



Analytical Stress Analysis in Single-lap Adhesive Joints under Buckling Loads

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PAPER INFO

Paper history:

Received 04 September 2020

Received in revised form 29 September 2020

Accepted 26 October 2020

Keywords:

Buckling Load

Single-lap Adhesive Joint

Adhesively Bonded Joints

Stress Distribution

ABSTRACT

Adhesive joints find numerous applications in various industrial fields. They represent a valid alternative to traditional joining methods. Much of the available scientific literature has focused on the study of adhesive joints subjected to tensile loads. There have also been numerous studies concerning the stresses distributions in the adhesive layer. However, in real case applications, adhesive joints could also be subject to cyclic tensile-compression loads and therefore could be subject to buckling phenomena. The objective of the present paper is to investigate the numerical study of the stress distribution in the adhesive layer under buckling condition. The study presented develops with the analysis of a single-lap joint with a combination of steel adherends and three different structural adhesives with different thickness and Young's modulus. The joints are modeled using FE ANSYS®19 software. Through numerical analyzes, it is possible to predict the value of the critical load for each single analyzed combination. Once the critical load is determined, the stresses in the middle plane of the adhesive layer are determined. The results obtained show that for small adhesive thicknesses (i.e. 0.30 mm) it is possible to reduce the stress peaks - with the same critical load value - by using structural adhesives with low elastic modulus (e.g. silicones).

doi: 10.5829/ije.2021.34.02b.02

NOMENCLATURE

EPX1	First epoxy adhesive	ρ	Density (kg/m ³)
EPX2	Second epoxy adhesive	ν	Poisson ratio
SIL	Silicone adhesive	E	Young Modulus

1. INTRODUCTION

Adhesive bonding nowadays represents a joining technique widely used in numerous applications [1-3] (e.g. automotive, naval, footwear and civil engineering applications). This type of joint provides considerable advantages over traditional joining techniques, such as a more uniform stresses distribution obtained without adding weight to the structure.

Among the most studied joints in the literature, there is the Single-lap joint (SLJ) [4-6]. Most studies focus on assessing its mechanical properties for shear and bending stresses.

Adams and Peppiatt's [7] studies were among the first in deepening the knowledge about the mechanical behaviour of the adhesive joint under tensile loads. The

main result was that the stress distribution is characterized by stress peaks at the edges of the bonded region. Hamdan [8] analysed the effects of non-dimensional geometric parameters on stress concentration factors of circular hollow section brace-to-H-shaped section T-connections under axial compression. Rastegarian et al. [9] studied the dependency of structural performance level and its corresponding inter-story drift in conventional RC moment frames. Specimens were studied by pushover analysis and equations were proposed to predict inter-story drift. Rahman et al. [10] studied the improvement in stress distribution of flexible pavement due to the application of geo-jute at three specific positions. Results showed that the inclusion of geo-jute on flexible pavement significantly improves its mechanical

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performance. Ferdinand et al. [11] analysed the application of BRB in strengthening of RC frame structures to meet Chinese seismic design code. The results show that buckling restrained braces demonstrated better performance of strengthening the structure and make it meet the requirement of code. Haghollahi [12] presented a numerical study on the behavior of connection between steel I-beam and H-column affected by cyclic loading. The results showed that welded flange plate (WFP) connection which did not satisfy the criteria of AISC seismic provisions for special moment frames, can be upgraded by a vertical triangular rib plate in order to be used in special moment frames.

Mohammed et al. [13] presented a numerical analysis using FE method to investigate the effect of semi-rigid connections on post-buckling behaviour of two-dimensional frames with different supporting types and different lateral loading cases. Abdolvahab [14] investigated local buckling of sinusoidal corrugated plates under uniform uniaxial loading on the transverse edges of the plate using the Galerkin method. The results obtained for the critical buckling load of sinusoidal corrugated metal plates and the results relating to the metal homogeneous flat plates were compared using the same supporting conditions and loading. Selahi et al. [15] presented a solution for stress distribution using the energy method, considering the effect of adhesive thickness. Further studies [16] investigated a numerical 3D stress distribution in a composite single-lap adhesive joint, determining also the location of the damage initiation. Bai et al. [17] studied a method for interfacial stress analysis of composite single-lap joint based on full-field deformation. Li et al. [18] modeled a 2D FE analysis to determine the stress in the adhesive thickness of composite single-lap joints. The results showed that the stress peaks increase with adhesive thickness and Young's modulus.

Although numerous studies have been carried out on adhesive joints under tensile loads, those on other loading conditions are still relatively scarce. In fact, in several real applications, adhesive joints are subjected to different types of loads (e.g. bending, cyclical tensile and compression loads, pure compression). In the case of axial compression stresses, instability phenomena may occur. As with other structural elements, compression loads can lead to the buckling condition of the adhesive joint and then can cause its failure. This failure mode may lead to the failure of the structure for stress values much lower than the ones related to the characteristic strengths of the materials. The innovation of the present paper is that it focuses on the stress distribution in the SLJ taking into account the compression loads in buckling condition.

Holston [19] provided a closed-form solution for buckling loads based on potential energy for a rectangular composite plate. Kim and Kwon [20]

determined a closed-form solution for one-edge-free composite plates under buckling loads.

Since the problem of instability is quite common in the various applications of structural adhesives, the study and verification of structural performance under axial load conditions is fundamental in the design phase. Figure 1 illustrates the research methodology.

The present paper focuses on different combinations of structural adhesives (i.e. two epoxy adhesives and a silicone) in a single-lap adhesive joint and their stress distribution as the thickness of the adhesive layer varies (0.30, 0.60, 1.00 mm) in the buckling load condition.

The following section reports on the materials and methods considered for the consequent FE analysis. In particular, all geometrical and physical characteristics of the joint are illustrated, as well as the FE analysis settings. The results obtained are detailed and discussed in the following.

2. FINITE ELEMENT ANALYSIS

A configuration of a typical single-lap joint, used as a model for the FE following analysis is depicted in Figure 2.

The dimensions of the adherends are $140 \times 25 \times 5$ mm, representing its length, width and thickness, respectively. The bonding area is 25×25 mm; the thickness of the adhesives varies in relation to the configuration considered (0.30, 0.60 and 1.00 mm).

The same boundary conditions have been applied to all the configurations considered. The surfaces of the clamping areas on the adherends are shown in Figure 2. Tables. 1-2 show the mechanical properties of the materials and the adhesives considered.

A plane strain condition is used for FE analysis by specifying the width in the definition of the elements. The numerical modeling is carried out with the software ANSYS®19. The model is meshed with PLANE 182, a 4-node structural solid and a base element size of 0.10 mm. The analysed joints are made of S235JR steel adherends and different adhesives (two epoxies and one silicone).

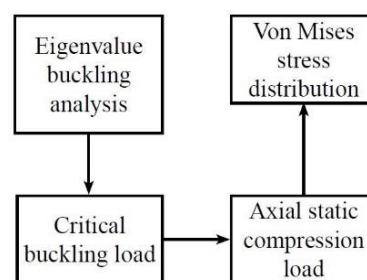


Figure 1. Research methodology

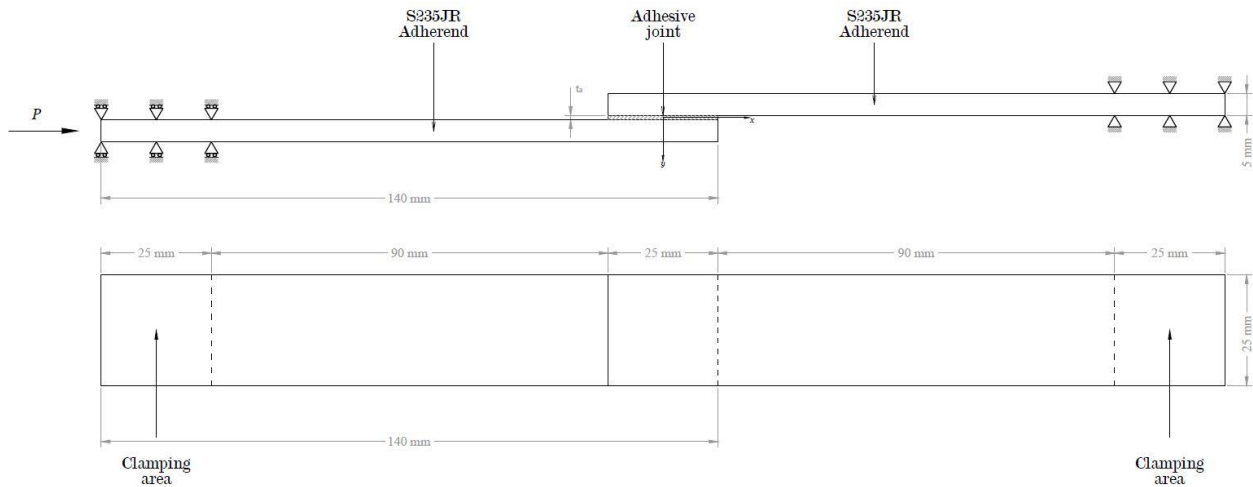


Figure 2. Geometry of Single lap adhesive joint: lateral and top view

The FE analysis here presented is a “Linear Eigenvalue Buckling Analysis” which returns the buckling load for the first buckling mode for each configuration. Once the buckling load is determined, the structure is axially statically loaded with the critical load in order to determine the stress distribution in the middle plane of the adhesive layer. The results are detailed in the following.

3. RESULTS AND DISCUSSION

This section reports on the buckling analysis of the single-lap adhesive joint illustrated in section 2.

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 [-]
17.50	0.30
EPX 2	
E [GPa]	ν [-]
3.25	0.40
SIL	
E [MPa]	ν [-]
1.00	0.30

Different combinations of adhesives (i.e. epoxy and silicone adhesives) with various thicknesses (0.30 mm, 0.60 mm, 1.00 mm) are considered and analysed. The eigenvalue analysis is carried out with the FE software ANSYS®19.

The buckling load condition, and hence its value is determined through the linear eigenvalue analysis. Once the critical load is known, the joint is statically loaded with the buckling load. Therefore, the stress distribution (Von Mises criterion) is determined along the adhesive layer midplane.

Figures 3-5 show the stress distribution obtained for each configuration. Figure 3 shows the stress distribution for EPX1 configuration: stresses values are almost constant and equal to the peaks for the adhesive thickness of 0.30 and 0.60 mm. It could be observed that the 1.00 mm thickness of the adhesive influences the stress distribution. In fact, it is characterized by two lower peaks at the edges of the bonding region and almost a parabolic trend in the middle area.

Figure 4 shows the stress distribution for EPX2 configuration: stresses values are almost constant for the first two configurations (0.30 and 0.60 mm adhesive thickness). Also in this case, it could be observed that the 1.00 mm thickness of the adhesive presents two peaks at the edges of the bonding region and almost a parabolic trend in the middle area. In this case, the highest stress peaks are observed in the 1.00 mm thick adhesive.

Figure 5 shows the stress distribution for SIL configuration: stresses values are very low if compared to other configurations (0.03 MPa) and almost constant for the first two thickness values. In this case, the 1.00 mm thick adhesive presents a higher stress value (0.61 MPa).

Tables 3-5 show the buckling load and stress peaks values obtained for each configuration. It could be

observed that every combination, except for SIL with 1.00 adhesive thickness, shows almost the same buckling load value (always between 813-854 N).

On the other hand, stress peaks are very different in relation to the adhesive considered. In fact, EPX 1 shows high values of stresses; EPX 2 shows lower values, almost half compared to the previous adhesive. SIL adhesive configurations show always very low-stress peaks values (between 0.03 and 0.61 MPa) since the adhesive is the less stiff among all the adhesives

considered. In particular, considering the stress values, the first two SIL configurations are optimal since at the same buckling load they allow to reach very load value in the adhesive layer. This mechanical behaviour of the joint is due to the ductility typical of silicone adhesives.

The last configuration for SIL adhesive (1.00 adhesive thick) shows the effect of the adhesive thickness: buckling occurs for very low axial compressive load (8.36 N).

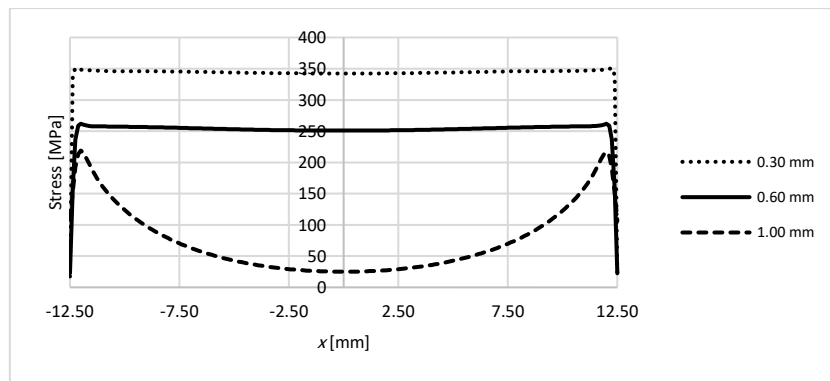


Figure 3. Stress distribution for EPX1 adhesive configurations

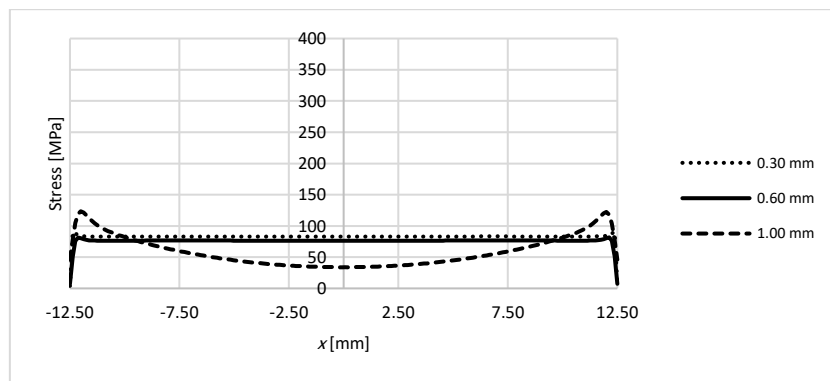


Figure 4. Stress distribution for EPX2 adhesive configurations

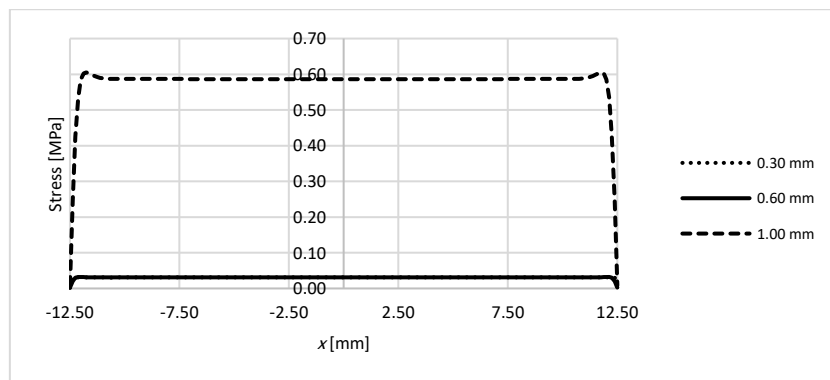


Figure 5. Stress distribution for silicone (SIL) adhesive configurations

TABLE 3. Buckling load and stress peaks – EPX1

Adhesive thickness [mm]	Buckling load [N]	Stress peak [MPa]
0.30	852.13	351.54
0.60	853.14	261.91
1.00	841.74	219.06

TABLE 4. Buckling load and stress peaks – EPX2

Adhesive thickness [mm]	Buckling load [N]	Stress peak [MPa]
0.30	850.97	90.30
0.60	851.29	81.65
1.00	813.50	123.45

TABLE 5. Buckling load and stress peaks - SIL

Adhesive thickness [mm]	Buckling load [N]	Stress peak [MPa]
0.30	850.57	0.03
0.60	850.56	0.03
1.00	8.36	0.61

4. CONCLUSIONS

The majority of the scientific literature about structural adhesives dealt with both numerical and experimental studies of adhesive joints subjected to tensile loads. Since in the real application cases adhesive joints could be subject also to compression loads, such as cyclic tensile-compression loading conditions, therefore the adhesive joints may undergo buckling.

This paper investigates the buckling phenomena with a numerical study of the stress distribution in the adhesive layer under the buckling condition. In particular, a S235JR steel-steel single-lap joint is considered. In this study, three different adhesives with different mechanical and geometrical properties are analysed and compared. The study therefore deals with the influence of the thickness and stiffness of the adhesive on the global mechanical performance of the joint.

The main outcomes are:

- the adhesive thickness and stiffness influence the stress distribution and the buckling load value. In fact, the choice of an adhesive should consider these points to prevent undesired failure modes;
- the choice of a ductile adhesive (e.g. SIL adhesive) with an appropriate thickness could allow to provide the same mechanical performance of a more stiff

adhesive (e.g. EPX2 or EPX1) with much lower stress distribution;

- the design phase of a structural element involving the use of structural adhesive should properly consider the buckling analysis (buckling load and stress distribution).

In conclusion, the study of the stability of the adhesive joint is necessary to predict the real behaviour of the structural system, in order to prevent premature failures.

The study of buckling phenomena allows to provide the correct indications about the correct choice of the adhesive joint. This analysis allows to avoid sudden and undesired failure phenomena.

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Persian Abstract

اتصالات چسبیده کاربردهای بی شماری را در زمینه های مختلف صنعتی پیدا می کنند. آنها جایگزین معتبری برای روشهای پیوستن سنتی هستند. بیشتر ادبیات علمی موجود به مطالعه اتصالات چسبی تحت بارهای کششی متمرکز شده است. همچنین مطالعات زیادی در مورد توزیع تنش در لایه چسب انجام شده است. با این حال، در موارد واقعی، اتصالات چسبیده نیز می توانند تحت فشارهای فشاری کششی حلقوی قرار گیرند و بنابراین می توانند تحت پدیده های کمانش قرار بگیرند. در این مقاله مطالعه عددی توزیع تنش در لایه چسب تحت شرایط کمانش بررسی می شود. به طور خاص، یک اتصال تک دور با ترکیبی از چسبیده های فولادی و سه چسب ساختاری با ضخامت و مدول مختلف یانگ در نظر گرفته می شود. مفاصل با استفاده از نرم افزار © 19 ANSYS FE مدل سازی شدند. از طریق تجزیه و تحلیل عددی، پیش بینی مقدار بار بحرانی برای هر ترکیب تجزیه و تحلیل شده واحد امکان پذیر بود. پس از تعیین بار بحرانی، تنش ها در صفحه میانی لایه چسب تعیین شد. می توان مشاهده کرد که برای ضخامت های کوچک چسب (یعنی 0.30 میلی متر (می توان با استفاده از چسب های ساختاری با مدول الاستیک کم) به عنوان مثال سیلیکون ها)، قله های تنش را کاهش داد - با همان مقدار بار بحرانی.
