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Investigation of Design Parameters in Tensile Loads of the Diamond Joints in Composite Structures with a Finite Element Approach

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Abstract: Adhesively bonded joining in composite structures is carried out using mechanical or adhesive techniques with commonly single or double lap. In laminated structure elements joined in this way, damage generally occurs at the upper layer. That is loading capacity goes down due to the fact that the axial width goes up. In this paper, mechanical joints with joint lock in the shape of diamond are offered to replace adhesively bonded butt joints. E-glass/vinyl ester composite laminates was used as the plate material in the system, the diamond material in the middle was composite, aluminum and steel and Loctite Hysol 9464 was used as the adhesive material. Finite element models were performed in different values of the ratio of the end height of diamond to the height of the specimen (c/height), the ratio of the upper height of diamond to the end height of diamond (a/c) and the ratio of the half-length of diamond to the height of specimen (b/height). Using these dimension values, the effects of the joint geometry parameters are evaluated. Diamond joints model was analyzed by using finite elements method and obtained stresses values. These stresses values were examined and the appropriate design parameters for the diamond lock were decided. Before damage occurs in a composite structure, damage to the diamond lock is seen, and with this important observation, the life of composite structures can be extended by repairing the diamond lock.

Keywords: Diamond joint, Composite, Tensile load, Joint types, Finite element analysis

Introduction

For composite materials are widely used in mechanical and structural components due to their high specific strength and stiffness-to-weight ratios. Composites can also be designed and optimized in many ways, for example; The requirement for different strength and stiffness in various aspects dictated by the design and performance of a structural component. Compared to metal structures, modeling and analysis of composite structures is a challenging task. The load-bearing capacity of composite materials continues to be severely limited due to weaknesses in the joints or joints to the main structure. Because composite materials do not have anisotropy and homogeneous properties, their response to loading is more complex than metallic structures. For a reliable design of composite structures, it is necessary to thoroughly understand their behavior under static and dynamic loading under various environmental conditions, and to determine the lifetime of the joint. The development of such design methods depends on test data, analytical and computer modeling and numerical models created using finite element techniques.

Composite materials are found in industrial sectors such as aerospace, marine and automotive. Most of the giant structures in these sectors consist of two or more joints. The purpose of these connections is to transfer force through the main structure by combining two or more materials. The biggest problem in composite joints is the weakness in the joints. In the joints of composite structures, the damage strength of the composite material, the direction of the first damage and the production method are important. For this reason, many studies on the joining of composite materials have taken place in the literature. (Morgado et al., 2022; Silva & Adams, 2007; Santos et al., 2019; Kötter et al., 2020; Purimpat et al., 2013; Gunnion & Herzberg, 2006; Moya-Sanz et al.,

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2017; Sebastiani et al., 2019; Kumar et al., 2006). In present paper, E-glass/vinylester laminates was used as composite material.

E-glass fiber has better tensile and good compressive strength and good stiffness, besides it has poor impact resistance. E-glass is the most widely used fiber reinforcement in composite materials. Polyesters are high performance and good engineering polymers that find use in different applications (Davallo et al., 2010). Woven fabric composites are more resistant to damage than non-woven fabrics if a delamination is present. Due to the non-planar interlayer structure of woven fabric composites, a delamination crack will interact with the woven structure during propagation, resulting in significant crack growth resistance. Vinylester resins have higher toughness values compared to polyester resins (Young, 1997). Glass-polyester composites are already well established. But if the glass/vinyl ester composite can provide sufficient toughness, then the use of vinyl esters in composites may be more attractive. In present paper, E-glass/vinyl ester composite materials were bonded in the form of butts with the help of a diamond aluminum.

A general discussion of adhesion, adhesives, and especially adhesive bonds and repairs in metallic alloys, polymers and composite materials can be found in (Kinloch, 2004; Baldan, 2004(a); Baldan, 2004(b)). Some representative studies on lap joints and mechanical behavior of lap joints can be found in (Keller & Vallée, 2005; Zhang & Keller, 2008; Ascione, 2009; Goyal & Johnson, 2008; Castro & Keller, 2008). Fewer studies in literature deal with butt joints (Ascione, 2009; Adams et al., 1978; Adams & Coppendale, 1979; Öchsner & Grácio, 2007; Öchsner et al., 2007; Ikegami et al., 1996; Sampaio et al., 2004; Taib et al., 2006).

While Adams et al. (1978) and Adams & Coppendale (1979) were more concerned with the stress analysis of axisymmetric butt-joints, some other articles were concerned with the determination of elastic constants as well as evaluation procedures for butt-joint testing of adhesive technology (Öchsner & Grácio, 2007), To date, only a few studies have examined the effect of adhesive thickness and geometry on the stiffness of bonded butt joints (Öchsner & Grácio, 2007; Öchsner et al., 2007; Ikegami et al., 1996; Sampaio et al., 2004; Taib et al., 2006). In general, as an alternative to welded joints, joints with different geometries (mainly aluminum/epoxy systems as in this study) are used. At butt joints, the bonded area is not excessively large and the nominal shear stress (tensile force/bond area) is nearly constant for a constant adhesive thickness. The thickness of the adhesive layer is the most important main geometric effect. A tensile test may show cohesive failure, adhesive failure, or mixed failure, depending on the adhesive/adhesive materials, surface coating, and adhesive thickness.

Tensile tests are used for determining the strength of a given butt joint, but these tests do not provide all the key parameters to be used directly in engineering design and estimating the strength of a bonded/connected system with arbitrary geometry is still a challenge. In general, complex finite element simulations are required (Castagnetti & Dragoni, 2009). In the butt joint method, the adhesive bonding technique is generally used throughout the thickness. In this type of joints, inclined or stepped joints are preferred more than simple butt joints in order to prevent peeling stress and reduce its value. Although different joint types are used in butt jointing, shear stress negatively most biggest affects joint life.

In this presented paper, mechanical butt joints with diamond shaped joint locks are proposed instead of glued butt joints. In mechanical butt jointing, diamond-shaped joint lock elements are used to fix the composite laminate plates face to face with a tight fit procedure. The main purpose of this study is to examine the effects of changes in the material and geometric parameters of the diamond joint lock components on the maximum load carrying capacity of the joint using the finite element method.

Materials and Method

Preparation of Design Parameters of the Diamond Lock Joints in E-glass/Vinylester Laminates

In this study, material models with diamond geometry shown in Figure 1 were prepared by using three types of materials: composite, aluminum and steel. Finite element models are performed in different values of the ratio of the end height of diamond to the height of the specimen (c/height), the ratio of the upper height of diamond to the end height of diamond (a/c) and the ratio of the half-length of diamond to the height of specimen (b/height) (Table 1). Using these dimension values, the effects of the joint geometry parameters are evaluated.

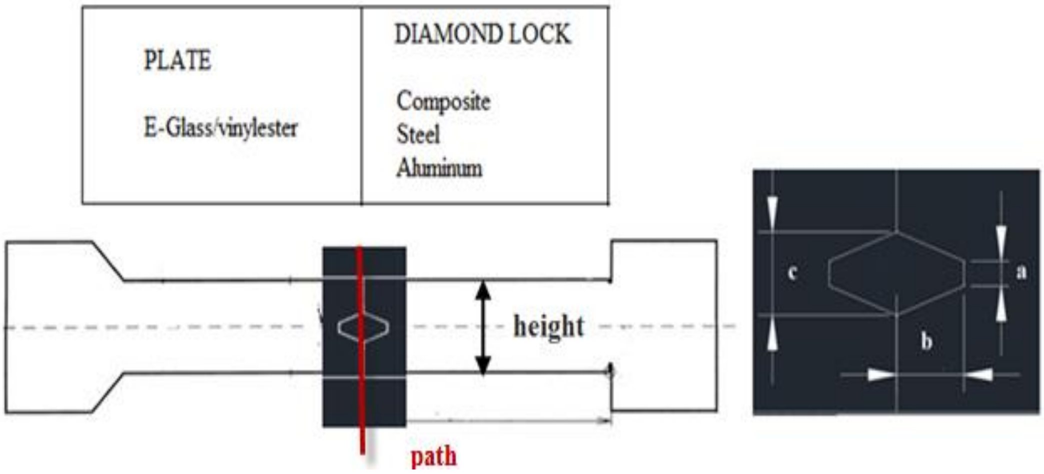

Figure 1. Composite laminates combined with diamond lock and diamond geometric parameters

As seen in Figure 1, specimen dimensions were chosen as follows: specimen height (h) is 20 mm, total specimen jaw length L=160 mm and specimen thickness t= 5 mm. Keeping constant the specimen's main dimensions (h, L, t) that are joined in mechanic butt joint, the end width (c), middle width (a) and half the length (b) of the joint lock in the shape of diamond were changed. To see the effects of geometric parameters on tensile loads, several models were performed by changing the ratio of the end width of diamond to the width of the specimen (c/height) and the ratio of the middle width of diamond to the end width of diamond (a/c) from 0.3 to 1.2. In these finite element models, the ratio of the half-length of diamond to the width of the specimen (b/height) was chosen as 0.3, 0.6 and 0.9. The dimensions of diamond lock joint components are given in Table 1. Half specimens are jointed with diamond joint components by using tight fitting. Diamond parts used as joining components were made up of both metal (steel and aluminum) and composite materials. Therefore, the effect of the diamond material on tensile load was considered as well.

Table1. Diamond lock component dimension parameters

Dimension Ratio		c/height				Dimension (mm)
		0.3	0.6	0.9	1.2	
		6	12	18	-	c
a/c	0.3	1.8	3.6	5.4	-	a
	0.6	3.6	7.2	10.8	-	
	0.9	5.4	10.8	17.2	-	
	1.2	7.2	14.4	-	-	
b/height	0.3	6				b
	0.6	12				
	0.9	18				

In this study, the composite material, whose material properties are given in Table 2, was used in both plate and diamond geometry. Tensile properties such as longitudinal modulus (E_{11}), transverse modulus (E_{22}), transverse modulus (E_{33}), Poisson's ratio (υ_{xy}) etc. are given in Table 2. The laminated composite material is 10 layers and directions 0° and 90°, one layer thickness is 0.5 mm.

Table 2. Mechanical properties of composite adherends

Properties	Composite
Modulus of Elasticity, E (GPa)	$E_{11=}22$ $E_{22=}22$ $E_{33=}9$
Shear Modulus, G (GPa)	$G_{12}=5.3$ $G_{23}=3.1$ $G_{13}=3.1$
Poisson's ratio,υ	$\upsilon_{xy}.0.27$ $\upsilon_{yz}.0.38$ $\upsilon_{xz}.0.38$

Steel S235JR and Aluminum 5083 are used as a diamond lock and their mechanical properties are given in Table 3.

Table 3. Mechanical properties of steel and aluminium diamond lock

Materials	Modulus of Elasticity (GPa)	Poisson Ratios
Aluminum 5083	70	0.3
Steel S235JR	235	0.3

Modeling of Diamond Lock Joints in Composite Structures

The thickness of the adhesive layer is 0.1 mm. In the Figure 2 , the schematic illustration of adhesives areas in the model can be seen. The mechanical properties of the adhesive material are given in the Table 4. It is an adhesive applied by mixing epoxy and hardener in a ratio of 1:1, by weight and volume. The same type of materials (metal, ceramic, plastic, etc.) and different materials (composite, etc.), It is an ideal adhesive for bonding. The main mechanical properties specified by the manufacturer for the adhesive with a setting time of 180 minutes after application are given in Table 4.

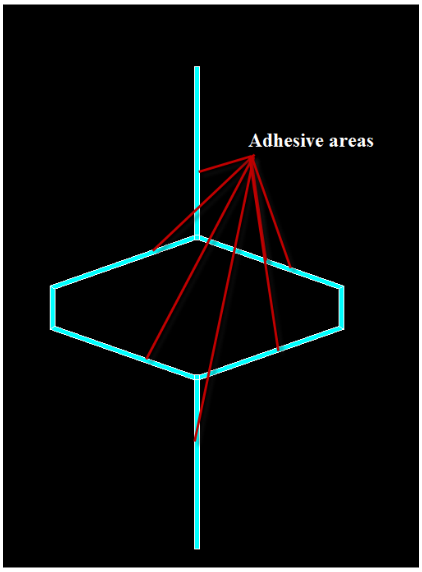

Figure 2. The schematic illustration of adhesives areas in the model

Table 4. Mechanical properties of adhesive

Properties	Loctite-Hysol 9464
Shear Strength (MPa)	20
Peel Strength (MPa)	10.6
Modulus of Elasticity, E (GPa)	1.65
Shear Modulus, G (GPa)	0.75
Poisson's ratio,υ	0.356
Mixture by volume rate	1:1

Finite Element Model

The finite element model of fixed pointed diamond lock joint was developed using the commercial software package ANSYS. This finite element program provides an estimate of the overall strain behavior of the composite panel when subjected to a tensile load (30 MPa). The thickness of one panel is 10 mm, the adhesive thickness is 1 mm.

When drawing the first aluminum lock model, 0.3-0.3-0.3A is selected the name of the model, the explanation for this is as follows; The values c/height =0.3, a/c=0.3 and b/height =0.3 are selected from the Table 1 and a model is created by drawing the corresponding diamond in the shape of c=6 mm, a=1.8 mm and b=6 mm by using aluminum material (A). All models are named according to this rule. The numerical model of the panel is divided into a finite number of elements that ensure stability and cohesion at each node. As a result, the optimal combination of mesh accuracy and element size was found (Figure 3).Element edge is selected as 0.025mm. The model has contact pairs, the contact position of the adhesive and adherend plates. The relevant literature (Uysal and Güven, 2015) can be consulted for bonding mechanics and modeling details.

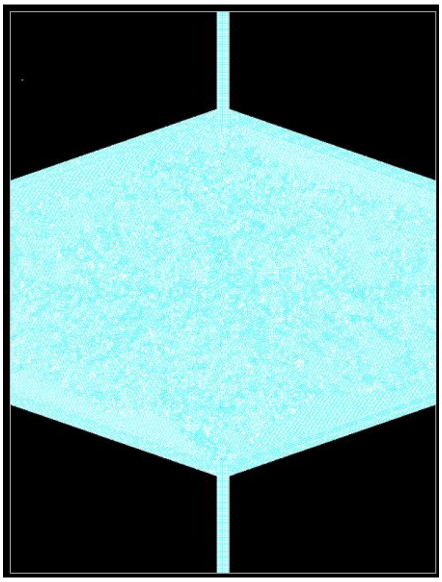

Figure 3. The mesh detail in diamond and adhesives areas

Results and Discussions

The diamond-shaped connection lock components used in the finite element analysis are modeled using both steel (S235 JR) and aluminum (Aluminum 5083) and composite (E-glass/vinylester composite) materials. In this paper, the load carrying capacities of the models were investigated by changing both the geometrical parameters and the materials of the diamond lock elements. Figure 4 shows the variation of metal and composite diamond on maximum von-Misses stresses (σ von-misses) for different b values (diamond half length value). The most suitable b compatibility for all materials seems to be 12 mm. For this reason, length b was chosen as 12 mm.

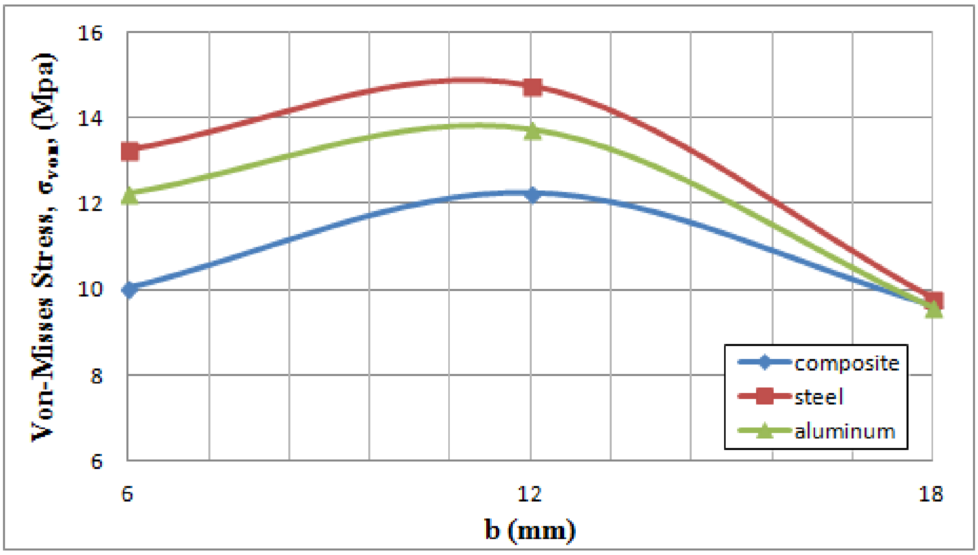

Figure 4. Von-Misses stress respect to diamond half length (b) parameters.

The changes in the load carrying capacity of the samples made with various (a/c) ratios according to the (c/h) ratio of the diamond key element are shown in the Figure 5. As seen in Figure 5, it depends on the load carrying capacity (c/h) ratio. When the a/c ratio is equal to 0.3 and the c/h ratio is equal to 0.6, the load carrying capacity for both metal(steel and aluminum) and composite diamond locks is maximum. As a result, it can be concluded that the choice of diamond width is very important in terms of load carrying capacity.

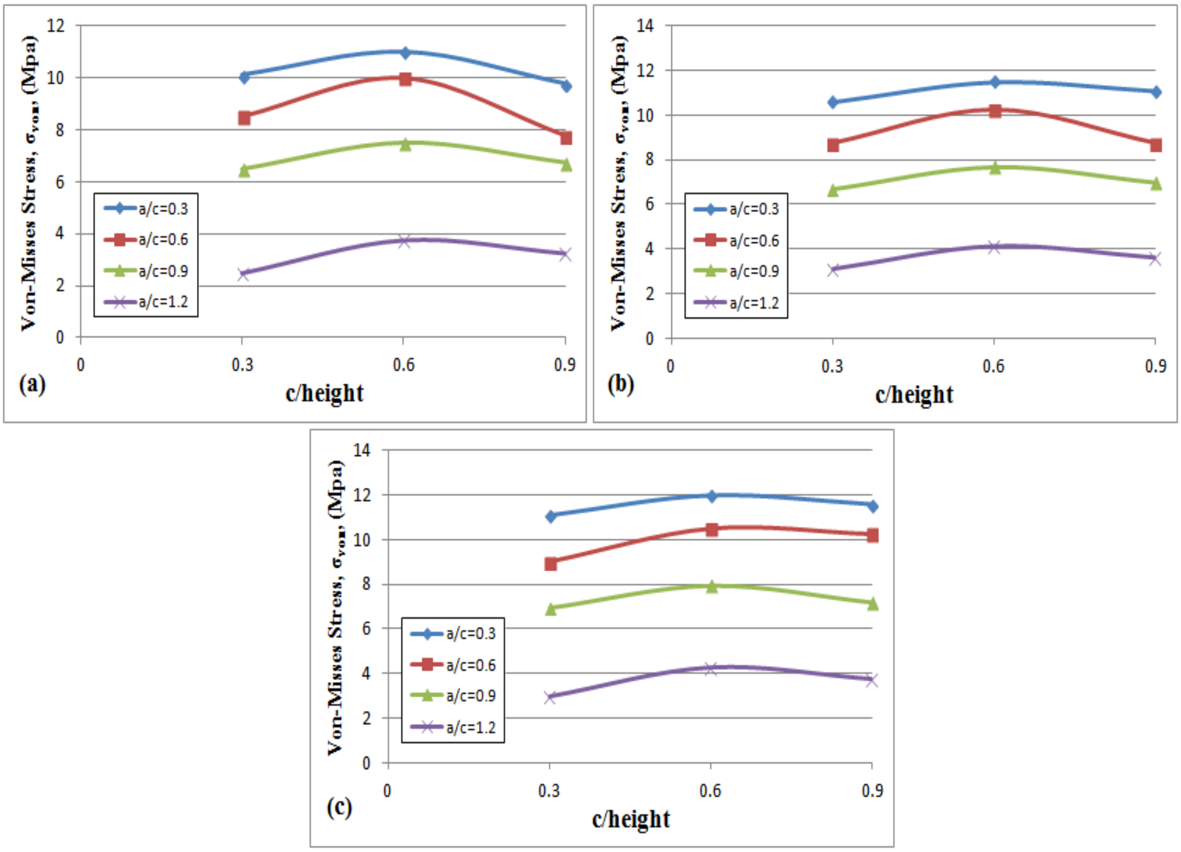

Figure 5. Von-Misses stress respect to c/height parameters for
a) Composite diamond b) Aluminum diamond , c) Steel diamond

The variation in the maximum von misses stresses with respect to the a/c ratio is shown in Figure 6. When the c/height ratio is 0.6 and the a/c ratio is equal to 0.3, the load carrying capacity of both metal and composite diamonds is maximum. The decrease in the maximum load with the increase of the a/c ratio shows the importance of the diamond middle width. As the middle width of the diamond decreases, the shape of the diamond lock element begins to resemble a square or rectangular shape. The diamond lock element starts to lose its locking feature and this causes the load carrying capacity to decrease. When the a/c ratio is equal to 1, the square or rectangular lock element is no longer load-bearing.

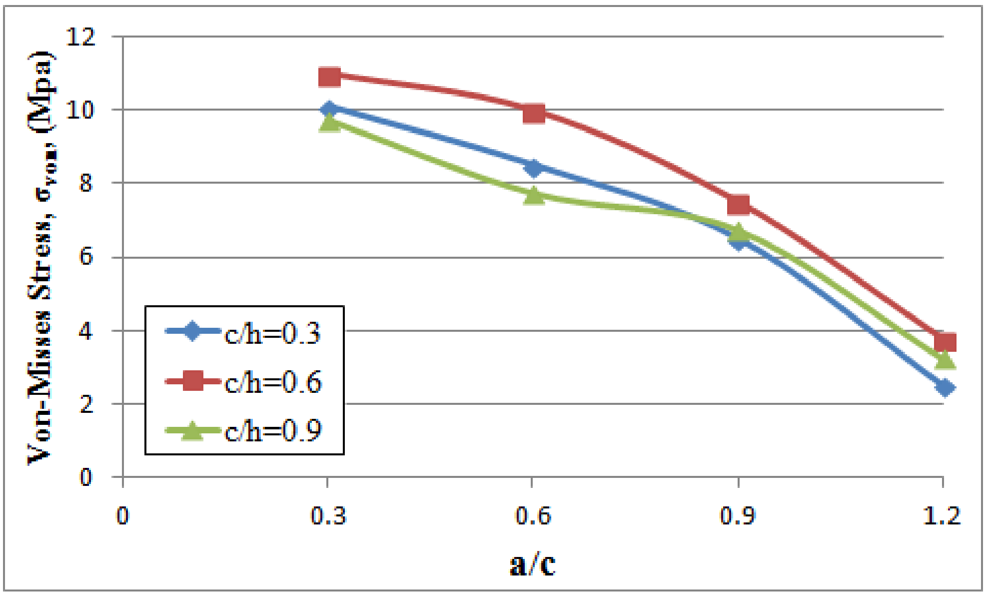

Figure 6. Von-Misses stress respect to a/c parameters

Path that appears as a red line in the diamond lock model is drawn in Figure 1. The path is exactly 20 mm and runs right through the middle of the adhesive layer and also the model. Normal stresses (σ_y), shear stresses (τ_{xy}) values were taken from the path in the solution for the model named 03-03-03A. (on the aluminum model, the values c/height =0.3, a/c=0.3 and b/height =0.3 are selected from the Table1). Since the shape is symmetrical, symmetry is observed in all stresses. The distributions of stresses are similar in other models.

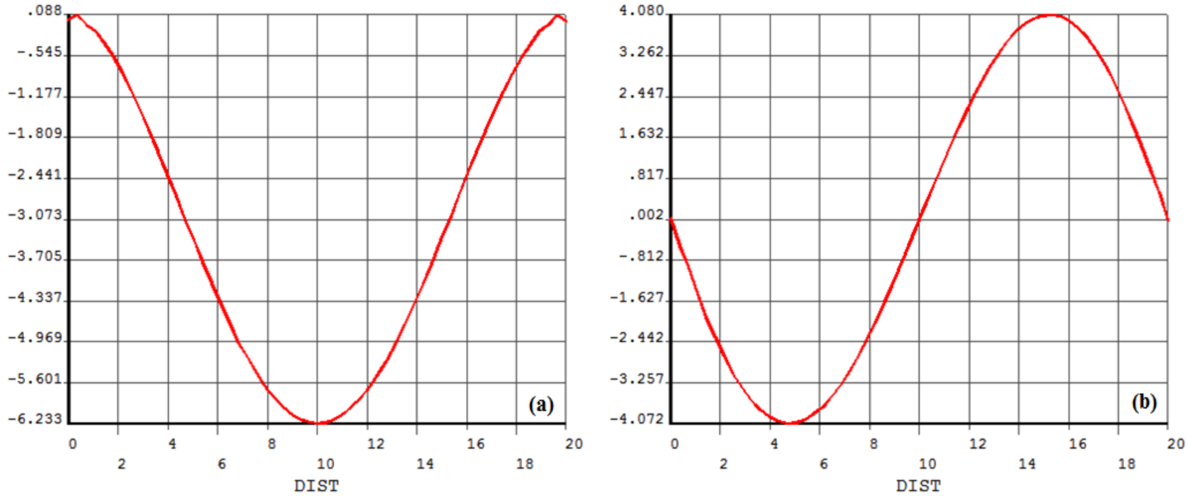

Figure 7. a) Normal stresses (σ_y) and b) Shear stresses (τ_{xy}) distributions on the path

Conclusion

In this presented study, effects of joints in the shape of diamond, its materials and geometric parameters on the load capacity were all considered by using finite element method. E-glass/vinyl ester composite materials, aluminum 5083 and S235JR steel was chosen for diamond lock material parameters. Models were made in different values of the ratio of the end height of diamond to the height of the specimen (c/height), the ratio of the upper height of diamond to the end height of diamond (a/c) and the ratio of the half-length of diamond to the height of specimen (b/height). Diamond joints model was analyzed and obtained stress values. The stress values were examined and the appropriate design parameters were decided for diamond joints. At high values of the ratio of the middle width of diamond to the width of diamond (a/c), von-misses stress decreases gradually. When (a/c) reaches 1, since angled surface disappears, diamond carries no load. For this reason, in such cases, adhesively bonding technique is preferred and the adhesive material holds the joint together. Compared to the composite diamond samples, the steel and aluminum diamond samples have higher load carrying capacities. While the ratio of c/height increases, it is concluded that load carrying capacity decreases gradually. In a specimen that has a constant height, when diamond end width rises, it suffers from the weakened area at both sides of diamond joint component and its load carrying capacity decreases. The ratio of c/height can become 0.6 for composite diamonds model. The mechanical butt joint technique can be used together with the bonding technique. In this case, the negative effects on adhesive joints can be minimized by changing the material and size parameters in diamond lock. It is also possible to have different joint load carrying capacities by changing the shape of the diamond locks.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

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