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# Stress analysis of composite adhesive bonded joints under incipient failure conditions

Amir Ghorbani*

*University of Padova - Department of Management and Engineering, Stradella S. Nicola, 36100 Vicenza, Italy*

**Abstract**

Composite structures with their remarkable properties often require assembling different components and repairing the damaged regions by employing mechanical or adhesive bonding joints. Among the bonding techniques, adhesive bonding is considered the most diffused and efficient method.

Analysis of stress distribution that develops in the joint is a crucial field of research to put effort with the aim to develop engineering strength criteria. Once an adhesive bonded joint is subjected to the axial tensile load, shear and peel stress intensification takes place at the ends of the overlap. With regard to the literature, it can be concluded that there are few reliable predicting tools for brittle adhesives, for which failure usually initiates at the edge of the bonding area and propagates through the interface region. The aim of this paper is an investigation on stress field in single-lap joint (SLJ) and scarf-lap joint (ScJ) under the tensile loading. A two-dimensional numerical analysis by employing Finite Element Method (FEM) and a developed analytical solution were implemented to realize the correlation of the results. Furthermore, a comparison between possible failure criteria was performed by using FE results. Adherend thickness, overlap length, and scarf angle were considered as the joint geometry parameters. Effects of these parameters on the fracture behaviour of bonded joints were evaluated.


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*Keywords:* Bonded joint, Brittle adhesive, Finite element method, Composite structure;

* Corresponding author.
*E-mail address: amir.ghorbani@studenti.unipd.it (A. Ghorbani)*


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## 1. Introduction

Composite structures with their notable features and widespread of applications are considered as an important subject to put the effort in study and research. Distinguished industry sectors from the traditional to the high technology required industry such as automotive, aerospace and sports equipment use composite structures.

In some structures due to complex shape or difficulty in assembling, bonded joints are needed. Damaged components are required to be repaired as well through this technique also. Adhesive bonding is an effective and diffused methodology which offers simple and light assembling and provides more uniform stress distribution in comparison with other types of joining. Increased willing to implement mentioned technique, push researchers to study on constraints of limitations to solve and optimize them.

There are many configurations of joint design. Single-lap joint (SLJ), double-lap joint (DLJ), scarf-lap joint (ScJ), juggle-lap joint (JLJ) are some of the standard types that each has appointed features coming with the design to match with the loading conditions. The strength of the bonded joints is affected by several parameters that can be categorized into; local geometry (adherend thickness and width, adhesive thickness, overlap length and overlap end geometry), material properties and environmental conditions. Several studies have been carried out to define the optimal thicknesses of the adhesive and adherend (Taib et al. (2006), Ji and Li (2013) and Castagnetti et al. (2011)). Although any universal relation has not been found between strength and adhesive, however, experimental studies recommend a thickness of 0.1-0.2 mm for adhesive to achieve the maximum strength (Gleich et al. (2011)).

Overlap length as an efficient parameter has been considered to be investigated in the literature as well (Li et al. (2015), Reis et al. (2005), Neto et al. (2012) and Campilho et al. (2013)). With respect to the reports, joint strength increases by the overlap length increases. Throughout the study on overlap length, mechanical properties of the components should also be kept in mind. For instance, Neto et al. (2012) illustrates that in the case of ductile adhesive, the failure load increases proportionally with the overlap length, while for the brittle adhesive the failure load increase up to a certain length and then remained constant.

With respect to the applied load, joint geometry, and component properties, adhesive bonded joints usually experience three distinct failure types: adherend failure, adhesive failure (failure at the interface) and cohesive failure (ASTM D5573) (Fig. 1.). Adhesive and cohesive failures can be classified together as the bondline failure. Predicting of the accurate stress and strain fields and applying a reliable failure criterion are the significant difficulties in the design of adhesive composite bonded joints.

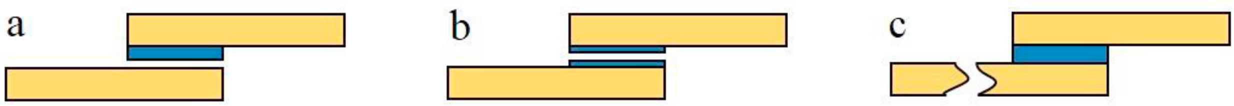



Fig. 1. (a) Adhesive Failure: Failure of the joint at the adhesive/adherend interface; (b) Cohesive Failure: Failure of the adhesive layer; (c) Adherend Failure: The adherend fails and not the adhesive

In accordance with the literature, there is no a universal failure criterion to implement in satisfactory design. Therefore, several researchers studied analytical and numerical methods to develop and improve the predicting tools for the joint strength.

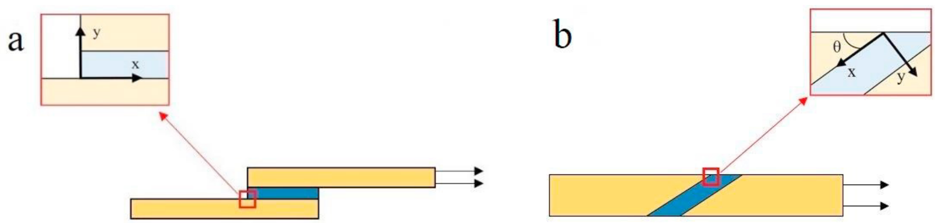



Fig. 2. Joint configuration and local geometry at the singular zone (a) Single-lap joint; (b) Scarf-lap joint

As it mentioned above, adhesive type and properties influence the joint strength and occurred failure of the joint. Severe plasticization of ductile adhesive leads the joint to fail within the adhesive (cohesive failure), where the failure initiates after a significant plasticization. The maximum principal strain has already introduced to be a suitable predictive parameter for ductile adhesive (Harris et al. (1984)). Da Silva et al. (2009) presented the maximum shear stress as an accurate criterion for this adhesive type. Ductile adhesives can carry loads during the yielding; therefore, failure criteria of ductile adhesive are not suitable for the brittle adhesive. There are fewer reliable predicting tools for brittle adhesives, for which failure usually initiates at the edge of the bonding area and propagates through the interface region. In another hand, stress concentration caused by sharp corner with dissimilar materials is the crucial issue. Fracture mechanics approach can be employed in the case of presence of the quantified stress singularity at bi-material sharp corner to predict the strength of the joint.

In this study, by referring to the several experimental campaign, the stress analysis of SLJs and ScJs (Fig. 2.) under incipient failure condition was carried out. Efficient parameters of adherend thickness, overlap length, and scarf angle were considered to study (Li et al. (2015), Neto et al. (2012), Campilho et al. (2013) and Kumar et al. (2006)).

## 2. Stress analysis of ductile adhesives

High degree of plasticization at the ductile adhesive layer initiating when the limiting stresses are attained, by increasing the load, the failure starts to propagate stably within the adhesive and then usually moves through the laminate (Reis et al. (2005)). The failure occurs at the maximum value of the shear stress which is the dominant stress of the ductile adhesive bonded joints. The joint strength is improved by promoting failure at a much higher value of shear stress. In the literature, maximum principal strain and average shear stress are most frequently used failure criterion in the case of plastic deformation.

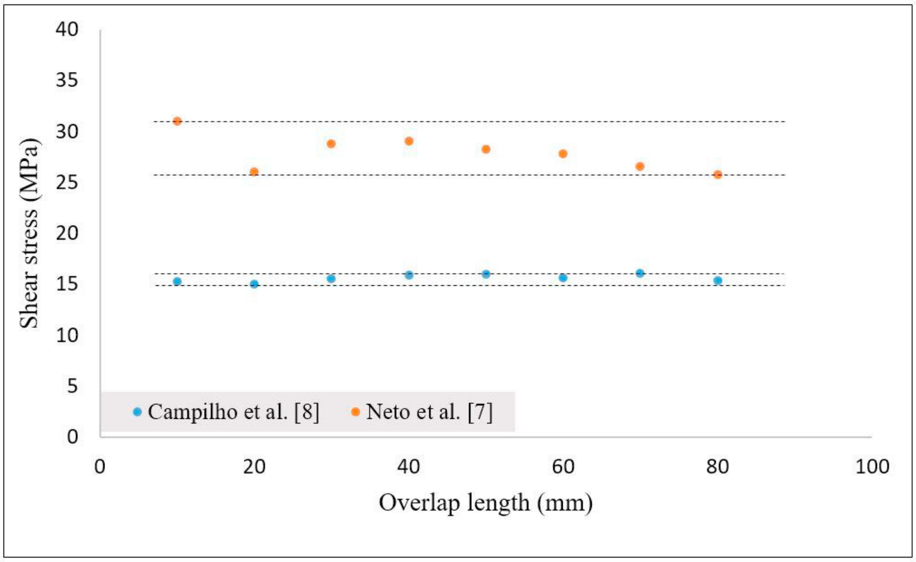



Fig. 3. Influence of the overlap length on the shear stress

Campilho et al. (2013) and Neto et al. (2012) studied on the SLJ adhesive bonded joints with overlap length from 10mm to 80mm. After experimental tensile tests, the ductile cohesive failure was observed for all the joints. With respect to the reported experimental result, the shear stress for different geometries were calculated simply dividing failure load by overlap area. Fig. 3. shows that the nominal shear stress of the bonded joints does not vary significantly with the overlap length. The stress values distributed in a satisfactory horizontal scatter band.

## 3. Stress analysis of brittle adhesives

Bonded joints with very brittle adhesives present a distinguish failure mode in comparison with ductile adhesives. For the interface failure, it is expected that a crack initiates at the bondline corner and propagates through the bondline at the interface. In this case, the stress-strain curve shows a linear behavior caused by less plasticization and absorbed relatively little energy before fracture.

Two main fracture mechanics criteria, based on stress intensity factor (SIF) and energy release rate (ERR) can be employed to stress analysis of the joints (Gent (1974)). In fact, before failure occurs there is not a crack at the adhesive, but a stress singularity caused by the sharp corner with dissimilar materials appears. The stress components in the singular zone are computed by following formulation (*ij=x,y* or *r,θ* with respect to the coordinate system):

$$\sigma_{ij} = \sum_n \frac{K_n}{r^{\lambda_n}} f_{ij,n}(\theta) \tag{1}$$

Where $K_n$ is the Stress Intensity Factor, $\lambda$ is the singularity exponent and $f_{ij}$ is the angular function at the corresponding r distance from the corner. Indeed, the first term is dominant which describes stress field.

Zappalorto et al. (2015) developed an SIF approach for a bi-material corner, where the k-factor can be calculated for the crack angle less than 180˚. This argument was employed in the adhesive-adherend interface of composite scarf-lap joints. Material properties and experimental test results were chosen from Li et al. (2015) and Kumar et al. (2006). Both studies experienced the interface failure for the specimens with different scarf angle and adherend thickness.

For validation of the theoretical results, a two-dimensional finite element (FE) analysis was done on the bi-material corner of ScJs. Finite element analysis by utilizing ANSYS software with using PLANE82 elements under plane strain conditions was carried out. The boundary condition was applied so that the specimen only could move along the loading direction and a high density meshing was performed in the singular zone in order to achieve a fine degree of accuracy (Fig. 4.). The size of the smallest element was chosen equal to $2\times10^{-4}$ mm.

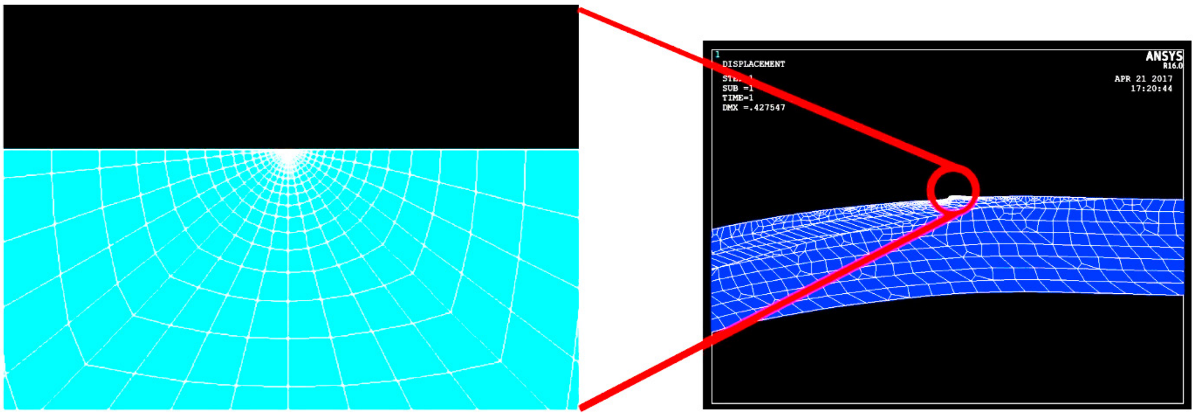



Fig. 4. Deformed shape of the ScJ model after applying the load and detail of the meshing at the singularity zone

Fig. 5. shows the shear and peel stresses in the distance from the singular zone along the interface (see Fig. 2. for ScJ configuration and adherend-adhesive interface) were computed by FE method. It is evident that for two scarf angles of 5.71˚ and 8.13˚ (Li et al. (2015)) shear stress is the dominant stress component. In addition, a satisfactory agreement was concluded by correlation of the theoretical shear and peel stresses results and FE data. It could be mentioned that K-factor can be assessed by aforementioned correlation. The slope of the logarithmic graph supply λ of eq. (1), which has been reported in Table 1.

Table 1. Experimental and numerical results for various scarf angle ScJs

| References | Scarf angle (˚) | Failure load (KN) | $\lambda$ | $K$ |
|---|---|---|---|---|
| Kumar et al. (2006) | 1.8 | 13.15 | 0.38 | 1.1 |
| | 2.9 | 9.44 | 0.4 | 1.8 |
| | 4 | 6.64 | 0.41 | 3.5 |
| Li et al. (2015) | 3.81 | 9.2 | 0.44 | 2 |
| | 5.71 | 6.9 | 0.44 | 2.6 |
| | 8.13 | 5.5 | 0.43 | 5 |
| | 11.3 | 4 | 0.40 | 5 |

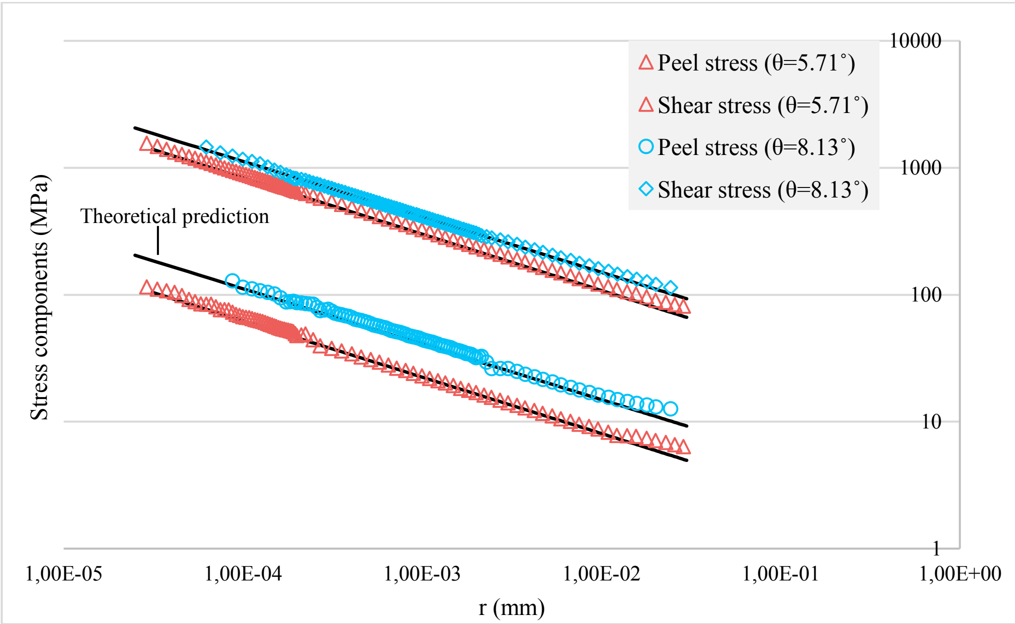
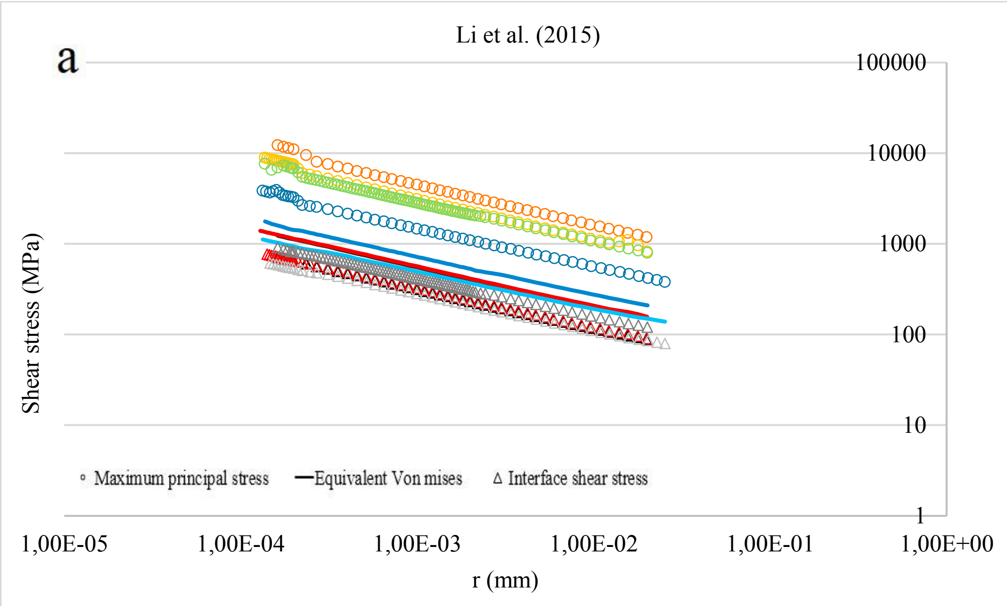



Fig. 5. Stress components along the bi-material interface and comparison between theoretical and FE results

In another hand, the study on FE results demonstrated that the shear stress is the dominant stress component. Logarithmic Fig. 5. presents the shear stress at the overlap corner and stress distribution through the interface. To understand the influence of scarf angle on stress distribution of the bonded joint, different angles have been analyzed in the literature. Kumar et al. (2006) tested the adhesive bonded composite joints with scarf angle ranging from 0.5˚ to 5˚. Specimens with scarf angles of 1.8˚, 2.9˚ and 4˚ experienced an interface failure. By FE stress analysis of these samples, a desirable overlapping of the results was observed (Fig. 6.).

Li and his coworkers (2015) examined the effects of the scarf angle and adherent thickness. Adhesive bonded joints with scarf angles of 3.81˚, 5.71˚. 8.13˚ and 11.3˚were studied. As the adherend thickness 0.96 mm, 1.92 mm and 3.84 mm with stacking sequences of $[45/0/\text{-}45/90]_s$, $[45/0/\text{-}45/90]_{2s}$ and $[45/0/\text{-}45/90]_{4s}$ were tested. By modeling these geometries with particular boundary conditions, the stress components were computed. Fig. 6. shows the plots of the shear stress along the bi-material interface. It is evident that increasing the scarf angle, cause a small deviation of the shear stress value and a satisfactory overlapping can be seen. A good convergence of the result is indicated, once adherend thickness is considered as the influencing parameter as well.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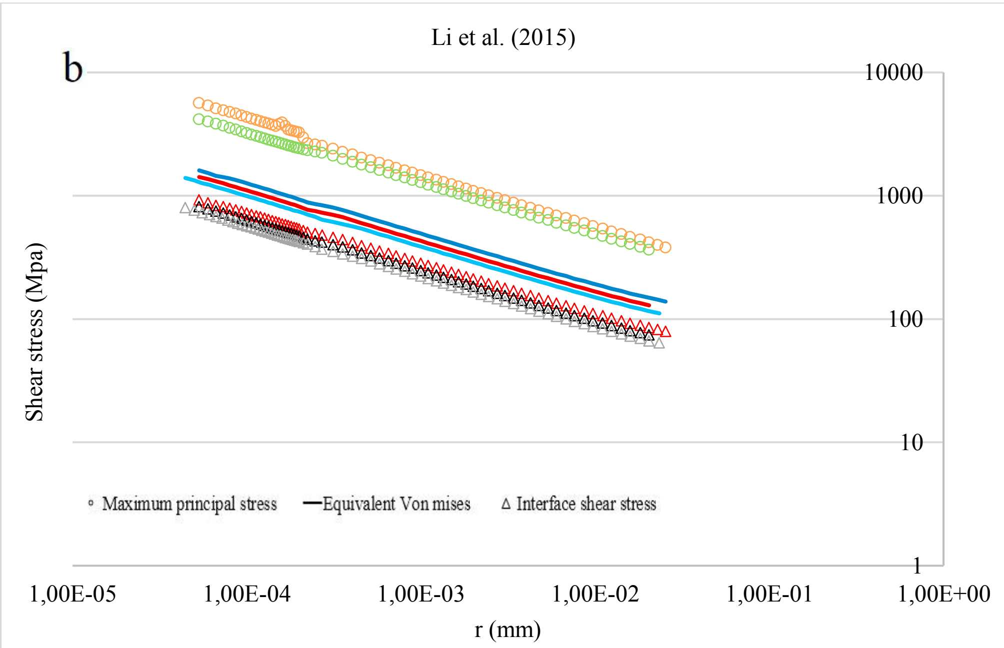
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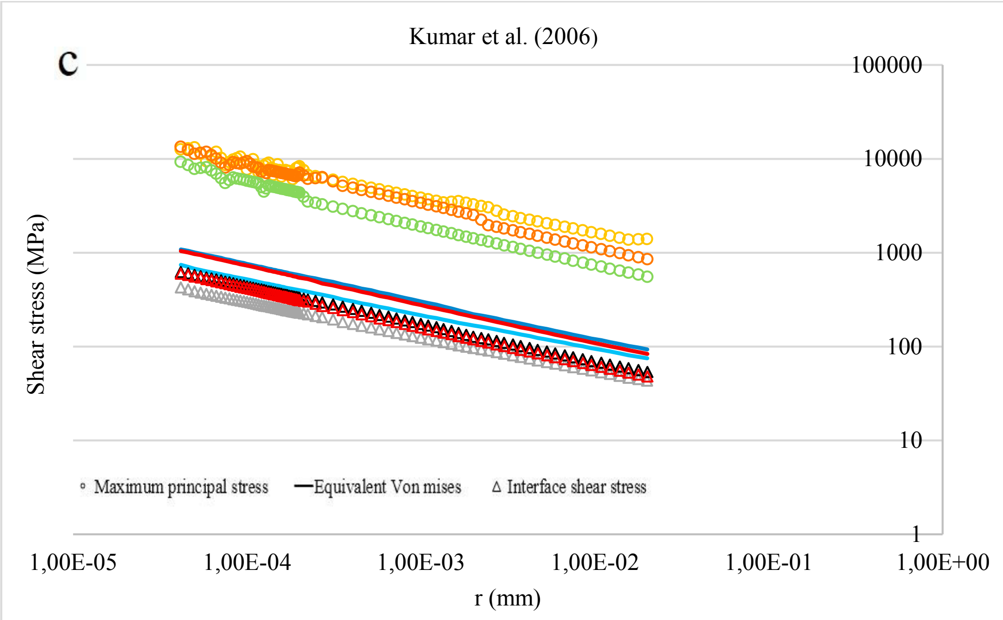


Fig. 6. Stress in close neighborhood of the overlap corner for (a) various scarf angle (Li et al.); (b) various adherend thickness (Li et al.); (c) various scarf angle (Kumar et al.)

In addition, according to the FE results, Von mises and maximum principal stress are obtained by following formula,

$$\sigma_{VM} = \sqrt{\sigma_y^2 + 3\tau_{xy}^2} \tag{2}$$

$$\sigma_1 = \left\{\sigma_x + \sigma_y + \sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2}\right\} \Big/ 2 \tag{3}$$

Respectively.

The comparison between possible strength criteria for the various scarf angle and adherend thickness are displayed in Fig. 6. Interface shear stress and Von mises equivalent stress for the joints with scarf angles of 3.81˚, 5.71˚. 8.13˚ (Li et al. (2015)) demonstrates a well-overlapped plot, while for 11.3˚ it has slightly deviated. Von mises and interface shear stress criteria in all the data series behave almost similar. It is also obvious that for the joints with scarf angles of 1.8˚, 2.9˚ and 4˚ (Kumar et al. (2006)) interface shear stress works well at the points very close to the singular zone, although the scatter increases with becoming distanced from the singular point. In addition, any trend could not be found between angles.

## 4. Discussion

To examine the overlap influence on the strength of the SLJs with ductile adhesive, average shear stress, which is introduced as an accurate criterion, was employed on experimental results collected from the literature. The shear stresses were calculated with an insignificant deviation for overlap length in Campilho et al. (2013) campaign. Slightly larger scatter for Neto et al. (2012) was caused by an impure cohesive failure of the joints.

Different angles for the ScJs with brittle adhesive were considered to understand the joint's strength. Table 1. shows the numerical K-intensity factor and the ultimate failure load obtained from experimental tests. It can be seen that the failure load decreases by the scarf angle increases. Different SIF values were calculated in the close neighborhood of singular zone also. With respect to the fracture mechanics for the brittle failure, it can be concluded that the recorded failures are not a pure brittle interface failure and other failure types occur and presence in the specimen. However, the shear stress is quite well overlapped (Fig. 6.). It means this parameter could be the driving force for the joint's failure.

In order to analyze the possible failure criteria for ScJ, maximum principal stress and Von mises equivalent stress were considered based on FE results to compare with interface shear stress. The FE shear stress value for different scarf angle and adherend thickness for Li et al. (2015) represent a small scatter, while a larger scatter can be seen for Von mises and principal stress curves. An approval comparing on Kumar et al. FE results, also demonstrates that the shear stress can be employed as a reliable failure criterion for ScJ with brittle failure in the interface.

## 5. Conclusion

In this study, after a literature survey on the experimental and numerical studies, compiled results were analyzed in failure mechanism point of view. The failure of the bondline region was categorized into two main types of ductile and brittle. The average shear stress which is introduced an accurate criterion for ductile adhesives was employed to understanding the influence of the overlap length on the single-lap composite bonded joint's failure. In consequence, considerably small to be neglected amounts were calculated for the shear stress in the different overlap length.

Afterwards, a two-dimensional numerical analysis by employing Finite Element Method (FEM) and a developed analytical solution were implemented to realize the correlation of the results and understanding the failure behavior of the brittle adhesive bonded joints. scarf-lap joints with interface failure was considered. Despite the fact of the different amount for K-factor, a satisfactory agreement was concluded in comparing the results.

Finally, a discussion on the possible failure criteria for brittle failure in the bi-material corner of ScJs was performed. The best results were found for the interface shear stress with a well overlapping for various scarf angles.

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