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Influence of spew fillets geometry on the bond strength of adhesively bonded FRP composite elements

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Summary

The adhesive bonding is a suitable joining technique for structural assemblies made of composite materials. Adhesive bonding of fibre reinforced polymer (FRP) composite elements is utilised in several applications, including surface repairing for various composite materials, strengthening/retrofitting techniques and, as a sustainable alternative/replacement, when mechanical fastening methods are not suitable.

This paper focuses on some specific aspects related to the influence of stress reduction methods using various spew fillets on the structural response of adhesively bonded FRP composite elements. Also, this paper presents the influence of the adhesive spew fillet geometry on the peak values and on the distributions of the shear and the normal stresses in adhesively bonded FRP composite members.

Keywords: FRP composites, adhesive bonding; adhesive spew fillets, numerical analysis.

1. INTRODUCTION

Nowadays, fibre reinforced polymer (FRP) composite elements represent a feasible alternative to structural elements made of traditional materials (*i.e.* concrete, steel, wood, aluminium) [1], offering substantial advantages in terms of high mechanical strengths, low weight, tailorability of properties and corrosion resistance [2]. For some particular applications, connections between different FRP elements are required in order to design and construct complex structural assemblies. Thus, the designers must select from several alternatives ranging from mechanical connections (using screws, bolts or rivets) to adhesive bonding [3].

The main disadvantage of mechanical connections refers to the necessity of drilling the FRP composite members that are being assembled which usually leads to discontinuities in the internal reinforcing fibres and significant stress concentrations [4]. The adhesively bonded connections are more suitable for FRP composites materials since the stress transfer through the elements is more uniform. However, stress concentrations may still arise in FRP adhesively bonded

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joints, when the thicknesses of the adhesive and the adherents change and due to the differences of the elastic moduli [5].

The most common configuration for FRP adhesively bonded connections subjected to tensile forces is the single lap joint (SLJ). The distributions of the shear and normal stresses in SLJs are influenced by two critical features [6]. The first one refers to the offset of the adherents which produces a bending moment in the joint, adding the corresponding peeling stress component. The second important feature of SLJs relates to the fact that the stresses distributions in the lap are not constant along the bond length since the peak values concentrate at the ends of the overlap.

The peak values of the shear stresses and the normal (peeling) stresses can be diminished by the presence of an overflow of the adhesive at the ends of the overlap region. The spew fillet is defined as the fraction of the adhesive that is squeezed from the overlap ends as the two FRP composite elements are joined. Thus, a smooth transition in bond geometry significantly increases the joint strength. Many investigations have been conducted in order to identify the effect of shaping the edges of the adhesive layer (*i.e* chamfering, rounding, grading) upon the stress state in the adhesively bonded joints [7, 8, 9, 10, 11]. Based on these studies, it has been concluded that the spew fillet shaping is one of the most suitable techniques for reducing the peak values of stresses in FRP adhesively bonded connections.

The main objective of this study is to numerically investigate and compare the stresses distributions for several configurations of SLJs composed of FRP composite elements. All the specimens were conceived using the same adhesive and a constant bond-line length, the variable parameter being the angle of the triangular adhesive spew (*i.e.* 15°, 30°, 45°, 90°).

2. TYPICAL STRESS-STRAIN STATE OF FRP COMPOSITES ADHESIVELY BONDED JOINTS

For any structural application of adhesively bonded joints, the main stress components that develop along the bond length are the shear stresses (τ) and the normal stresses (σ), respectively [12]. The shear stresses are induced by forces acting parallel to the adhesive layer, while the normal stresses are the result of forces acting perpendicularly to it. The shear stresses generate diagonal deformation, known as shear strains (γ), while the normal stresses develop normal strains (ε). The typical stress flow for FRP composite adhesively bonded joints [12] is illustrated in Figure 1.

In adhesively bonded FRP connections subjected to tensile forces, the main function of the adhesive layer is to transfer the load from one adherent to the other. Thus, the adhesive is mainly subjected to shear stresses and the maximum values

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are concentrated near the extremities of the bond length. However, when relatively thick and stiff FRP composite elements are connected in single lap joint configuration, the final mechanical characteristics of the bond are mainly influenced by the intensity of the through-thickness normal stresses.

The shear force acting at the interface level between the FRP composite element and the adhesive is balanced by the axial force in the adherent. The shear force and the axial force are coupled by a lever arm which is the distance measured from the mid-thickness of the FRP composite element to the adhesive-adherent interface (Figure 1). The bending moment is counterbalanced by the through-thickness forces in the adhesive layer. The latter is generally referred to as peeling forces. These forces generate through-thickness normal stresses (peeling stresses) in the adhesive layer.

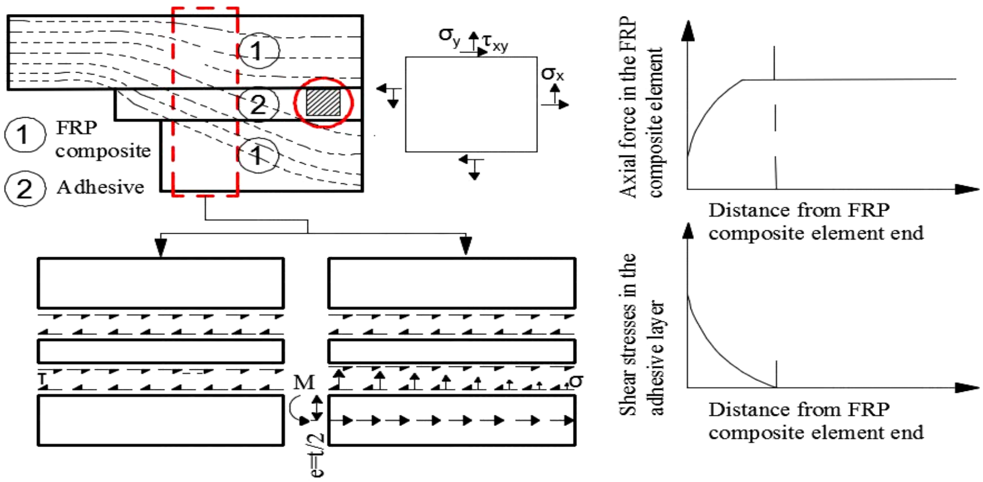

Figure 1. Typically stress flow through adhesively bonded FRP connections (adapted from [12])

3. MATERIAL PROPERTIES AND SPECIMENS GEOMETRY

3.1. Material property

3.1.1 GFRP composite material

For the numerical analysis in this study, the adherents were modelled according to the properties of Fiberline structural plate profiles made up of glass fibre reinforced polymer (GFRP) composite. The FRP composite elements are made of E-glass fibres embedded in an isophthalic polyester resin. The physical and mechanical properties of the GFRP plates are given in Tables 1 to 3. The main directions for strength and stiffness are presented in Figure 2 [13]. The longitudinal direction is indicated as 0° and the transversal direction is indicated as 90°.

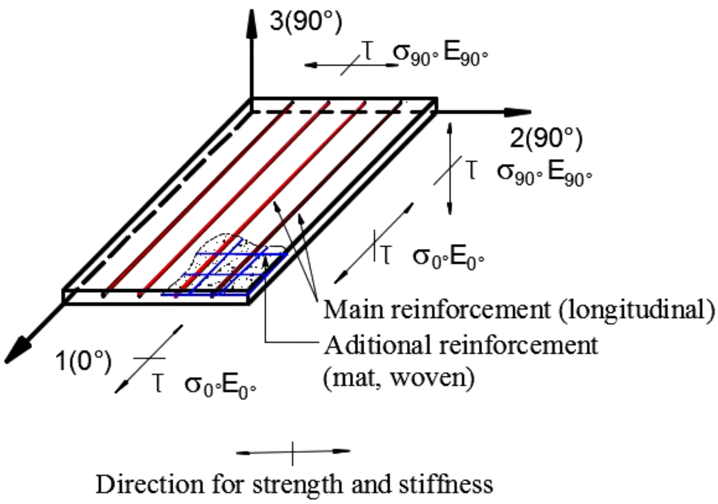

Figure 2. Indication of directions for strength and stiffness [13]

Table 1. Fiberline GFRP composite strip. Physical characteristics [14]

Density [kg/m^3]	Operating temperature [C°]	Fibre volume fraction [%]
1500	-20 ~ +80	>60

Table 2. Fiberline GFRP composite strip. Typical stiffnesses [14]

Longitudinal elasticity modulus [MPa]	Transversal elasticity modulus [MPa]	Modulus in shear [MPa]	Poisson's ratio, 0°, 90°	Poisson's ratio, 90°, 0°
23000	8500	3000	0.23	0.09

Table 3. Fiberline GFRP composite strip. Mechanical characteristics – Strength values [14]

Tensile strength, 0° [MPa]	Tensile strength, 90° [MPa]	Compressive strength, 0° [MPa]	Compressive strength, 90° [MPa]
240	50	240	70

3.1.2 Adhesive

The GFRP composite strips are considered to be bonded with a structural, two-part epoxy adhesive Sikadur30. The adhesive properties are presented in Table. 4

Table 4. Properties of the adhesive [15]

Density [kg/m^3]	Elasticity modulus [MPa]	Compressive strength [MPa]	Shear strength [MPa]	Tensile strength [MPa]
1650	12800	70-80	20	25-28

3.2. Specimens geometry

The SLJ considered in this study is presented in Figure 3. For comparison purposes, a benchmark joint configuration was maintained throughout the study. The benchmark dimensions consist of a 2 mm adhesive thickness (t_a), 6 mm substrate thickness (t_s), 170 mm length and 25 mm width of the GFRP strip and 70 mm bond length. In order to be easily identified and appealed to, when the results will be analysed and compared, each specimen was marked with a nominal code (Table 5).

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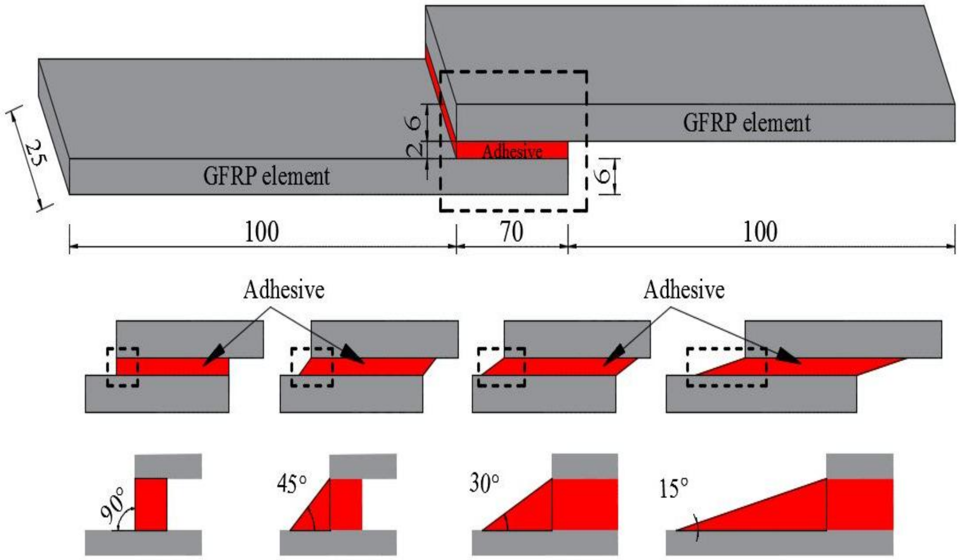

Figure 3. Model geometry in mm (Not at scale)

Table 5. Specimen notation

Specimen name	Specimen description
NSP	Benchmark geometry
SP15	15° triangular spew fillet
SP30	30° triangular spew fillet
SP45	45° triangular spew fillet

4. FINITE ELEMENT MODELLING

In this study, finite element models (FEMs) were used to perform tensile testing simulation on SLJs with and without spew fillets. The simulations were implemented using commercially available ANSYS Workbench software. The GFRP strips have been modelled as being linear elastic orthotropic materials, while the adhesive was modelled as a linear elastic isotropic material.

Each model consisted in three primitives of parallelepiped shape connected together to match the specimen geometric specifications. For each node, the parameters of position and connectivity have been defined. The final models were meshed using rectangular elements for the GFRP strips and triangular elements for the adhesive layer (Figure 4) [6, 11]. Two refinement levels were used for the model meshing. The first one was defined for the adhesive layer and consisted in triangular mesh elements of 1 mm while the second one was defined for the edges

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of the adhesive layer and for the spew fillet, having triangular mesh elements of 0.1 mm. These particular areas of the mesh are usually used to closely monitor the distributions of stresses and to track down any sudden change in stresses magnitudes. Also, a smooth transition region was considered in order to avoid mesh discontinuities. The specimens were considered as simply supported and the tensile loads (5 kN) were applied at the ends of the GFRP strips. The loading conditions are presented in Figure 5.

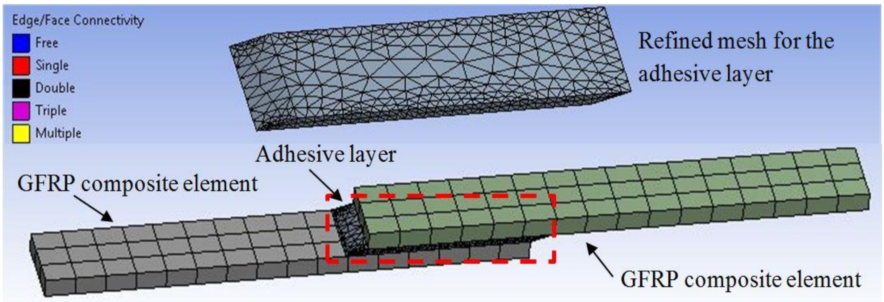

Figure 4. Meshing procedures

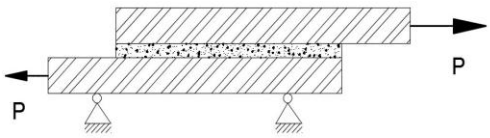

Figure 5. Loading conditions

5. RESULTS

The initial investigation has consisted in the stress state analysis in a square ended SLJ without any spew. The purpose of this investigation is to provide a benchmark for comparing SLJs with different spew configurations. The numerical analysis predicted that the shear stresses and the normal (peeling) stress in the adhesive layer are symmetrical with respect to the centre of the bond line and their peak values are at end of the bond line. However, the distributions of stresses across the thickness of the adhesive are more irregular with respect to the centre of the overlap, being much larger at the interface level. Thus, the shear stresses and the normal stresses distributions were investigated at the interface level between the GFRP strips and the adhesive. The shear stresses and normal stresses maps of the specimens are presented in Figures 6 to 13. Also, the comparison between the stresses distribution for the proposed models is graphically depicted in Figure 14 and Figure 15.

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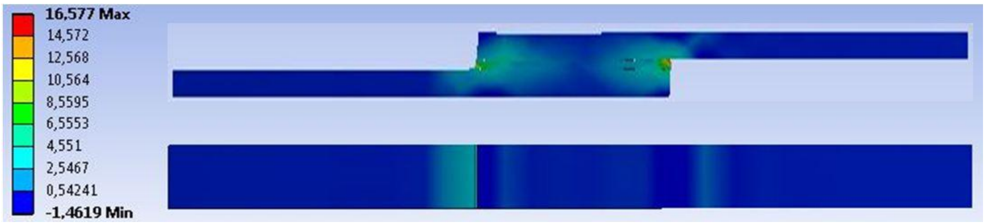

Figure 6. NSP model - Shear stress map [MPa]

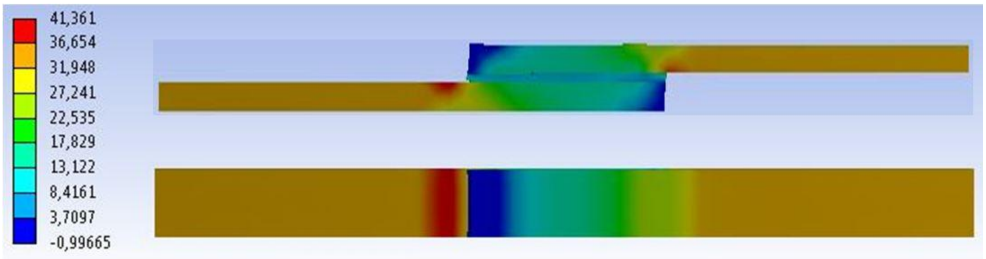

Figure 7. NSP model - Normal stress map [MPa]

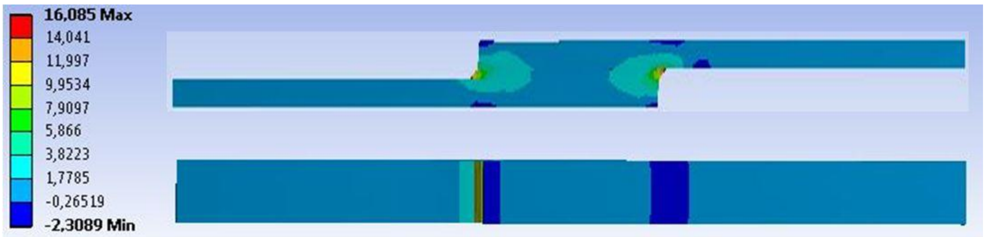

Figure 8. SP 45 model – Shear stress map [MPa]

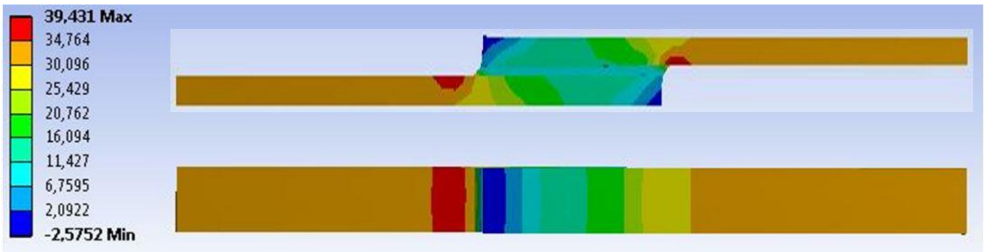

Figure 9. SP 45 model - Normal stress map [MPa]

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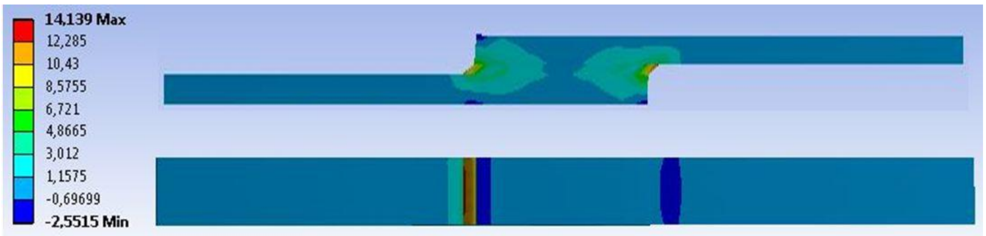

Figure 10. SP 30 model - Shear stress map [MPa]

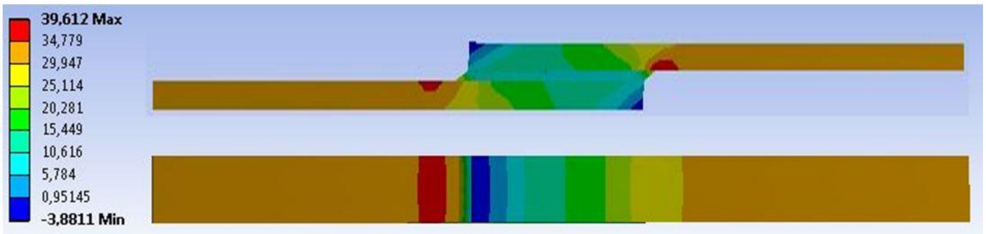

Figure 11. SP 30 model - Normal stress map [MPa]

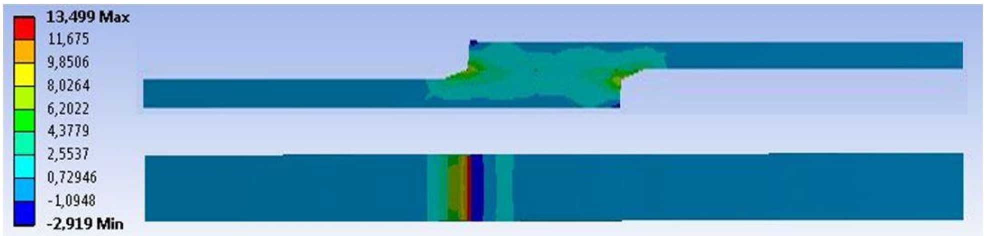

Figure 12. SP 15 model - Shear stress map [MPa]

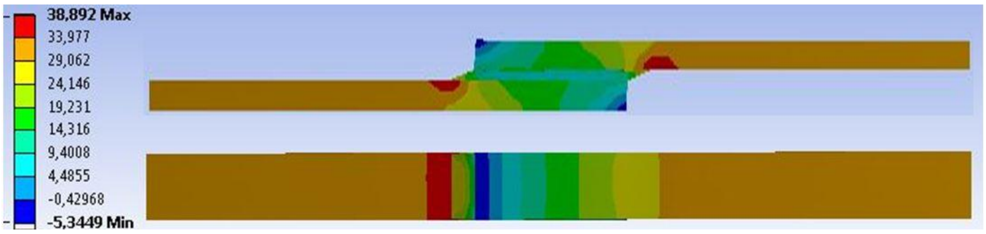

Figure 13. SP 15 model - Normal stress map [MPa]

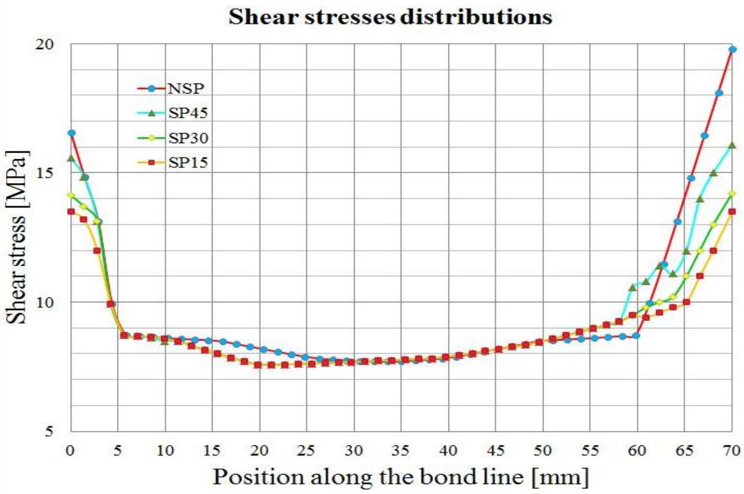

Figure 14. Spew effect on the adhesive shear stress distribution

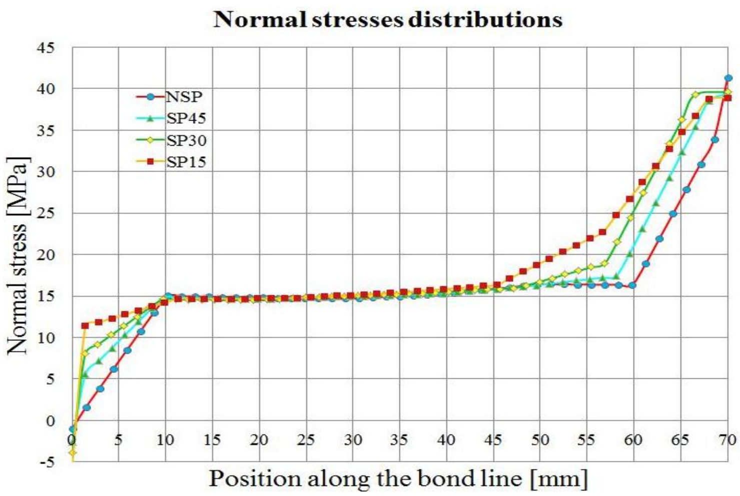

Figure 15. Spew effect on the adhesive normal stress distribution

6. DISCUSSION OF THE RESULTS

The influence of the adhesive spew geometry on shear stresses and normal stresses was investigated by considering the variation of stresses along the top interface between the GFRP strip and the adhesive. It can be noticed that all specimens have similar stress distribution patterns, but display different magnitudes of stresses. Due to the presence of spews, the peak shear stresses are diminished with 3% for a 15° entry angle (SP15), 15% for a 30° entry angle (SP30) and up to 20% for the

45° entry angle (SP45), respectively. However, the percent reduction in peak normal stresses is lower than that of the peak shear stresses. This may be explained by the disadvantageous geometry features of the SLJs and of the adherents in particular (thick GFRP strips). For the SP15 and the SP30 models, the peak shear stresses diminished with only 4.3% and 5% when compared to the model with square ended adhesive (NSP). For SP15, a slight change in the graph pattern was observed (Figure 15), tending to shift the location of the maximum normal stresses from the end of the overlap. However, the peak normal stresses were reduced with almost 6.5% when compared to the benchmark model.

7. CONCLUSIONS

This paper presented the outcomes of a numerical study that was conducted in order to determine the effect of adhesive spew geometry on the stress state in FRP adhesively bonded connections. Several triangular spew geometries consisted in different entry angles (*i.e.* 15°, 30°, 45°) had been considered. Based on the investigation of the distributions of the shear stresses and the normal stresses, the following conclusions can be drawn:

- The adhesive spew fillet significantly reduces the stress level in SLJs of bonded FRP composite elements.
- For triangular spew fillets, the lower entry angles cause larger reduction of peak stresses.
- The larger size spew fillets cause a higher reduction of shear stresses and normal stresses.
- The study has pointed out that for the proposed SLJs configurations, the most appropriate triangular spew fillet has a 15° entry angle.
- With respect to other stress reduction solution (*i.e.* rounding), the triangular spew fillets are feasible and simple to assemble.

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