Comparison of the adhesive dynamic shear stress homogeneity between metallic and composite substrates of a double lap joint.

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Adhesive joints endure non-homogeneity of shear stress field under both static and dynamic loading, where peak of stresses occur at the edges of the layer. In this work, a homogeneity coefficient was defined and investigated for double lap bonded joint under dynamic shear where the target is to compare the homogeneity between the case of metallic adherents (Steel) and composite adherents (Glass/PEEK). Many geometrical and mechanical parameters were varied: adhesive thickness, adhesive Young's modulus, adherent thickness and overlap length. It was found that steel offers better homogeneity than glass/PEEK for the same configuration due to the high difference between their Young's moduli. Moreover, the sensitivity of the homogeneity coefficient was studied in terms of each of the mentioned parameters: composite substrates have shown less sensitivity than metallic ones. A unified parameter was defined to quantify analytically the homogeneity in case of composite adherent. Finally, a configuration of the composite joint giving same homogeneity as metallic one was established by just increasing the adherents' thickness: it conserves the same adhesive strength, offers better resistance against bending and is lighter by about 11% than the metallic case.

Keywords: *Adhesive, Metallic adherents, Composite adherents, Dynamic shear stress, Homogeneity.*

1. Introduction

Adhesively bonded joints are actually widely used in many industrial fields in general and in transportation means fabrication in specific; one may cite for instance works [1-3] where bonded joints applied to cars were studied experimentally and numerically. However, the stress distribution along the joint length, either shear or peel, is not uniform at all: under both static and dynamic loading, stresses concentrate at the extremities of the adhesive layer

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(aspect known as edge effect) while they pass by a minimum at the middle of the joint, hence critical points exist in such assemblies which may constitute a source of crack initiation that weakens the entire assembly. Many efforts were done to minimize the most possible this dangerous aspect. Some of them proposed geometrical changes to the bonded assembly as Mylonas and De Bruyne [4] did by tapering the adherents from outside in the zone close the joints edge in order to decrease locally the stiffness and thus the peak of stress. Sage [5] designed a variable thickness adhesive joint where it is thin at the middle and thick at the extremities. The several works of Adams and co-authors were remarkable in this field: they showed in [6] that spew fillet at the edges contributes in decreasing the peak's level; they established analytically in [7] a variable thickness profile using the shear lag model and then validated it numerically and experimentally while they showed in [8] through a 3D finite element analysis that tapered adherents near the joint edges improve the homogeneity of the stress field and the spew fillet improves its strength. A T-shape substrate (metallic and composite) with special form at the beak was proposed by Cognard et al. [9-10] to be tested under static loading; a numerical validation was also carried out. Vable and Maddi [11] examined numerically the effect many values of spew fillet radius on the shear stress distribution for single and double lap geometries.

On the other hand, and far from geometric changes, Henning [12] proposed a mixed-adhesive solution where a ductile, i.e. soft adhesive is used at the edges and another brittle adhesive is used inside the joint. Da Silva and João [13] tested experimentally this mixed-adhesive approach.

Yi Hua et al. [14] have changed numerically both material and geometrical nonlinearities of the adhesive with a crack initiation in a single lap dissimilar joint Titanium-Composite and concluded that the spew fillet improves both homogeneity and strength under tensile loading.

Another approach to quantify this aspect was established by Challita and Othman [15] who defined a stress homogeneity coefficient for a double lap joint under dynamic shear with steel adherents. They studied the effect of many parameters of the specimen on this coefficient. They defined in addition a coefficient of stress concentration to quantify the peak of stress at the edges and used it for experimental shear strength evaluation in [16]. In the same context, Hazimeh et al. [17] repeated a similar study but for unidirectional Glass/PEEK composite adherents. In [18], they extended the work for dissimilar adherents. Saleh et al. [19-20] examined the effect of fibers distribution in the substrates (UD; 2.5 D; 3 D) on this homogeneity coefficient in a double lap joint. They defined later in [21] a coefficient of stress concentration to quantify the peak shear stress for composite substrates.

In this work, and based on the works in [15] and [17], a comparative study towards homogeneity between metallic and composite substrates will be carried out by studying many geometrical and mechanical parameters of a double lap bonded joint under impact shear. Sensitivity of this homogeneity coefficient will be studied. A design of configuration in both cases (metallic and composite) that gives the same homogeneity coefficient will be also carried out. The software used for numerical simulations is commercial ABAQUS in its explicit module.

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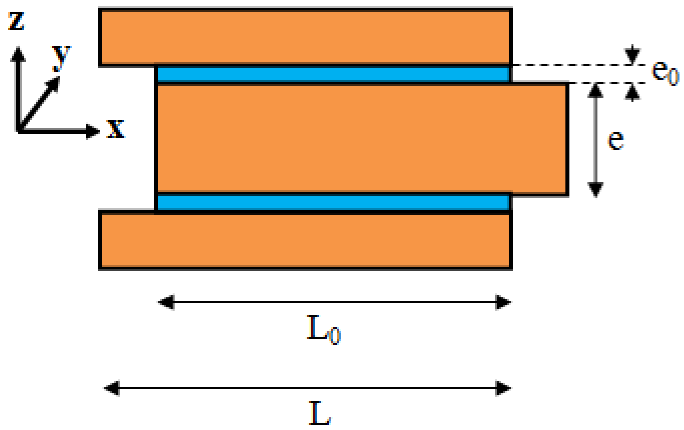
2. Specimen

The geometry adopted for the specimen is the double lap joint (DLJ) shown in fig.1. The middle plate's thickness is always twice the thickness of an extreme plate; both extreme plates are identical. All the plates have same width w = 12 mm along y-axis.

An axial compressive loading parallel to x-axis will charge the right end of the middle plate while the left ends of the extreme plates are held; thus the adhesive layer between the plates will be subjected to shear stress. However, the shear stress field is not homogenous along the length: peaks of stress concentrate at the edges while the middle of the layer bears low shear stress level. It has been shown that this homogeneity depends on many mechanical and geometrical parameters of the specimen for metallic substrates in [15] and composite ones in [17].



In this comparative study, metallic substrates are made from steel while composite ones are made from unidirectional Glass/PEEK laminates (V_f = 60%). All mechanical properties of both types of substrates and of the adhesive are summarized in tab.1

Properties	**Steel**	**Glass/PEEK**	**Adhesive Epoxy**
E_{xx} (GPa)	200	44.84	1
E_{yy} (GPa)	200	9.44	1
E_{zz} (GPa)	200	9.44	1
ν_{xy}	0.3	0.292	0.4
ν_{yz}	0.3	0.4	0.4
ν_{xz}	0.3	0.292	0.4
G_{xy} (GPa)	77	3.05	0.35
G_{yz} (GPa)	77	3.37	0.35
G_{xz} (GPa)	77	3.05	0.35
ρ (kg/m^3)	7800	2070	1200

On the other hand, the geometrical parameters of the specimen are summarized in tab.2

Parameters	L	L_0	e	e_0
Values (mm)	16	14	4	0.1

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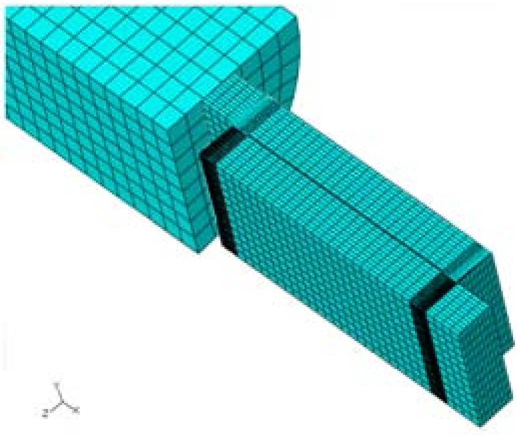
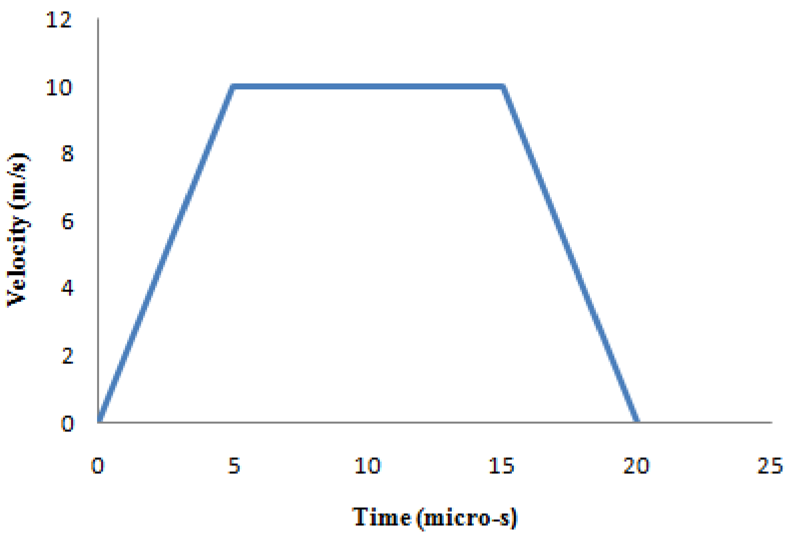
3. Numerical model

The Split Hopkinson Pressure Bar system (SHPB) is the device used to apply impact loading on the specimen. Details of the SHPB theory are found in [15]. Numerical model, carried out on ABAQUS Explicit, is identical to the one used in [15] and [17] where just the output bar is considered. It is made from the same steel mentioned in tab.1; it has a length of 600 mm and a diameter of 16 mm. It is supposed to be cantilevered at its far end while it has a frictionless contact with the specimen at its other extremity.

The mesh type is C3D8R 8-node solid element; tied node-to-surface was used as contact adhesive-adherent. The size of each adhesive element is 25 μm through thickness. At the layer's extremities a refinement of 5 μm x 25 μm x 100 μm was applied. Since the model has two planes of symmetry hence its one quarter could be kept only as fig.2 shows: this will help in time and memory cost reduction. The impact is modeled by a trapezoidal velocity signal of 20 μs duration and 10 m/s amplitude as shown in fig.3.





4. Homogeneity coefficient

It is well known that the shear stress field in the adhesive layer is heterogeneous along the overlap length either under static or under dynamic loading. To quantify this

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heterogeneity, a coefficient denoted by α and known as homogeneity coefficient is defined. It has the same expression and significance as it was done in [15] and [17]:

$$\alpha(t) = \sqrt{\frac{1}{L_0}\int_0^{L_0} \frac{\left|\tau_{xz}\left(x, y = \frac{w}{2}, z = \frac{e_0}{2}, t\right) - \tau_{xz}^{av}(t)\right|^2}{|\tau_{xz}^{av}(t)|^2} dx}$$

where the average shear stress in the layer is given by:

$$\tau_{xz}^{av}(t) = \frac{1}{L_0}\int_0^{L_0} \tau_{xz}(x, y = \frac{w}{2}, z = \frac{e_0}{2}, t)dx$$

Moreover, it has been shown in [15] and [17] that, in the first few microseconds, this coefficient is not significant since the dynamic equilibrium is not yet established in the specimen. When the wave's travel through the specimen finishes and the equilibrium is established, the value of α stabilizes and becomes independent of time. This value depends on many geometrical and mechanical parameters of the specimen.

In this paper, the evolution of α with respect to E_0; e_0; L_0 and e for both cases of steel and glass/PEEK substrates will be compared where:

E_0: Young's modulus of the adhesive.

e_0: thickness of the adhesive layer.

L_0: overlap length.

e: thickness of the central substrate.

The variation of the values of each of the above mentioned parameters follows the table 3 shown below:

E_0 (GPa)	e_0 (mm)	L_0 (mm)	e (mm)
0.2	0.05	10	2
0.5	**0.1**	12	**4**
1	015	**14**	6
2	0.2	16	8
4		18	

It should be noticed that for each simulation, only one of those values is changed; all the other parameters keep their reference values shown in tab.2. These reference values are marked in bold in tab.3.

5. Results

Graphs of figs 4.a, 4.b, 4.c and 4.d show the superposition of the homogeneity evolution curves of metallic and composite substrates in function of the four above mentioned parameters. For both cases of substrates materials, and as found in [15] and [17], the homogeneity of the shear stress field improves for thicker adherents and for softer, thicker but shorter adhesive layer. This tendency appears clearly in each of the four graphs. However, it was proven also that stiffer adherents improve the homogeneity of the shear stress field and that for composites; it is the longitudinal Young's modulus E_{xx} that controls this stiffness.

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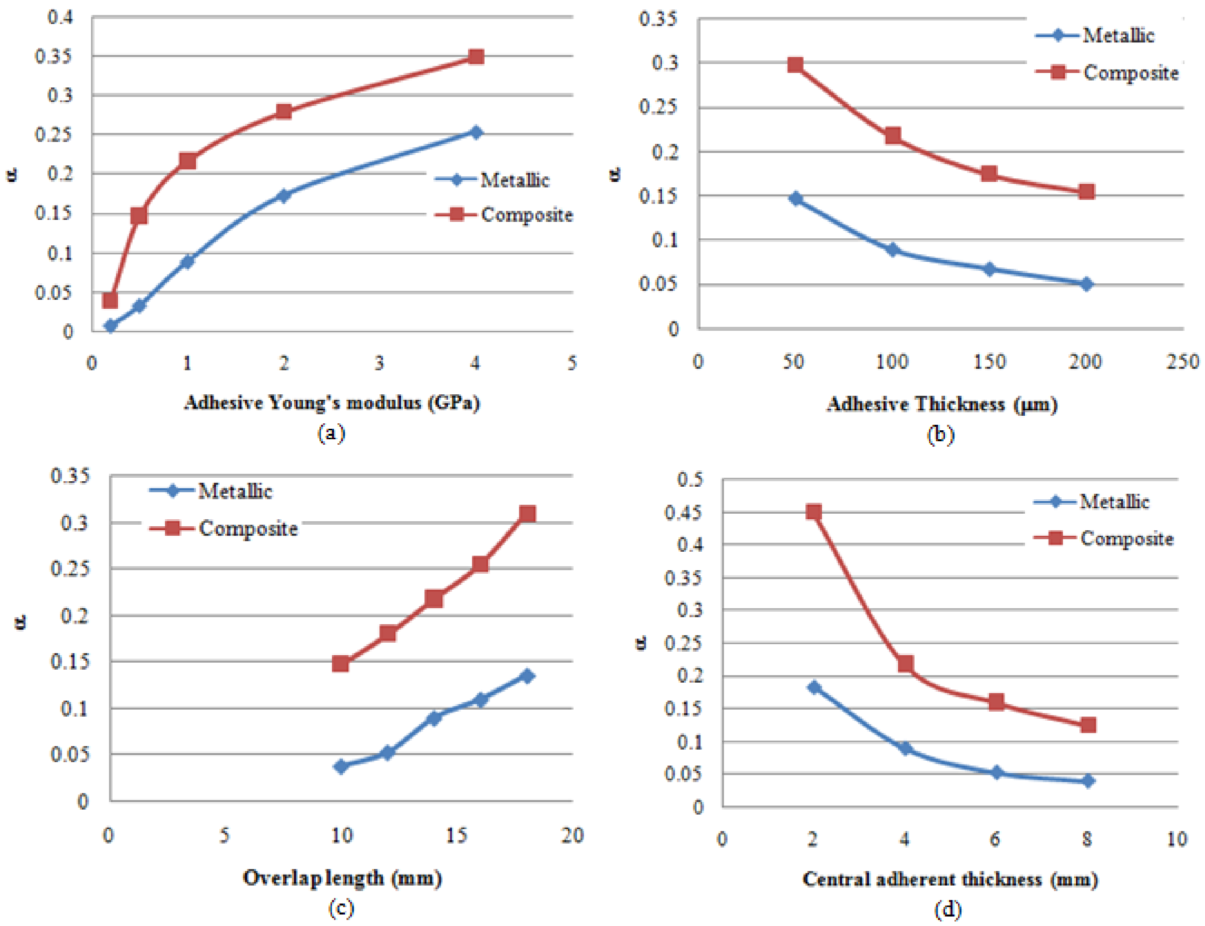

Since the Young's modulus of steel is largely greater than the longitudinal Young's modulus of glass/PEEK, it is obvious to see that steel adherents offer a better homogeneity by 2.5 to 3.5 times when all other parameters are identical.

6. Discussion

In this part, it is worth to go deeper in the analysis of the results through many aspects.

The first aspect to discuss is the sensitivity of change of α when a chosen parameter passes from one value to another. The sensitivity is calculated as the relative change of the homogeneity coefficient between each two consecutive values. The results are depicted in graphs of figs. 5.a to 5.d.

One can remark in all the graphs that the bonded joints with composite substrates show less sensitivity of the homogeneity of their dynamic shear stress field when some mechanical and geometrical parameters change. Moreover, the sensitivity for both cases of substrates decreases globally when any of the discussed parameters increases. Such curves might be helpful for design of bonded structures when it is requested to find an optimum configuration of a double lap joint with improved homogeneity, since an heterogeneous stress field will no doubt lead to stress concentration at critical points that could constitute a source of crack propagation and thus fracture.

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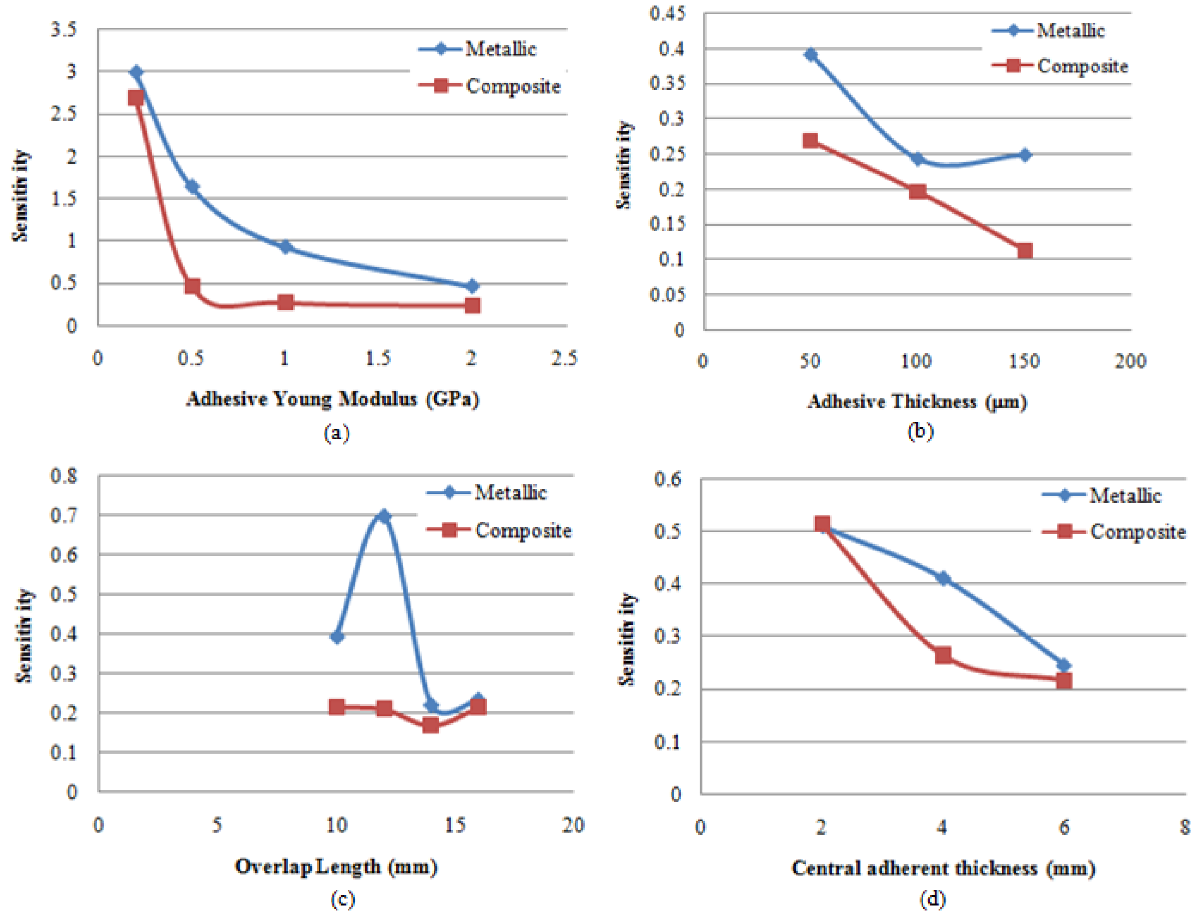

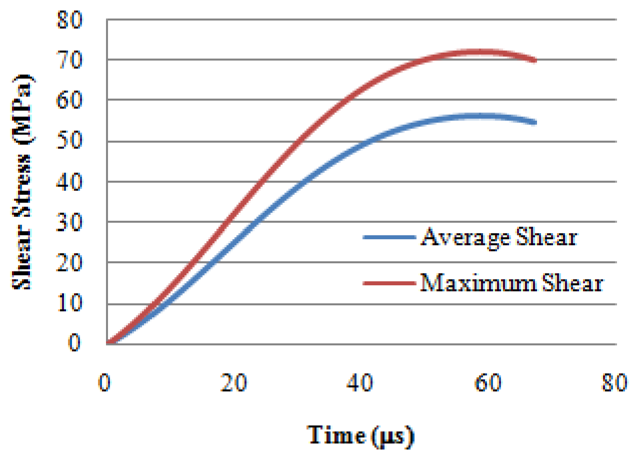

One may discuss a second important aspect: the numerical use of the homogeneity study to evaluate the maximum shear stress in the adhesive layer, since the experimental devices give only an average value which is not very accurate towards fracture prediction. In [15], a coefficient of stress concentration was established numerically to calculate the maximum stress from the average experimental measured value.

As example, one may give the graph of fig.6 that shows the evolution of the shear stress in its average value measured on a DLJ specimen with steel substrates and epoxy adhesive subjected to an impact of 8 m/s speed using the SHPB device; the surfaces of the substrates were treated with ethanol. The experiments have given a critical average stress of 56 MPa, while, using the results of [15], this stress should be amplified to give a critical maximum stress (occurring at the edges) of about 72 MPa.

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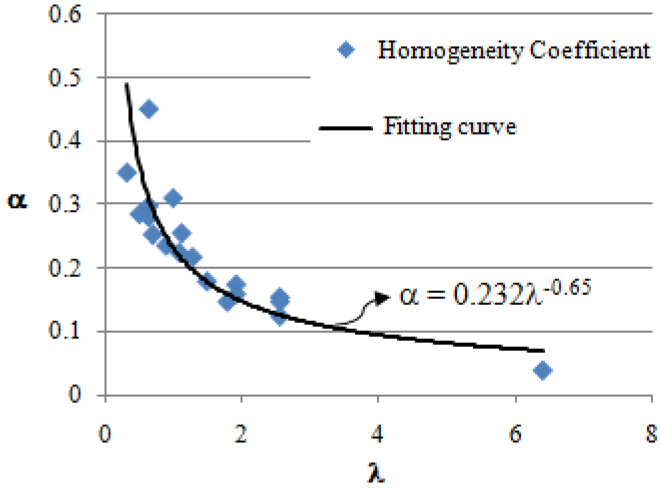
The final aspect of this work will be based on establishing a unified parameter λ gathering mathematically all the mechanical and geometrical parameters influencing the homogeneity for the case of composite substrates. Indeed this was done for metallic substrates in [15]:

$$\lambda = \frac{E_{xx}.e.e_0}{E_0.l_0}$$



Graph of fig.7 shows all the numerical values of α obtained from the different simulations by varying all the parameters one by one; a fitting curve was proposed to get a mathematical expression that allows quantifying approximately the homogeneity knowing the configuration of the specimen. The approximate equation is given by:

$$\alpha = 0.232.\lambda^{-0.65}$$

This equation could be used to define a geometry of the specimen when materials are imposed and vice-versa to reach an acceptable homogeneity of the stress field; moreover it allows establishing a corresponding global configuration (materials and geometry) of the assembly to reach a desired homogeneity.

A practical example could be detailed: which geometry of a DLJ glass/PEEK substrates would give the same homogeneity as offered by steel substrates for the reference values of the parameters? The coefficient α is about 9% for steel and 21.8% for glass/PEEK. To reach an homogeneity of 9% for glass/PEEK, the configuration should give λ = 4.292253 mm according to eq.4. By keeping E_{xx} and all adhesive parameters the same, one will get that a central adherent thickness of 13.4 mm. In mass terms, this will lead to about 11.9 g of steel substrates and 10.49 g of glass/PEEK substrates which will lead to a gain in mass of about 11%.

7. Conclusion

Homogeneity is an important aspect in designing DLJ bonded assemblies since a non homogeneous stress field leads to critical points and thus cracks initiation in the adhesive; this means that the measurement of average strength values is not sufficient.

In this paper, a comparison of the homogeneity of stress field between metallic and composite substrates was carried out. For same configuration, the longitudinal Young's modulus controls the homogeneity, which is globally better for metallic cases, those latter present higher sensitivity of the homogeneity towards parameters variation. However, a change in configuration of assemblies with composite substrates would lead to better homogeneity with gaining other secondary aspects such as weight of the structure. For a

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certain range of assembly's parameters, this design could be simplified through an approximated mathematical equation established by numerical simulations.

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