of structure (primary/secondary, single multiple load path)
- Type of loading (tensile/compression, shear)
- Type of damage (including damages observed in-service)
- Operational environment (temperature and moisture ranges)

With respect to the type of structure, a clear distinction must be made between factory made bonded structures (bonded window frames, bonded stringers and clips, doublers etc.) and in-service bonded patch repairs. The difference between these two categories is related to the quality assurance and validation of applied heating and pressure methods. These aspects will not be taken into account in the proposed philosophy, because it is considered beyond the scope of this paper. However, the philosophy is believed to be applicable to both categories.

Most bonded structures are designed to transfer loads by means of shear stresses, because the adhesive is considered to be optimally loaded in shear. Typical examples for these cases are the overlap joints, bonded patch repairs and so on [1,2]. On the other hand, several bonded structures have been designed where the bond line is loaded in tension. Examples of these structures are for instance frames or clips bonded to the skin [3,4].

The type of damage in a bonded structure is either related to the bond line or to the adherents. Among others, the following damage scenarios might have to be considered for a bonded structure: cracking and debonding, scratch and scribe marks, impact damage, environmental aspects (corrosion, temperature ad moisture) and lightning strike. Note that in case of bonded patch repairs one adherent already contains a damage for which the proper analysis needs to be performed [5-7].

3 CURRENT STRUCTURAL ANALYSIS METHODS

Structural analysis of bonded structures in general and bonded lap joints in particular has been topic of many researches presented in the literature [1,2]. The developed analysis methods can be categorized in two main classes:

- Stress/strain based methods
  - *Peak peel and shear stresses for bond line failure*
  - *Peak tensile/compressive stresses over normal stresses for adherent failure*
- Fracture mechanics based methods
  - *Energy balance methods for bond line damage growth*
  - *Stress Intensity Factor for adherent damage growth*

It could be argued that the analysis of bond line failure and substrate failure should be addressed separately in the design. However, the author believes that a several designs, especially the bonded patch repairs, influences both aspects and that therefore both cases should be assessed simultaneously in a similar approach. The reason that most approaches presented in the literature tend to either look at bond line failure [1,2] or at substrate failure [5- 7] could be attributed to the complexity of a generic structural analysis method for design. Nevertheless, the current methods consider static strength failure criteria only. Even the very few damage growth methods [8] only consider damage growth under static load with critical energy or stress intensity parameters. The lack of a reliable damage tolerance method considering damage initiation and growth under operational loading sequences is the background of this paper. The method proposed here is to fill the gap in damage tolerance analysis of bonded structures.

In general, the stress based methods are well suitable for damage initiation prediction and in many cases for static load requirements. Note that the adherent failure methods as referred to in this paper are validated for the metal damage initiation and propagation behaviour. For fibre reinforced polymer composite substrates, the methods might be slightly different, however, often still based on the peak stress predictions. However, for damage growth, these methods are often less suitable, and energy balance methods are advised.

Rather than optimizing a specific method for bond line failure [9] with dedicated stress singularity methods, this paper envisions proposing a generic philosophy and approach applicable to any bonded structure. Once the approach is agreed upon by the manufactures and airworthiness authorities, further refinement of the method on a more detailed level can then be performed using all the work published in the literature.

4 BONDED STRUCTURES CONSIDERED FOR VALIDATION IN THIS PAPER

The concept of Fibre Metal Laminates (FML’s) has been developed at Delft University of Technology as an inherently damage tolerant bonded structural material concept. This concept provides second load paths via the embedded fibre layers in case of any damage, which increases the residual strength. The damage tolerance concept for FML structure has been developed based on a large amount of experiments, ranging from fatigue initiation, crack growth, residual strength on flat coupons to structural components. Especially, with respect to durability aspects, temperature and moisture [10,11].

The fatigue behaviour of FML’s, i.e. damage growth related to structure usage, has been investigated extensively in the past. It is concluded that the major mechanisms are crack initiation and propagation in the metal layers and delamination growth in the wake of these cracks at the interfaces with the intact fibre layers.

The generic analytical model developed to describe the interaction between delamination growth and crack propagation has proven that if the mechanisms are fully understood a physical sound description is possible. In fact, the method is applicable to fatigue crack growth and delamination growth in any FML, if the constituent properties are known. Based on the experience with the followed methodology, the approach has been extended towards other bonded applications such as the bonded doubler run-out configurations [12] and the bonded patch repairs [10]. However, the approach is believed to be applicable to any of the following bonded structures: bonded skin-stiffener structures, frames/clips bonded to the skin [4], FML’s [13-16] and structures bonded with adhesive and with bondpreg [17].

5 RECONSIDERING ENERGY BALANCE APPROACHES

As mentioned earlier, most of the analysis methods are based on calculation of the local shear and peel stresses [1]. These stresses are used to determine minimum overlap lengths and are related to the joint strength. More sophisticated methods include elastic and plastic adhesive behaviour for further and detailed joint optimization [9]. These methods, however, are meant to calculate the static strength of the structure. Damage accumulation is often only considered by applying sufficient overlap lengths to avoid risking bond integrity.

The approach proposed in this paper is based on the assessment and prediction of damage growth in bonded structures in presence of damage. The necessary fracture mechanics based approach applies the Strain Energy Release Rate (SERR) as major parameter describing the damage growth.

Before any damage growth assessment can be implemented in actual designs, proof has to be given of the applicability of the method to relevant bonded structures. The proposed approach should not only predict damage growth accurately, but also the final fracture. In addition, the method should be based on adherent and adhesive properties that easily can be related to standardized tests, like for instance standardized fracture toughness tests.

To validate the proposed approach and to illustrate the robustness of energy balance considerations for damage growth assessment, several configurations reported in the literature are re-evaluated in this section with the proposed method. It should be noted again, that the adherent material in all these cases is aluminium. The approach should be validated for composite adherents in a later stage.

5.1 Delamination in FML's

Fatigue in FML's consists of crack initiation and crack propagation in the metal layers. The intact fibre layers in the FML provide a second load path, which results in high residual strength values. In addition to the crack propagation, delamination occurs at the interfaces between the metal and fibre layers as result of this fibre bridging mechanism.

To be able to model the fatigue crack growth behaviour of FML's, it is also necessary to be able to predict the delamination growth at the interfaces. The delamination growth is related to the load transferred by shear stresses at the interface, which is equivalent to the bridging stress distribution along the crack. For this case, correlating the delamination growth rate to the SERR, which is a function of the material geometry and the occurring local stresses, has been proven to be a very successful and robust approach [14,15,18]. In principle, the relation is given by a Paris type relation between delamination growth and the minimum and maximum SERR, which is illustrated for various FML's in Figure 1.

$$\frac{db}{dN} = C_d \left(\sqrt{G_{d,\max}} - \sqrt{G_{d,\min}} \right)^{n_d} \tag{1}$$

A lot of research has been performed to develop methods to calculate the local shear and peel stresses in order to correlate these stresses to failure strengths. From the research on delamination growth at the metal/fibre interfaces in FML's, it is evident that these shear and peel stresses are directly related to the SERR considered here. Furthermore, it can be concluded that the delamination growth rate under fatigue loading is related to the mode II shear loading only. The various specimens tested, with either a pure mode II or a mixed mode I and II loading all showed similar delamination growth. This conclusion is supported with observation reported in the literature [18,19].

This lead to the conclusion that delamination initiation is primarily related to the mode I peel stresses, after which an initial higher delamination growth rate occurs under the mixed mode loading until about 1 mm length, which decreases to the slow delamination growth rates under mode II loading. This phenomenon can be compared with the crack growth behaviour in FML's, which initially shows higher crack growth rates until a small crack has been formed, after which the crack growth rate decrease significantly.

The relation between delamination growth rate and SERR, equation (1), is illustrated for various FML's in Figure 1. It seems that the delamination resistance is mainly influenced by the adhesive type. The titanium-carbon laminate based on the FM94 adhesive system shows almost the same curve as aluminium-glass laminate based on the same system.

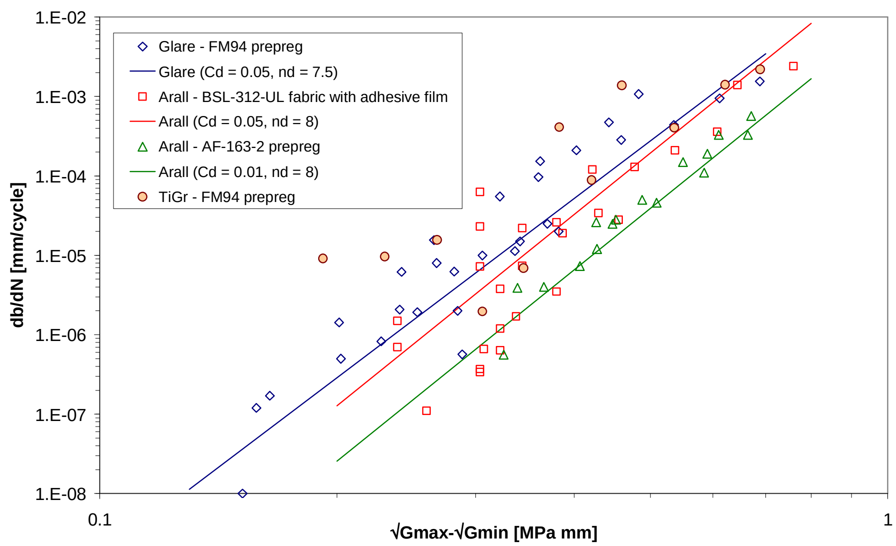

Figure 1: Delamination growth curves for two aluminium-aramid fibre FML's [data from 18], one aluminium-glass FML [14,15] and one titanium-carbon FML

The environmental affects are considered of great importance since the carbon fibre reinforced plastics are being introduced in more structural components. The delamination behaviour under fatigue loading exposed to low and elevated temperatures [11,20] has shown that the theory and analysis methods are still applicable. In principle, the delamination resistance should be quantified for a prepreg system, but once available, can simply be implemented in the method. To validate the static requirements with the proposed method, static delamination tests on various configurations are re-evaluated. The SERR for the three configurations investigated in [13] can be described by [15]

$$G_d = \frac{\sigma_{lam}^2}{2jE_{al}}\left[\gamma^2 (n_{al} - n_{cr})t_{al} - \lambda^2 n_{al} t_{al} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0} \left(\gamma^2 - \lambda^2\right) + \frac{E_{f,90}}{E_{al}} n_{f,90} t_{f,90} \left(\gamma^2 - \lambda^2\right)\right] \tag{2}$$

with

$$\gamma = \frac{t_{lam}}{(n_{al} - n_{cr})t_{al} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0}} \; ; \; \lambda = \frac{t_{lam}}{n_{al} t_{al} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0}} \tag{3}$$

where n_{cr} is the number of cracked aluminium layers and j the number of interfaces adjacent to cracked aluminium layers. Note that these relations do not consider any secondary bending as result of eccentricity and asymmetry. The onset stress and maximum stress reported in [13] can be calculated with the relations above to the SERR. The resulting values for all the 0° specimens are being plotted in Figure 2. The 90° specimens are not considered here, because the failure mode is different.

The observations of delamination onset were difficult and scatter has been observed either related to the measurement technique or to material. The material scatter for delamination is a known topic for composite materials. The scatter could explain the variations in Figure 2.

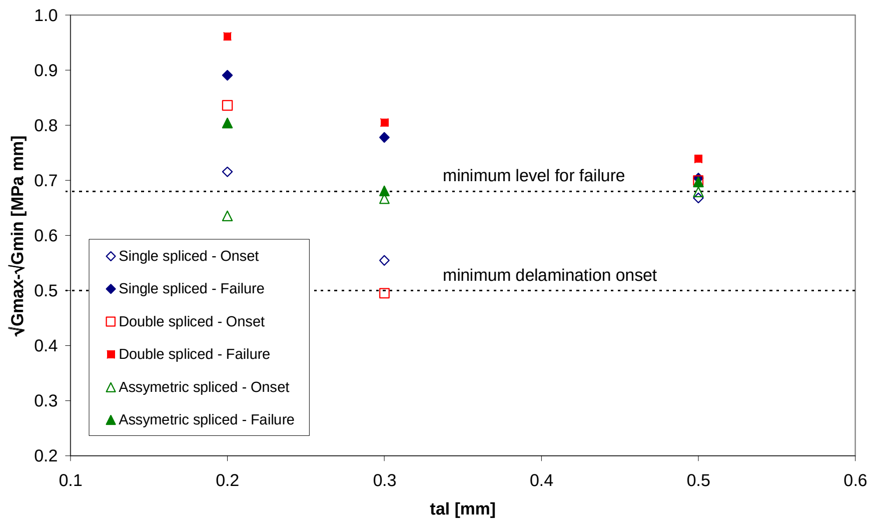

Figure 2: SERR calculated from the experiments reported in [2] for delamination onset and final failure.

In [16] fatigue tests have been reported on two specimen configurations containing interlaminar doubler run-outs. The objective of the tests was mainly to identify whether any failure in the metal layers occurred as result of the interlaminar doubler, which was observed not to be the case. The specimens have been tested at three different maximum load levels for 180 kcycles with a stress ratio of R = 0.05. According to the report no delamination growth has been observed, other than the debonding at the edge of the doubler run-out, see Figure 3.

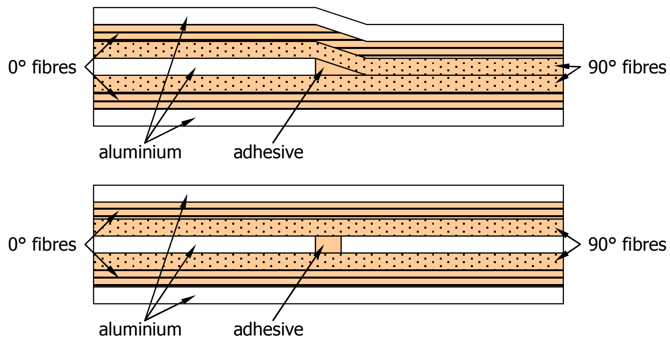

Figure 3: Two tested interlaminar doubler run-out specimen configurations [16]

The base material for the specimens was Glare3-3/2-0.4. Table 1 shows the SERR values calculated with the methods described in [15] with the delamination growth calculated with the relation for Glare (see Figure 1).

Table 1 Calculation results for the interlaminar doubler run-out in Glare3-3/2-0.4 baseline laminate

S_{min} - S_{max}	$\sqrt{G_{d,max}}$ - $\sqrt{G_{d,min}}$	db/dN	Δb (180 kcycles)
4 - 80	$1.31\cdot10^{-1}$	$1.18\cdot10^{-8}$	$2.13\cdot10^{-3}$
6 - 120	$1.96\cdot10^{-1}$	$2.47\cdot10^{-7}$	$4.45\cdot10^{-2}$
9 - 180	$2.45\cdot10^{-1}$	$1.32\cdot10^{-6}$	$2.37\cdot10^{-1}$
[MPa]	[√MPa mm]	[mm/cycle]	[mm]

Table 2 Calculation results for the interlaminar doubler run-out in Glare3-3/2-0.4 baseline laminate

S_{onset}	$\sqrt{G_{d,max}}$ - $\sqrt{G_{d,min}}$	S_{max}	$\sqrt{G_{d,max}}$ - $\sqrt{G_{d,min}}$
330	$5.68\cdot10^{-1}$	503	$8.65\cdot10^{-1}$
385	$6.62\cdot10^{-1}$	496	$8.53\cdot10^{-1}$
[MPa]	[√MPa mm]	[mm/cycle]	[√MPa mm]

From the results in Table 1, it is obvious that no delamination growth was observed during the 180 kcycles fatigue loading at the three applied stress levels. Interestingly enough, the specimens were subsequently tested for residual strength. During the static loading, delamination growth was observed. The onset stress values for at which the delamination progresses further than the deburred edges are 330 MPa and 385 MPa for the upper and lower configuration in Figure 3 respectively.

The delamination onset and specimen final failure stresses are listed in Table 2 together with the SERR calculated with equations (2) and (3). It is evident that the values correlate quite well with the observations reported in [13] and illustrated in Figure 2. Both the onset and failure SERR are somewhat higher and apparently there is less scatter is present in the data. This could be related to the fact that most data given in [13] has been obtained without applying paint to the specimen edges, whereas all specimens in [16] all specimens have been observed with the paint applied.

In theory, it is expected that static delamination failure occurs at a delamination growth rate of db/dN = 1. From the discussion of these experiments, it can be concluded that the onset of static delamination occurs at lower SERR levels. The reported failure levels are not only related to static delamination failure, but also to failure of the aluminium layers. To assess delamination growth in bonded structures, a minimum static delamination onset level is therefore proposed. This results in an operating window for delamination growth, being the triangular area below the delamination growth curve and left from the static delamination onset level.

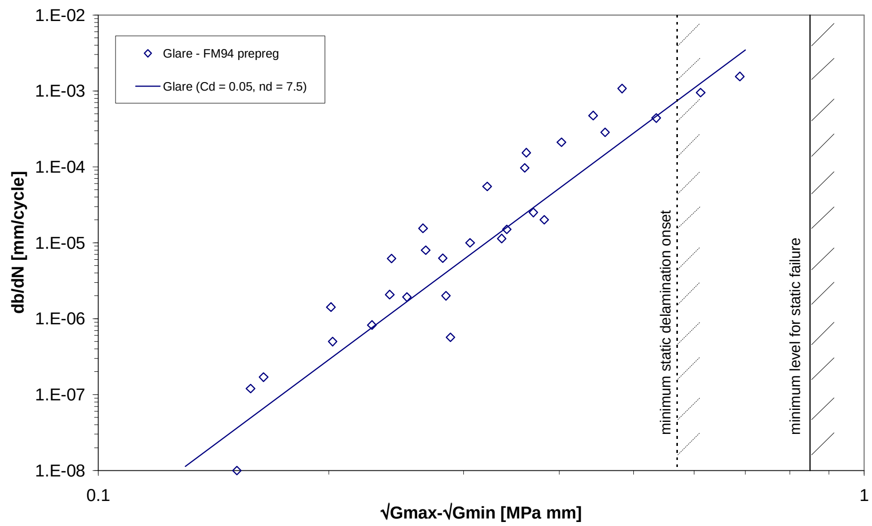

Figure 2: Delamination growth curves for the FML Glare from Figure 1 [15] together with the static delamination onset and failure boundaries listed in

5.2 Debond growth at doubler run-outs

To investigate the delamination growth behaviour at the bond line between two FML adherents, fatigue tests on doubler run-out specimens have been reported in [12]. The specimen configurations were varied with different adherent lay-ups and they were bonded back-to-back to avoid bending. In some cases crack initiation was observed in the adherent, but the majority of the specimens showed delamination initiation and growth at the bondline between the adherents.

Application of the SERR method to the investigated specimen configurations and plotting the observed delamination rates against the SERR, similar to Figure 1, results in Figure 4. In this figure, the line obtained for delamination growth in the aluminium-glass fibre laminate with FM94 adhesive system has been added [21]. It is evident that the delamination behaviour between bonded FML adherents shows similar behaviour as has been observed for interfaces within FML's. Apparently, the relation obtained for the S2-gass/FM94 prepreg also covers conservatively the bondline without fibres.

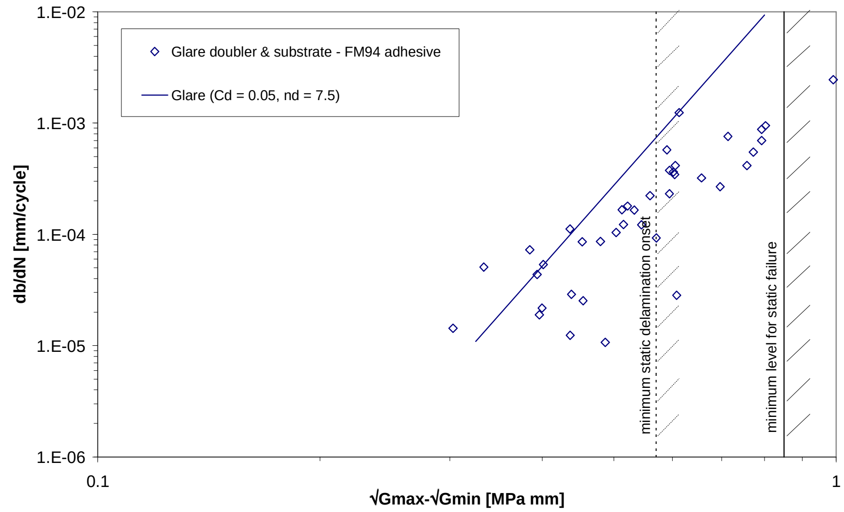

Figure 4: Delamination growth data from the bonded doubler run-out tests compared with the Glare curve from Figure 1

5.3 Bonded patch repairs

Beumler [10] reported tests on bonded patch repair panels. The panels were tested at a maximum skin stress of 106 and 120 MPa with R=0.1. The panel configuration is illustrated in Figure 5. To illustrate the predictive power of the proposed method, the delamination growth recorded in these tests is used to validate the predictions for this configuration.

The predictions in Figure 5 assume initiation at the first load cycle with subsequent growth with a constant rate. However, it is known that the initial delamination rate is higher during the very first few millimetres until a steady state phase has been reached [14,15].

For the test performed at S_{max}=120 MPa, the predictions are conservative, which is attributed to the occurrence of delamination initiation at a later stage in the test. For the S_{max}=106 MPa, the prediction is slightly unconservative. This is due to the fact that initial faster delamination growth is not accounted for and that delamination initiation occurred very early in the test. The method should therefore be further refined to account for the initial faster delamination rate or for the presence of an initial flaw.

The patch repair analysis is rather limited; to verify the approach for this configuration, the delamination growth was only predicted for the specimen centre line using a two-dimensional model. In time, the method can be extended to predict the growth over the full width.

The delamination of the patch from the base skin material initiated at the edge of the patch. Another damage case can be initiation of the delamination from the crack present in the base material, and subsequent growth towards the bonded patch edge. In that case, a complete analysis should be performed including damage growth in the base material and correlating delamination growth at the interface with the patch. It is envisioned that such method could be similar to the crack propagation and delamination method for FML's.

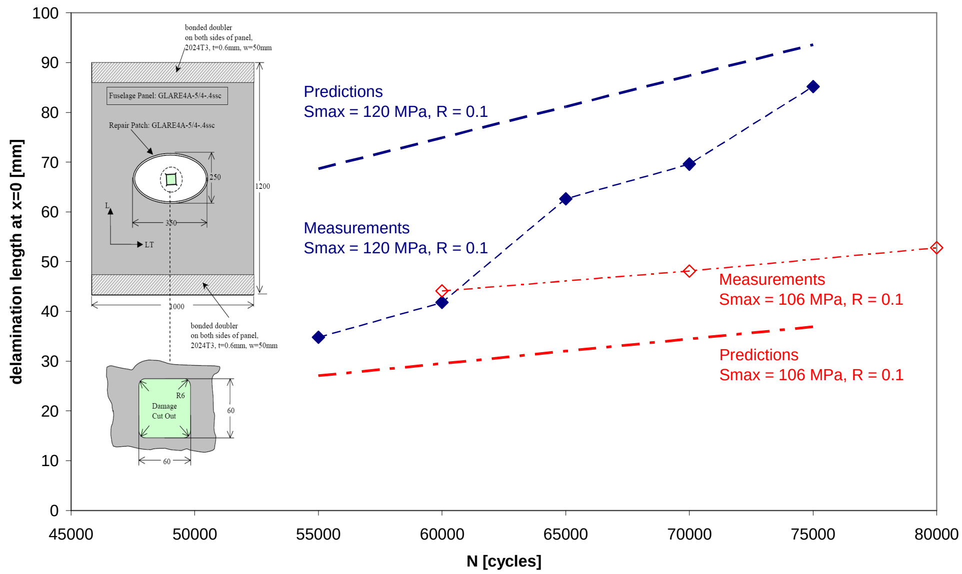

Figure 5: Comparison between measured and predicted delamination growth [21,10]

11 PROPOSED PHILOSOPFY

As a consequence of the initial faster delamination growth (delamination initiation induced by the mode I peel stresses) two approaches can be followed:

- Predicting delamination initiation based on mode I peel stresses and subsequent delamination growth with the propose method
- Assuming an initial manufacturing flaw and performing the delamination analysis as proposed.

For the time being, it is proposed to apply the second approach. The delamination growth analysis discussed in this paper can then be applied to the bonded structure starting from the initial flaw. The maximum delamination or disbond size can be described for each bonded structure for which limit load capability then can be proven by similar analysis and experiments.

The approach has been justified with experiments relate to metal and FML substrates. For several bonded structures for these substrates, the relevant damage modes are illustrated in Figure 6. The left-hand side presents the monolithic metal substrates and the right-hand side the FML substrates. For the case of Figure 6, there are two damage modes to be verified:

- Damage initiation and growth in the substrate
- Damage initiation and growth in the bond line

As mentioned earlier, for bonded patch repair, the damage growth in the substrate must be assessed together with the adjacent delamination growth.

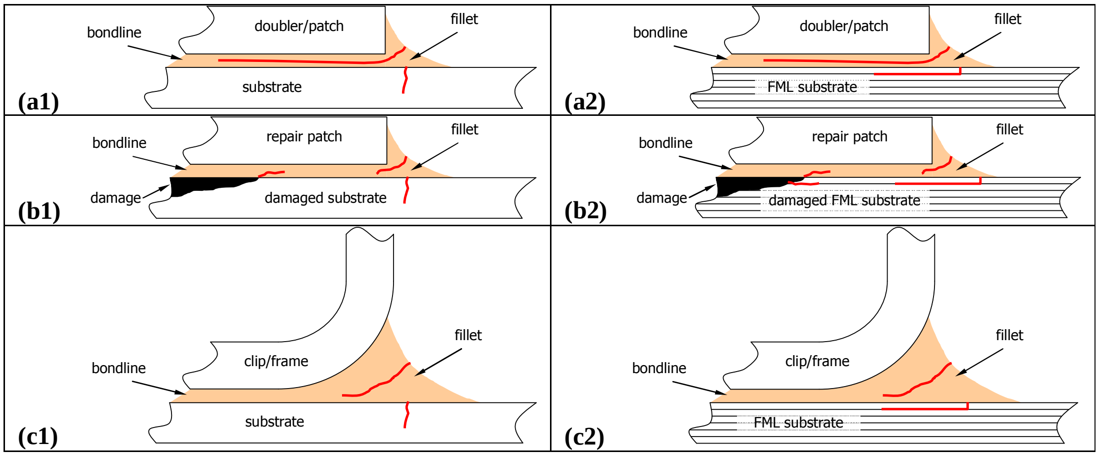

Figure 6: Illustration of damage modes in bonded structures

12 CONCLUSIONS

A generic damage tolerance approach for bonded structures has been proposed based on the elastic SERR concept. The approach has been validated on metal-to-metal and metal-to-composite bonded structures. It is recommended to further verify the method to extend the damage tolerance approach to composite-to-composite bonding. In case the approach appears to be invalid for this type of bonded structures, other approaches must be developed.

The approach proposed to assess damage tolerance is generic of nature and applies to the following bonded structures: bonded patch repairs, bonded skin-stiffener/frame/clip structures, laminated metal sheets, FML's and structures bonded with adhesive and with bondpreg. Further refinement of the proposed methods/approach can be obtained, by including the plasticity affect of the metal adherents to the SERR method. This has not been considered for this paper.

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