Determination of the failure load of adhesive bonding by using a coupled criterion

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Abstract :

Adhesive bonding presents several assets compared to classical assembly solutions. The determination of the failure assembly strength is a key issue to enhance reliability of such structure. Yet, the design methodology are quite rare. In this study, a model able to predict the failure of bonded assemblies has been develloped. The model is based on failure criterion based on a coupled stress and energetic approaches. In order to reduce the computationnal cost and to adjust with Design Office requirements, this model has been developped with a semi-analytical approach. A first experimental validation has been performed with the modified Arcan devices. The comparison between the experimental and the numerical results are in good agreements.

Résumé :

Le collage structural est une solution d'assemblage présentant de nombreux avantages par rapport aux solutions classiques. La prévision de la charge à rupture de ce type d'assemblage reste un point-clé pour rendre fiable leur utilisation. Toutefois, les méthodes de dimensionnement restent rares. Aussi dans le contexte de cette étude, un outil prédictif de la tenue mécanique d'assemblages collés a été développé. Il repose sur l'utilisation d'une approche en contrainte et en énergie. Dans le but de réduire les couts de calcul, et de le rendre utilisable en Bureaux d'Etudes, cet outils de dimensionnement sera également développé dans un cadre semi-analytique. Afin d'établir une première validation de l'approche proposée, une étude à l'aide du dispositif Arcan modifié a été réalisée. La confrontation des prévisions issues des deux modèles (éléments finis et semi-analytique) a permis d'établir une bonne corrélation avec les résultats expérimentaux.

Key words : Adhesive bonding ; coupled criterion ; modified Arcan device ; Semi-analytical model

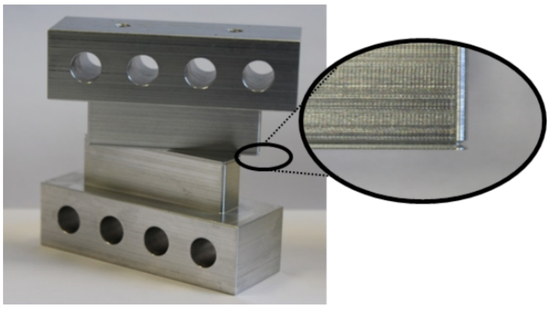
1 Introduction

This study will focus on a methodology to determine the assembly failure load of adhesive bonded structure. Quick determination of the assembly failure load is compulsory for industrial application.

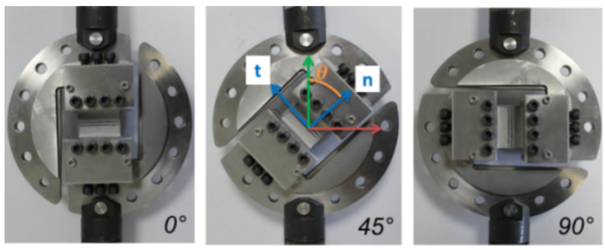
It avoids overdimensionning of the structure and also increase reliable of deisgn. The Finite Element Analysis (FEA) is widely used in various field for structural design. Yet, strong material and geometrical changes between adherent and adhesive disturb the numerical results near to this singular point. The stress distribution obtain from numerical tools tends to infinite values close to this singular zone. Stress criterion classicaly used present strong limitation to study this kind of configuration. In addition, these areas have been identified as privileged crack onset zone, because of the stress concentration. A coupled stress and energetic criterion is used to cope with this issue. Experimental data are obtained from modified Arcan device, with a geometry which strongly reduce the edge effects in bonded assembly[1]. Even if computer performance strongly improved, computational cost is still a key issue, especially in the case of industrial Design Office. According to that, a semi-analytical approach based on first order shear deformation theory is used [2]

2 Modified Arcan device

The modified Arcan device is relevant in the study of adhesive bonding assembly. The sample is composed of two adherents in aluminium alloy 2017 joined by a adhesive layer. The sample is clamped in a conventionnal unixial testing machine according to two parts (parts presenting holes on 1b). The force is applied with a specific angle θ normal to joint plan. The adherents present beaks at their extremities to reduce edge effects [1] [3]. (Z_N) and (S_T) are respectively the normal and tangential failure stresses of the adhesive and are presented in Table 1.



(a) Adherent and beaks geometry



(b) Sollicitations angles

Figure 1: Modified Arcan Samples

Failure stress [MPa]	Z_N = 26,1 ± 4,3	S_T = 49,4 ± 4,8
Toughness [N/m]	G_I = 191 ± 7,2 [4]	130 < G_{II} < 275 [5]

Table 1: Adhesive properties Hysol EA 9395

The numerical predictions of the assembly failure load will be compared to notched samples. The geometry of these symetric notched at each side of the samples is delineated in the Figure 2.

3 Failure force determination

Because of the strong variation of geometry and material changes near the corner edges, the stress distribution tends to infinite values near the this zone. Yet the stress distribution based obtained from the Linear Fracture Mechanics becomes reliable at a specific distance. The coupled criterion presented below is able to determined this internal length [6].

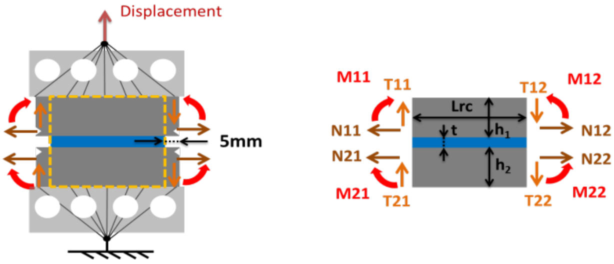


Figure 2: Evaluation of the section forces form FEA to analytical model

Section forces are evaluated from a FEA model. This efforts are estimated in the bonded area as presented in figure 2 by the dotted rectangle. The analytical model provide the stress distribution the adhesive layer despite the poorly mesh FEA model.

3.1 Stress criterion

The numerical stress distribution where $\sigma_N(x)$ is the normal stress according to joint plan $\sigma_T(x)$ is the tangential stress. The global stress $\sigma_{ap}(x)$ is defined for a combined stress in the structure. This structural stress distribution along the joint length is balanced by the ratio $r^\sigma(x)$.

$$\sigma_{ap}(x) = k_{ap}(x).E^{eq}.\epsilon.\sqrt{\left(\frac{r^\sigma(x)}{Z_N}\right)^2 + \left(\frac{1-r^\sigma(x)}{S_T}\right)^2} \tag{1a}$$

$$\sigma_{ap}(x) = \langle\sigma_N(x)\rangle_+ + \sigma_T(x) \tag{1b}$$

$$\langle\sigma_N(x)\rangle_+ > 0 \tag{1c}$$

$$r^\sigma(x) = \frac{\sigma_N(x)}{\sigma_{ap}(x)} \tag{1d}$$

We noticed that the only positive part of the normal stress is taken into account (Eq. 1c). The expression obtained in Eq. 1a presents a linear relationship between the strain applied (ϵ) to the structure and the non-dimensional parameter denoted $k_{ap}(x)$.

3.2 Energetic criterion

The energetic criterion is computed from a potential energy change between a crack $W_p(a)$ and uncracked state $W_p(0)$ with a the length of the crack [7]. The incremental energy is computed as the ratio between this energy change and the cracked surface. This value is compared to the toughness of the adhesive denoted $G^C(a)$, the evolution of this parameter is taken into account by mode mixity estimation. Analytically, the Strain Energy Released Rate is computed by considering the crack propagation equivalent to reduction of the overlap length [8].

$$G_{inc}(a) = -\frac{W_p(a) - W_p(0)}{\delta S} = A_{inc}(a).E^{eq}.\epsilon^2.h \geq G^C(a) \tag{2}$$

As presented for the stress criterion, a dimensionless parameter A_{inc} is defined and present a cubic relationship with the strain applied to the structure.

3.3 The assembly failure load

The specific fracture length of the material L_c is turn into a dimensionless parameter in order to be compared with the dimensionless stress and energetic parameters described previously. The formulation is given in equation 3 [6][7].

$$\frac{L_c}{h} = \frac{E^{eq} G^C(a)}{h \sigma_c^2} \tag{3}$$

where E^{eq} is the modulus of the considered adhesive, the evolution of the toughness G^C is describe by the mode mixity evolution and depends of the crack length a, σ_c the failure stress and h is a characteristic length (for instance the adhesive thickness) in order to obtain a dimensionless value.

This value is compared with the stress and energetic dimensionless parameters presented previously. When both criteria are simulteanously satisfied for a specific distance denoted a^* (eq 4a), the assembly failure is determined by Eq. 4b (by substitution in Eq.2).

$$\frac{L_c}{h} = \frac{A_{inc}(a^*)}{k_{ap}(a^*)^2} \tag{4a}$$

$$F^{failure} = K.\sqrt{\frac{G^C(a^*)}{A_{inc}(a^*).E^{eq}.\epsilon^2.h}} \tag{4b}$$

where K is the global stiffness of the structure. The boundary conditions of the FEA are displacements. This structural stiffness is considered as the sum of the force at the adherent extremities.

4 Results

Modified Arcan samples with notches were tested for three different angles of sollicitation (Figure 1b) (0°,45°,90°) as presented in Figure 3. These values are compared to the numerical prediction by FEA and semi-FEA approach by using the coupled criterion. Each experimental points correspond to 3 samples repetition.

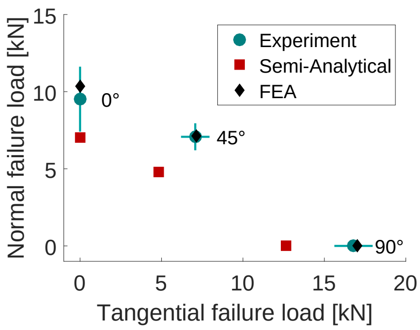


Figure 3: Comparison between numerical and experimental data

The comparison between numerical results obtained with FEA method and the experimental data are in good agreement. The coupled criterion applied analytically presents lower estimation compared to the FEA method. Yet, the computational cost ratio between the two methods is around 50. The coupled criterion applied with FEA gives failure predictions closer to the experimental data. The failure load predictions provided by numerical approach present slightly higher difference for the sample tested at $\theta = 0°$(tension) and 90° (shear). Semi-analytical results for shear-tension loading, the mode mixity is supposed to be constant and could explained the difference with the experimental data. Under shear loading, the toughness in mode II taken from the litterature [5] presents a large scattering as presented in Table 1. The obtained results are considering $G_{II} = 229,4N/m$

5 Conclusion

A design methodology is proposed to determine the bonded assembly failure load with a coupled stress and energetic approach. The semi-analytical approach is strongly reducing the computional cost. The comparison between the numerical and experimental predictions are in good agreement. The application of the coupled criterion with the analytical model could adjust with industrial requirements.

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