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Finite Element Analysis of Single-lap Adhesive Joints with Tapered Adherends

Francesco Marchione*

Dipartimento di Ingegneria Civile, Edile e Architettura (DICEA), Università Politecnica delle Marche, via B. Bianche, 60131, Ancona, Italy.

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ABSTRACT

Adhesive joints are becoming increasingly popular in various industrial sectors. However, in spite of numerous recent studies in literature, the design phase of the adhesive joint is still challenging. The main issue in the design phase is the determination of the stress distribution in the adhesive layer under external mechanical loads. In the present study, a classical adhesive joint is analysed in comparison to its modified geometric configuration (i.e. tapered) aimed at reducing the magnitude of stress peaks. In particular, a single-lap joint with steel adherends bonded with a commercial epoxy adhesive is analyzed. A 3D finite element (FE) analysis is conducted to determine the distribution of normal and shear stresses in the mid-plane of the adhesive layer. The results obtained from the present study show that the inclusion of a small taper angle (i.e. 5°) leads to a remarkable reduction of normal stresses (up to 30%) compared to the classical configuration. It is observed that the further increase of the taper angle (up to 15°) does not lead to significant reductions of the stress peaks. The trend in shear stresses, on the other hand, is in contrast: an increase in the taper angle leads to an increase in the shear peaks. The method of tapering the adherends is effective in reducing the normal stresses, which are responsible for triggering the failure in the adhesive joint.

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NOMENCLATURE			
EPX1	Epoxy adhesive		
α	Taper angles	***ν***	Poisson ratio (-)
ρ	Density (kg/m^3)	E	Young Modulus (GPa)

1. INTRODUCTION

Adhesive technology is experiencing numerous applications in various industrial sectors [1-3]. The widespread use of adhesive joints is due to a number of factors, including lower stress concentration, better fatigue behaviour and the possibility of joining different materials [4].

Although there are numerous studies in the literature [5-7], the design process of the adhesive joint is particularly difficult; both because of the non-linear mechanical properties of the adhesives [8, 9], and their behaviour after exposure to severe environmental conditions.

The adhesive joint known as single-lap joint (SLJ) presents a simple geometry for testing the joint's behaviour in tension. However, this type of joint, due to its geometric conformation, presents bending moments at the end of the adhesive region [10], which often represent the cause of the joint failure.

Several studies have been carried out with the aim of reducing the magnitude of the stress peaks at the ends of the adhesive joint, by making modifications on both the geometry of the adhesives - as demonstrated by Bouchikhi et al. [11], Marchione [12] – and on the geometry of the adhesives (e.g. spew fillet) - as shown by Crocombe et al. [13]. Sancaktar et al. [14] argue that adhesive failure depends on the tension peaks recorded at the ends of the joint. Therefore, by adopting techniques to contain the stress peaks - e.g. modifications in terms of geometry and materials - the value of the ultimate load can be reduced.

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*Corresponding Author Institutional Email: *f.marchione@pm.univpm.it* (F. Marchione)

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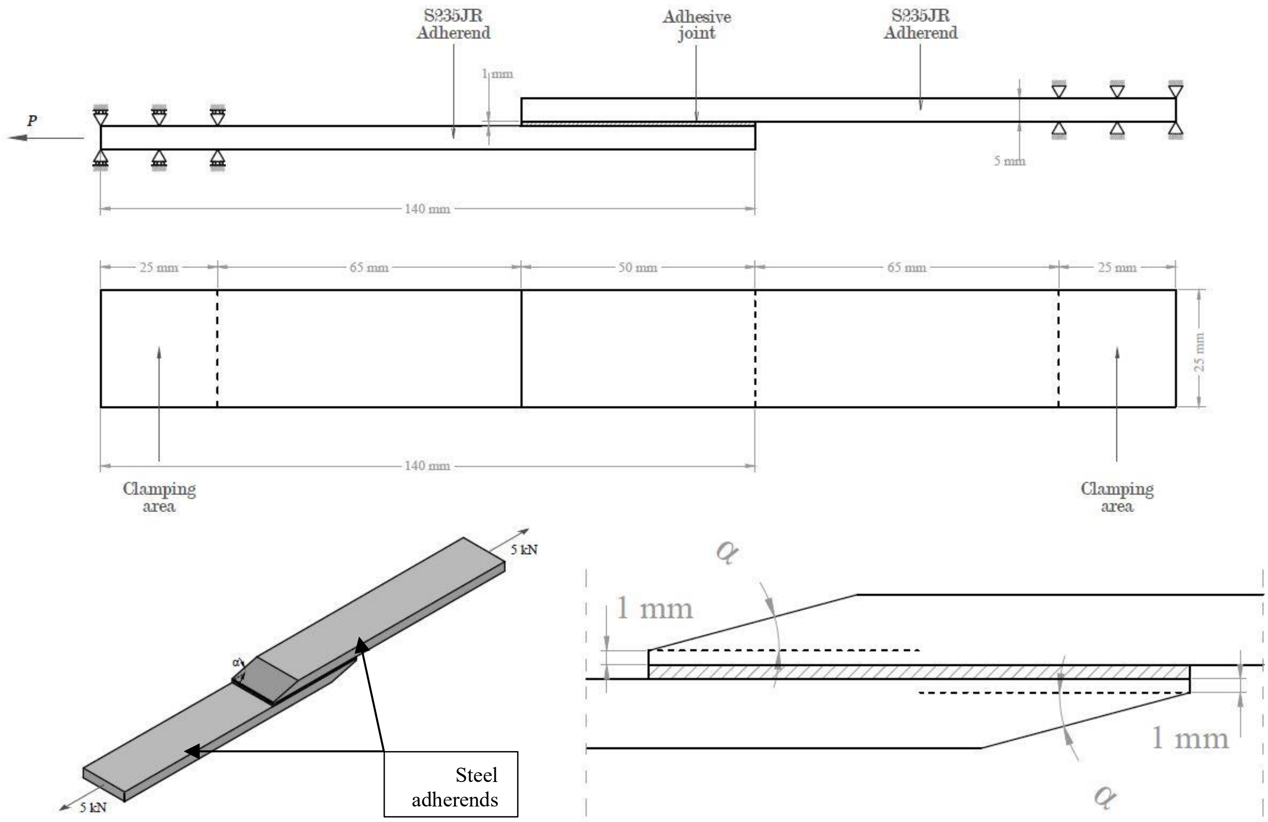


Figure 1. Geometry of Single lap adhesive joint: lateral and top view; 3D model and detail of the modified adherends' geometry in the bonding region

To date, there are numerous studies in the literature that illustrate valid methods for achieving this result, leading to a significant improvement in not only mechanical [15], but also thermal [16] and durability [17] of the adhesive joint. The major limitation of the current state of the art is the absence of a parametric FE study with adhesives and adhesion configurations such as those proposed here. The study presented below illustrates how slight geometric variations of the adhesives result in changes of the stress state in the adhesive. This study is the result of an application of the adhesive joint in civil engineering for the construction of new building components (e.g. windows and curtain walls).

In fact, in the context of engineering design, a fundamental role is played by FE analysis. In fact, the accurate and rapid knowledge of the stress state represents the starting point for a correct design. The objective of the present work is to perform a parametric study on the trend of the stress state in a single-lap adhesive joint (SLJ). In particular, the trend of normal and shear stresses in a classical SLJ joint is compared to that of the same joint modified in its geometry through different taper angles of the adhesives (i.e. 5°-15°). A parametric study on the influence of the taper angle on the distribution of stress peaks in the mid-plane of the adhesive layer is therefore carried out.

2. FE ANALYSIS

The adhesive joint used for the FE analysis is graphically shown in Fig. 1. This figure shows the geometry configuration of the adhesives in the modified configurations. The angle $\boldsymbol{\alpha}$ represents the inclination of the external surface of the adherends.

The adherends are 140 mm × 30 mm × 5 mm, in length, width and thickness, respectively. The bonding area is 30 mm × 50 mm; the thickness of the adhesive is set equal to 1.0 mm.

The same boundary conditions have been applied to all the configurations considered. Tables 1 and 2 show the mechanical properties of the materials considered.

Eight noded three-dimensional structural volume element (SOLID185 element) is employed for modelling the adhesive joints, with a maximum mesh dimension of 0.50 mm. The numerical modeling is carried out using the software ANSYS$^{\copyright}$19 with its solutor "Static Structural". Fig. 2 shows the FE model. The analyzed joints are made of S235JR steel adherends and one commercial epoxy adhesive.

TABLE 1. Materials' characteristics for the FEA model

STEEL S235JR		
E_t [GPa]	ρ [N/m^3]	**ν** [-]
69	78000	0.30

TABLE 2. Adhesive's characteristics for the FEA model

EPX 1	
E [GPa]	**ν** [-]
3.00	0.40

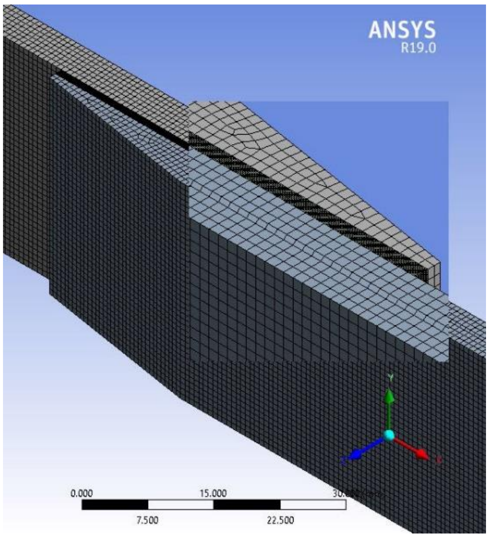


Figure 2. Meshed model for FE analysis

The analysis presented is of the static elastic-linear type, since it is intended to investigate the behaviour of the joint in the service phase, in which it is assumed to be in the elastic phase for all the materials constituting the joint. The load to which one of the two adherends is subjected is 5 kN, which is purely representative of the service phase for joints between steel adherends, as demonstrated in the study conducted by Machalicka et al. [18].

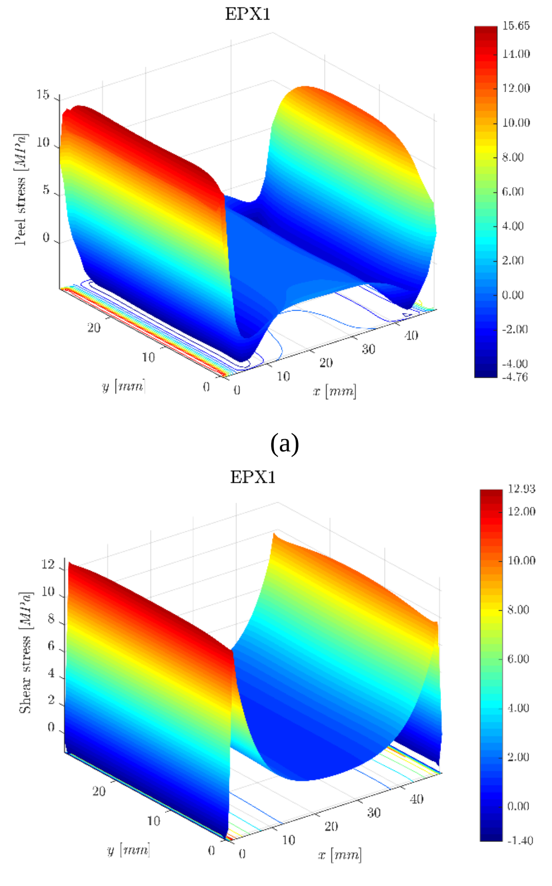
The load path used is ramped, with a total duration of 60 seconds and a linear trend from 0 to 5 kN.

After solving the mathematical model in ANSYS, the mapping of the normal and shear stresses is extracted and plotted using the software MATLAB©.

3. RESULTS AND DISCUSSION

This section reports the results derived from the FE analysis of the joint, according to different gemetric combinations.

In particular, as illustrated above, the results are compared for joints with a taper angle of 90° (classical joint) with joints characterised by taper angles of 5° and 10°, respectively. The results are graphically shown in Figs. 3 to 5. Figs. 3(a) and 3(b) show the stress curve for the unmodified adhesive joint.

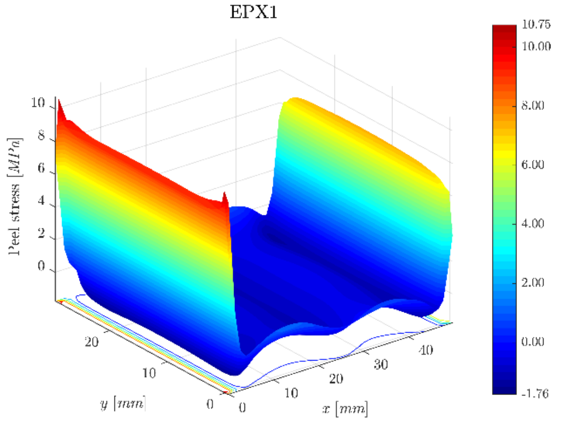


(a)

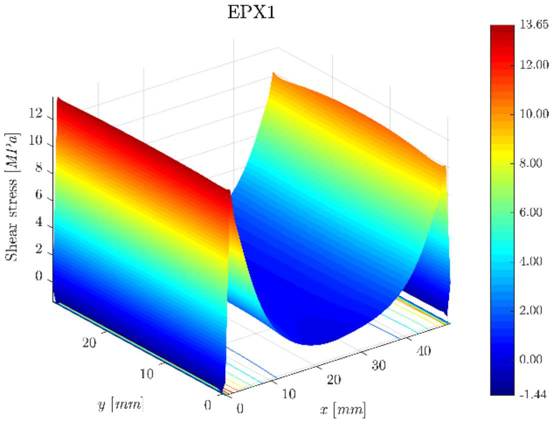
(b)

Figure 3. Peel and shear stress distribution for classical single-lap joint configurations

Figs. 4(a) and 4(b) show the stress distribution for the adhesive joint with 5° tapered adherends.



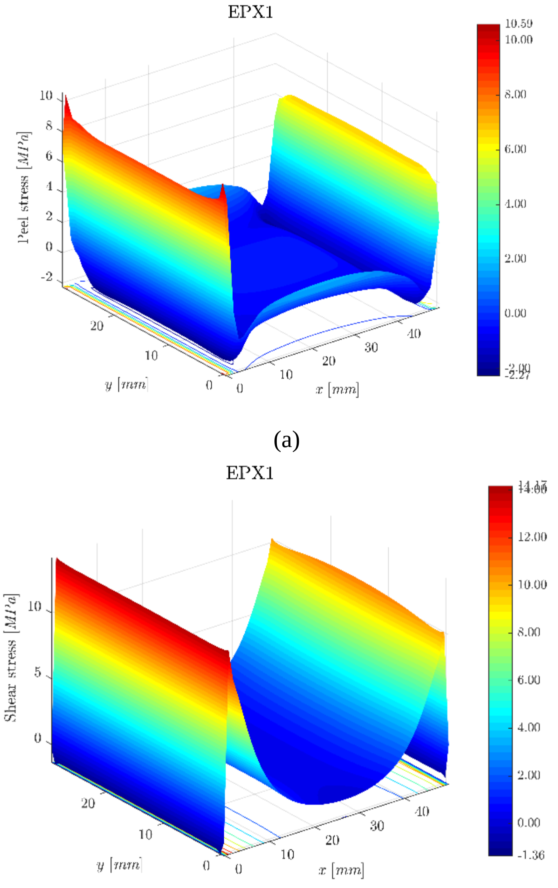
(a)



(b)

Figure 4. Peel and shear stress distribution for 5° taper adherends angle onfigurations

Figs. 5(a) and 5(b) show the stress distribution for the adhesive joint with 10° tapered adherends.



(a)

(b)

Figure 5. Peel and shear stress distribution for 10° tapering adherends angle onfigurations

As previously stated, and as could be observed in Figs. 3 to 5, the stress distribution presents stress peaks at the ends of the adhesive joint, both in the case of shear and normal stresses.

The presence of such peaks (especially for normal stress) represents a negative factor for the mechanical behaviour of the joint, since they can be identified as the cause of the initiation of damage in the adhesive region. Therefore, by reducing the magnitude of these peaks at the same load, it is possible to develop greater joint resistance, postponing the occurrence of the critical stress peaks for the joint to higher loads.

This type of distribution remains qualitatively identical for all the configurations considered. It is also observed that the stress distribution does not vary significantly in the width of the adhesive joint; this aspect enhances 2D or algebraic analyses, which are able to estimate the stress distribution in a simplified manor.

The maximum values of the stresses are obtained at the lateral edge of the adhesive area, as is known.

The introduction of the taper adherens involves - in any case - a decrease in the normal stresses.

Table 3 shows the values of the stress peaks measured.

TABLE 3. Stress peaks values

EPX 1

Taper angle [°]	Peel stress peak [MPa]	Shear Stress peak [MPa]
-	15.65	12.93
5	10.75	13.65
10	10.59	14.17

It can be observed that by inserting a taper angle of 5° in both adhesives, it is possible to obtain a reduction of the stress peaks of about -30% with respect to the classical configuration. In fact, compared to a normal stress peak of 15.65 MPa, it is possible to obtain a maximum value of 10.75 MPa.

Fig. 6 summarizes the stress peaks observed.

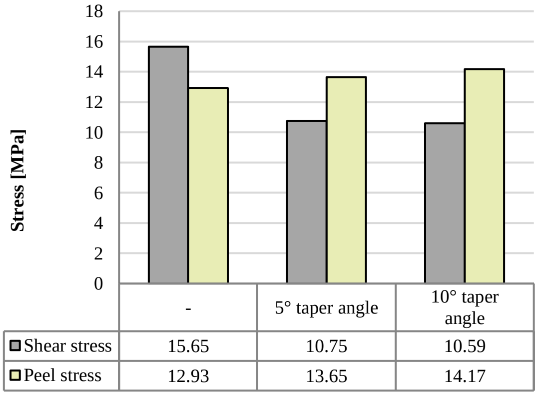


Figure 6. Peel and shear stress peaks observed for each geometric configuration

By increasing the taper angle of the adherends (10°), a decrease in the normal stress peaks is observed, although negligible compared to the previous configuration. On the contrary, for the shear stresses, an increase in the magnitude of the detected stress peaks is observed. In fact, an increasein the taper angle leads to an increase in the shear stresses, even if for low increments. This phenomenon is due to the decrease in stiffness of the adhesive joint, obtained by thinning the adhesives. This procedure leads to a reduction in the bending moments, bringing the behaviour of the joint closer to that of pure shear. Therefore, there is a considerable decrease in normal stress - often considered as the cause of the joint failure - accompanied by a slight increase in shear stresses.

4. CONCLUSIONS

To date, adhesive technology is very important for many production sectors. Therefore, the study and design of the joint is a fundamental element. The correct knowledge of the tensional state is the basis of this engineering process. In literature there are numerous studies aimed at improving the mechanical behaviour of the joint, through geometric, chemical, mechanical modifications of the materials that compose it.

The aim of the present study is to numerically analyze the mechanical behaviour of a SLJ adhesive joint. In particular, the effects of the insertion of taper in the adhesives on the distribution of stress peaks in the adhesive region are analyzed. In particular, a S235JR steel-steel single-lap joint is considered.

The main outcomes are:

- The stress distribution is almost constant across the width of the adhesive region; therefore shear-lag and 2D analyses prove to be valid design tools;
- The stress distribution always maintains stress peaks at the edges of the adhesive region; in particular, it is the highest at the lateral edge of the overlap region;
- The insertion of tapered adherends results in a decrease in normal stresses, while at the same time resulting in a slight increase in shear stresses;
- The inclusion of tapered adherends has a positive effect on the mechanical behaviour of the joint, which shows behaviour closer to pure shear.

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Persian Abstract

اتصالات چسبنده در بخشهای مختلف صنعتی به طور فزاینده ای محبوب می باشند. با این وجود ، علی رغم مطالعات متعدد اخیر در زمینه ادبیات ، مرحله طراحی اتصال چسب هنوز هم چالش برانگیز است. مسئله اصلی در مرحله طراحی ، تعیین توزیع تنش در لایه چسب تحت بارهای مکانیکی خارجی است. در مطالعه حاضر ، یک اتصال چسب کلاسیک در مقایسه با پیکربندی هندسی اصلاح شده آن (یعنی مخروطی) با هدف کاهش میزان قله های تنش ، مورد تجزیه و تحلیل قرار گرفته است. به طور خاص ، یک اتصال تک دور با اتصالات فولادی که با یک چسب اپوکسی تجاری پیوند خورده است ، تجزیه و تحلیل می شود. برای تعیین توزیع تنش های طبیعی و برشی در وسط صفحه لایه چسب ، یک تحلیل اجزای محدود D3 (FEA) انجام شده است. نتایج به دست آمده از مطالعه حاضر نشان می دهد که درج زاویه کوچک مخروطی (یعنی ۵ درجه) منجر به کاهش چشمگیر تنش های طبیعی (تا ۳۰٪) در مقایسه با پیکربندی کلاسیک می شود. مشاهده شده است که افزایش بیشتر زاویه مخروطی (تا ۱۵ درجه) منجر به کاهش قابل توجه قله های تنش نمی شود. از طرف دیگر روند تنش های برشی در تقابل است: افزایش زاویه مخروطی منجر به افزایش قله های برشی می شود. روش مخروطی کردن چسبنده ها در کاهش تنش های طبیعی که مسئول تحریک شکست در اتصال چسب هستند ، موثر است.
