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COMPOSITES THEORY AND PRACTICE

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STRESS HOMOGENEITY IN ADHESIVE LAYER OF COMPOSITE DOUBLE LAP JOINT UNDER DYNAMIC SHEAR LOADING

The main purpose of this work is to numerically investigate the shear stress homogeneity in the adhesive layer of a double lap joint specimen subjected to dynamic shear loading using the Split Hopkinson Pressure Bar technique (SHPB). This homogeneity is measured through a coefficient defined by the ratio of the standard deviation over the average shear stress in the adhesive layer. Three types of fiber textures of carbon-epoxy composite adherents were examined: unidirectional laminates, 2.5 D interlock H2 and 3D orthogonal. The influence of many parameters related to the adhesive was studied for the three types of composite adherents. For the same percentage of carbon fibers, it was found that the unidirectional composite substrates give the best homogeneity. Moreover, a thicker, shorter and softer adhesive layer ensures the best shear stress homogeneity for all the three types of substrates. The software used for this study is ABAQUS.

Keywords: **stress homogeneity, impact, adhesive, composite adherents, finite element**

JEDNORODNOŚĆ NAPRĘŻENIA W WARSTWIE ADHEZYJNEJ PODWÓJNEGO POŁĄCZENIA ZAKŁADKOWEGO KOMPOZYTU PODDANEGO DYNAMICZNEMU OBCIĄŻENIU ŚCINAJĄCEMU

Głównym celem pracy jest badanie numeryczne jednorodności naprężenia ścinającego w warstwie przyczepnej próbki z podwójnym połączeniem zakładkowym poddanej dynamicznemu obciążeniu ścinającemu przy użyciu pręta Hopkinsona (SHPB). Jednorodność tę mierzy się poprzez współczynnik definiowany przez stosunek odchylenia standardowego do przeciętnego naprężenia standardowego w warstwie przyczepnej. Badano trzy typy tekstur włókien kompozytów węglowo-epoksydowych: laminat jednokierunkowy, 2,5-wymiarowy laminat o gęstym splocie H2 oraz laminat trójwymiarowy ortogonalny. Dla tych trzech typów kompozytów badano wpływ wielu parametrów powiązanych ze spoiwem. Stwierdzono, że przy tym samym udziale procentowym włókien węglowych najlepszą jednorodność można uzyskać w przypadku jednokierunkowych laminatów. Co więcej, grubsza, krótsza i bardziej miękka warstwa przyczepna zapewnia najlepszą jednorodność naprężenia ścinającego dla wszystkich trzech typów substratów. Do badań użyto pakietu programów ABAQUS.

Słowa kluczowe: **jednorodność naprężenia, adhezja, kompozyty, element skończony**

INTRODUCTION

Light weight structures have become one of the main targets of modern industries in general, and of transportation industries especially, since such structures lead to saving huge quantities of fuel. The main problem of bonded assemblies is the heterogeneity of the stress field along the overlap length where the stress peaks are observed at the edges. A large number of parameters interfere in these assembly studies. Experimental tests alone seem to consume huge amounts of time and effort, thus numerical models will prove themselves more than necessary in this field.

The work of Adams and Wake [1] was one of the first numerical works tackling bonded assemblies: they applied the Finite Element Method (FEM) to prove that tapered substrates in the neighborhood of the adhesive ends improve the stress homogeneity while a spew fillet in the layer increases the joint strength. Wada et al. [2] simulated using ANSYS a dynamic test on dissimilar cylindrical bonded bars; one made from polymethyl methacrylate (PMMA) and the second from aluminum. Öchsner and Gegner [3] compared a 2D FEM analysis to Hooke's law to correct the adherent deformation in the static behavior of a single lap joint. Cognard et al. [4] and [5] proposed special substrate geometry to overcome the edge effect and validated it through FEM analysis. Only static loading was considered and the adhesive behavior was non-linear. The adherents were metallic and composite. A double lap bonded joint under tensile-shear static loading was examined in [6] by Osnes and McGeorge: they numerically validated an analytical model based on shear through the adherents thickness, thus the shear stress in the adhesive layer was calculated as interfacial shear between both the adherents. In [7], this study was extended by considering the elastoplastic behavior of the adhesive, which was validated experimentally. A particular 2D interfacial FEM was applied in [8] for a composite single lap joint in order to find the stress distribution in the adhesive layer, at the interface and within the substrates. The effect of the substrate materials was examined also. Vable and Maddi [9] proposed a numerical method called the Boundary Element Method (BEM) and compared it with classical FEM for a single and double lap joint. Many values of the spew angle were taken to examine the edge effect. Challita and Othman [10] simulated in ABAQUS the SHPB technique applied on double lap joints with steel adherents and an epoxy adhesive and concluded that this technique gives a good estimation for mean shear stress in the adhesive layer. Nevertheless, it overestimates the average strain, the maximum shear stress and strain; thus a unified parameter was established to correct the SHPB results. Hazimeh et al. [11-13] studied the shear behavior of the same double lap joint, under two types of loading, quasi static and dynamic impact using the SHPB method. However, the adherents were not made out of isotropic steel, but out of an anisotropic unidirectional composite, with glass E fiber, and a polyether ether ketone (PEEK) matrix. Both quasi-static and dynamic impact tests were simulated on ABAQUS. Therefore, the influence of many geometrical and material parameters of the double lap specimen was examined, one parameter was changed at a time to avoid having combined effects.

The aim of this paper is to construct double lap joints with textile composites, and analyze the parametric study of the adhesive influence on the explicit standard module of ABAQUS.

NUMERICAL MODEL

Specimen

In this study, we will use the geometry of the double lap joint in Figure 1. The central adherent in the double lap joint is shifted horizontally by 2 mm relative to the extreme ones in order to convert the compressive load on the central adherent into a shear stress state in the adhesive layer. The central adherent thickness is double the extreme adherents. The same material is used for all three adherents, and hence the name "balanced double lap joint". A double lap joint has an advantage over a single lap joint, which is that the peel stresses are reduced, so the shear stress in the adhesive layer can be considered as pure shear. Indeed, it was found in [10] that the peel stresses are 1% of the shear stresses based on a dynamic simulation of double lap joints. The set-up used was SHPB.

At the beginning, a reference model will be studied, later on the influence of different geometrical and material parameters will be investigated: adhesive thickness, adhesive Young's modulus and overlap length while all the properties related to the adherents will remain unchanged. One parameter will be changed per simulation to have a clear understanding of the influence of each parameter on the behavior of the double lap joint under dynamic shear, and to avoid combined effects. The parameters of the reference model are summarized in Table 1 shown above.

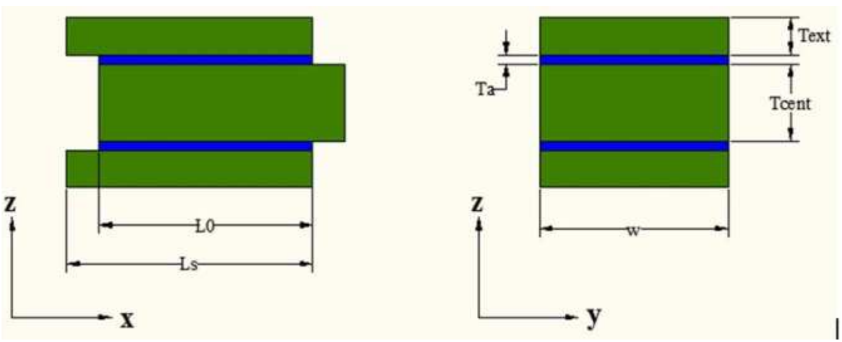


Fig.1. Double lap joint specimen

Rys. 1. Próbka z podwójnym połączeniem zakładkowym

TABLE 1. **Reference model parameter values**

TABELA 1. **Wartość parametrów modelu referencyjnego**

	Adversive					Adherent (Substrate)				
Parameters	L_0 [mm]	T_a [mm]	W [mm]	E_a [MPa]	v_a	L_s [mm]	T_{sext} [mm]	T_{scen} [mm]	W [mm]	E_{xx}, E_{yy}, E_{zz}, G_{xy}, G_{xz}, G_{yz}, [MPa] v_{xy}, v_{xz}, v_{yz}
Values	14	0.1	12	1000	0.4	16	2	4	12	Depends on material UD-2.5D-3D

Materials

Three types of architecture for the textile composite were studied and compared in terms of the behavior under dynamic shear stress: unidirectional type, 2.5D interlock-type H2, and 3D orthogonal. In order to conduct a simpler study, we will assume:

1. The adhesive and adherents are considered elastic
2. The adhesive is elastic and isotropic.

All three types of composite are made of T300-J, Carbon Fiber, Tex396, from Torayca SOFICAR, and RTM 6 resin from Hexcel. The properties of the unidirectional type are found using the mixing law, with a fiber volume of 39.6%, which is equivalent to the overall fiber volume in the representative elementary volume of the 2.5D interlock type H2 or type 1 composites. The properties of 2.5D interlock type H2 or type 1 are calculated using the improved analytical model for prediction of the elastic properties of the 2.5D interlock woven composites, and more precisely the three stages of the homogenization method using the Chamis micromechanical model, developed in [14]. The properties of the 3D orthogonal type are found using an analytical model, based on unit cell analysis [14].

The properties of these materials are summarized in Table 2.

TABLE 2. **Properties of three types of composite adherents**
TABELA 2. **Właściwości trzech typów kompozytów**

Property	Unit	Fiber, Carbon T300-J, 396Tex, Torayca, SPFICAR	Resin-RTM 6 Hexcel	UD, Vf = 0.396	2.5D-Type H2, Type1 - 3SHM-using Chamis micro-mechanical model	3D orthogonal
density	[Kg/m^3]	1780	1100	1360	1360	1360
E_{xx}	[GPa]	230	2.89	92.82	27.54	56.19
E_{yy}	[GPa]	15	2.89	4.248	53.92	60.05
E_{zz}	[GPa]	15	2.89	4.248	7.23	16.09
G_{xy}	[GPa]	50	1.07	1.748	3.212	3.76
G_{xz}	[GPa]	50	1.07	1.748	3.379	3.17
G_{yz}	[GPa]	5.77	1.07	1.574	2.868	4.64
v_{xy}	-	0.278	0.35	0.321	0.037	0.063
v_{xz}	-	0.278	0.35	0.321	0.362	0.339
v_{yz}	-	0.3	0.35	0.35	0.369	0.305

FEM model

Impact loading using the SHPB technique will be applied. This will be represented by a velocity impact pulse applied on the central adherent as shown in Figure 2a. The graph of this velocity input is shown in Figure 2b.

Since the specimen has two planes of symmetry, we will model its one-fourth. This will reduce remarkably the time needed for computation. We add the output bar of the SHPB setup in the simulation to measure only the transmitted wave in the specimen in order to avoid the formation of a reflected wave to the specimen because this wave will mix up with the incident wave and hence this will alter the intent of the simulation and the outputs, especially the shear stress in the adhesive layer. This output bar is a long elastic bar made of steel, of a cylindrical shape, having a 200 GPa Young's modulus, 0.3 Poisson ratio, and a density of 7800 Kg/m^3. A displacement of zero in the direction of the load, x direction in our case, was imposed at the free end of the output bar. The adherents and adhesive were assembled using the tied node-to-surface constraint; a frictionless interaction was imposed between the output bar and the bottom plate. The C3D8R element, explicitly linear, from the family of 3D stress, with reduced integration and hourglass control was used for the different parts. The mesh was refined at the edges since stress peaks occur at those points. In the direction of the thickness, each adherent was subdivided into a mesh of the size of 0.2 mm, the adhesive into a mesh of the size of 0.025 mm.

a)
b)

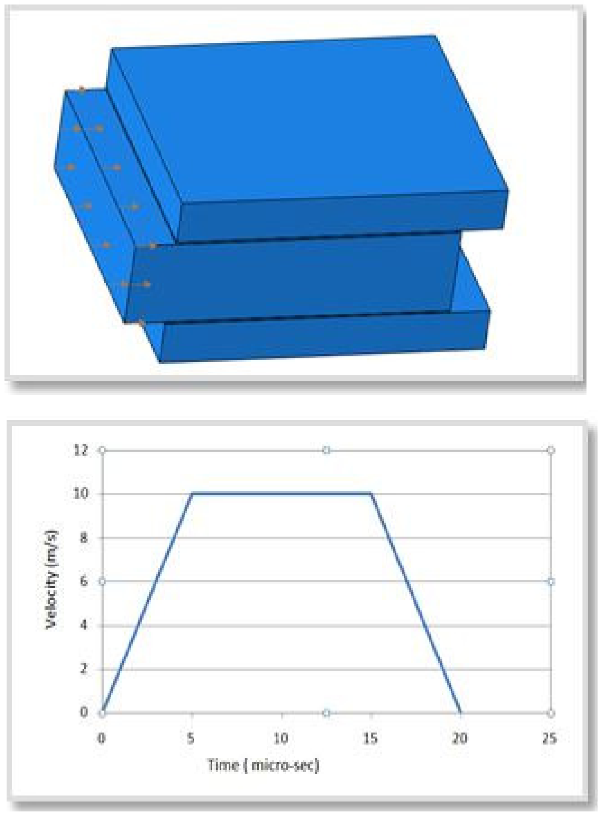


Fig. 2. Load on central adherent (a) and velocity impact pulse (b)
Rys. 2. Obciążenie elementu środkowego (a) i impuls wpływu prędkości (b)

Homogeneity coefficient

The quality of the stress distribution can be analyzed via the homogeneity coefficient, for which the following formula will be used.

$$\alpha_{xy}(t) = \sqrt{\frac{1}{L_0}\int_0^{L_0} \frac{\left|\tau_{xy}\left(x, y = \frac{w}{2}, z = \frac{T_a}{2}, t\right) - \tau_{xy}^{av}(t)\right|^2}{\left|\tau_{xy}^{av}(t)\right|^2} dx} \quad (1)$$

The average shear stress in the adhesive layer should be computed using the following formula:

$$\tau_{xy}^{av}(t) = \frac{1}{L_0 \times T_a \times W} \iiint_{0\,0\,0}^{L_0\,W\,T_a} \tau_{xy}(x,y,z,t)dxdydz \quad (2)$$

The shear stress being constant in the direction of the width, from previous studies [10] and [12], the values can be extracted at the vertical plane defined by ($y = w/2$), which also serves as one of the two planes of symmetry of the sample, the vertical one. Thus,

$$\tau_{xy}^{av}(t) = \frac{1}{L_0} \int_0^{L_0} \tau_{xy}(x, y = \frac{w}{2}, z = \frac{T_a}{2}, t)dx \quad (3)$$

Assuming further the stress to be constant in the direction of the thickness, we conclude:

$$\tau_{xy}^{av}(t) = \frac{1}{L_0} \int_0^{L_0} \tau_{xy}(x, y = \frac{w}{2}, z = \frac{T_a}{2}, t)dx \quad (4)$$

We will plot the average shear stress as a function of time only for the reference model. Our point of interest will be the highest point, hence the point at which the average shear stress in the adhesive layer reaches its maximum. The more the α values increase, the more the homogeneity of stress distribution in the adhesive layer decreases; thus for values closer to zero, the stress distribution in the adhesive layer tends to be uniform, in other words the stress field is homogeneous along the overlap length.

As discussed in [10] and [12], the heterogeneity of the shear stress in the adhesive layer is affected by two groups of parameters (i) geometrical and material parameters that yield to what is known as structural heterogeneity; and (ii) parameters due to the test setup such as rise time, impact velocity and material used for the output bar, which induce the dynamic heterogeneity. The dynamic heterogeneity will disappear after some oscillations of the waves, while the structural heterogeneity, intrinsic to the specimen, will remain there. Our interest is mainly in the permanent regime.

RESULTS AND DISCUSSION

Reference model

The graph in Figure 3 illustrates the shear stress distribution in the adhesive layer along the overlap length at t = 19.5 μs. As predicted, the edge effects are clear on the graph and thus a heterogeneous stress field is observed. Figure 4a illustrates the homogeneity coefficient for a 40 μs duration while Figure 4b illustrates the zoom-in of the homogeneity coefficient especially when the dynamic heterogeneity dies out and only the structural heterogeneity remains; this zoom-in clearly shows the levels of α for the three types of textures. The duration of 40 μs is chosen, twice the impact pulse duration, in order to record the results when the dynamic equilibrium is established. In each graph, three curves are present, each one relative to a texture of the composite.

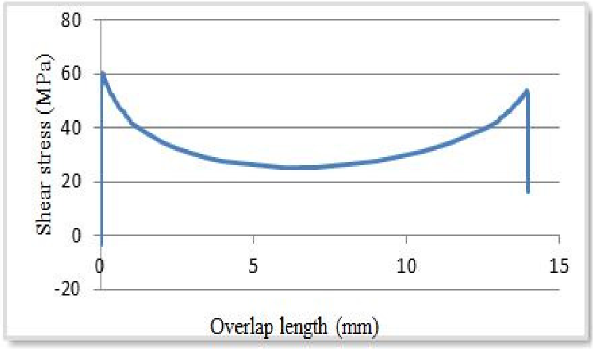
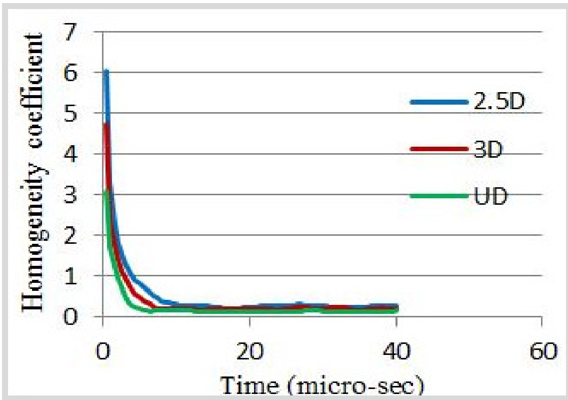


Fig. 3. Shear stress distribution along overlap length for 2.5 D interlock type H2

Rys. 3. Rozkład naprężenia ścinającego po długości nakładania się dla 2,5-wymiarowego laminatu o gęstym splocie, typu H2

a)



b)

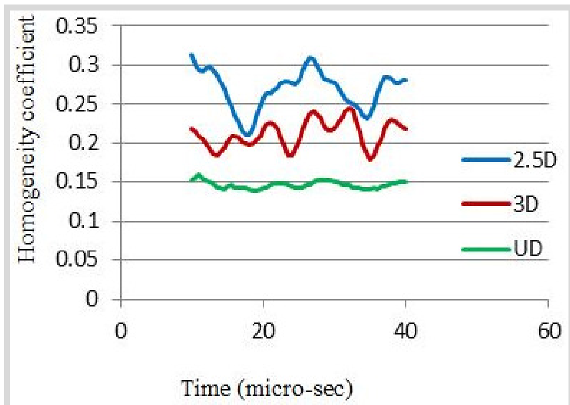


Fig. 4. Homogeneity coefficient along time (a) and zoom-in on homogeneity levels (b)

Rys. 4. Współczynnik jednorodności w czasie (a) i przybliżenie poziomów jednorodności (b)

In terms of homogeneity, it is observed in Figure 4a that the homogeneity coefficient in the adhesive layer has a very high value in the first moments of the simulation and then it drops to an almost constant value, around which it oscillates later on. In fact, after a certain time, the dynamic heterogeneity that is due to the parameters of the test setup and to wave propagation reasons will disappear leaving only the structural heterogeneity, which is intrinsic to the structure geometry and that will remain till the end. Figure 4b represents more clearly the values of this coefficient after the dynamic equilibrium has been established (after a duration of 10 µs approximately). Homogeneity in the adhesive layer is quantified by an average coefficient value of 0.15 with unidirectional adherents, 0.23 with 3D orthogonal substrates, and 0.28 with the interlock type used for the adherents. A direct conclusion is that with unidirectional substrates the homogeneity is by far the best one, it is the worst with the 2.5D interlock.

Parametric study of adhesive influence

Having concluded that the maximum average value of the shear stress in the adhesive joint is at 19.5 µs, we will only compare the homogeneity coefficient at that time. The parameter values of the adhesive are listed in Table 3: the geometrical parameters - L_0 - overlap length, T_a - adhesive thickness; and the material parameter - E_a - adhesive Young's modulus.

TABLE 3. **Adhesive parameter values**
TABELA 3. **Wartości parametrów spoiwa**

Parameters	Values
T_a [mm]	0.02, 0.05, 0.2, 0.3, 0.5
L_0 [mm]	10, 14, 16, 18, 20
E_a [MPa]	200, 500, 2000, 5000

Observing Figure 5a, the homogeneity coefficient decreases with a thicker adhesive. With the 3D orthogonal adherents, a homogeneity coefficient of 0.1 is obtained with the thickest adhesive, while this parameter is 0.37 with the thinnest adhesive.

Therefore the homogeneity is better with a thicker adhesive. However, the shear strength of the joint decreases. A thicker adhesive seems to reduce the shear stiffness and enhance the homogeneity. The graph in Figure 5b shows that when the overlap length increases, the homogeneity coefficient also increases, meaning that the shear stress field becomes more heterogeneous.

For instance, the 3D orthogonal adherents yield to a homogeneity of 0.12 with the smallest overlap length, while with the largest overlap length, the homogeneity coefficient is 0.31. A longer overlap length seems to increase the shear strength but to worsen the stress homogeneity (higher homogeneity coefficient).

In Figure 5c, one can observe that a stiffer adhesive induces high heterogeneity in the shear stress field in the adhesive layer. Looking at the 3D orthogonal type for instance, the homogeneity coefficient is 0.05 with the softer adhesive (E_a = 500 MPa), it is 0.35 with the stiffer one; hence, homogeneity is obviously worsened although the high stiffness improves the shear strength.

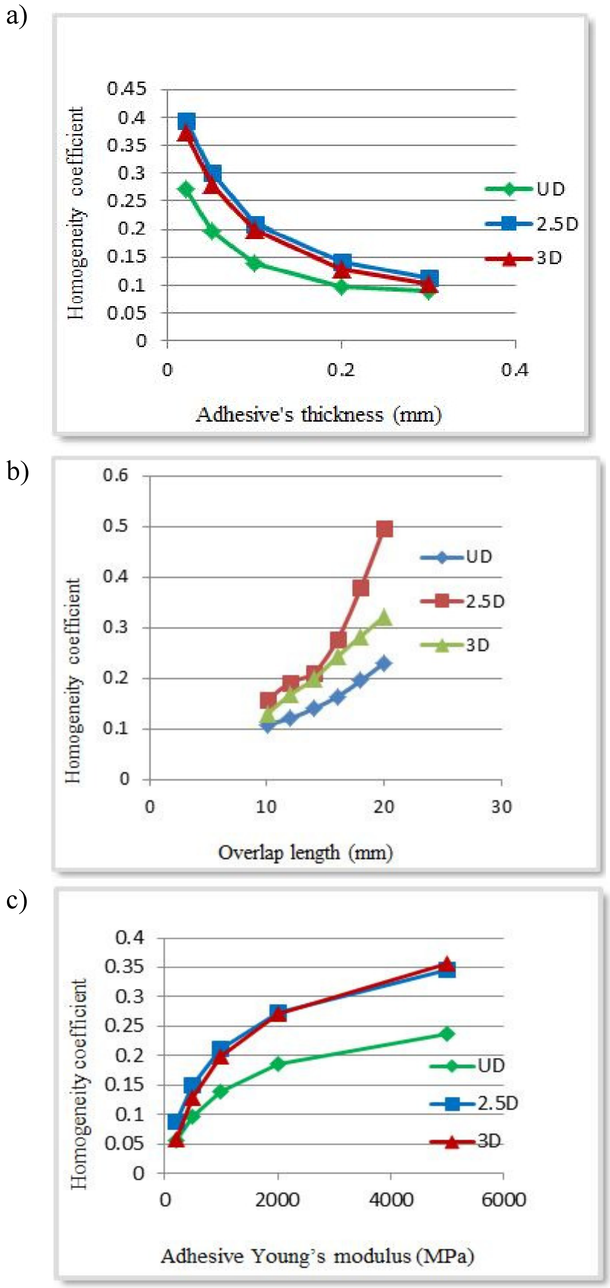


Fig. 5. Effect of adhesive thickness on stress homogeneity (a), effect of overlap length on stress homogeneity (b) and effect of adhesive Young's modulus on stress homogeneity (c)

Rys. 5. Wpływ grubości spoiwa na jednorodność naprężenia (a), wpływ długości nakładania się na jednorodność naprężenia (b) i wpływ modułu Younga dla spoiwa na jednorodność naprężenia (c)

CONCLUSION

Three-dimensional finite element analysis was carried out on double lap joints made out of different composite materials: unidirectional, 2.5D interlock type 1 or also called type H2, and 3D orthogonal composites, all three being carbon fiber reinforced composites. These structures were subjected to a dynamic impact compressive load, using the widely-known split Hopkinson bars. Structural homogeneity, the one intrinsic to the model, is independent of time, and is therefore the subject of our interest. The dynamic homogeneity related to the test setup parameters disappears once a permanent regime is established. A thinner adhesive seems to induce worse homogeneity, while a smaller overlap length decreases the spatial difference between peaks at the edges and low stresses within the joint, thus the strength increases and the homogeneity improves. In addition, for a higher Young's modulus of the adhesive, the softness decreases which induces high heterogeneity.

Finally, the results show that the longitudinal Young's modulus of the substrates (parallel to the loading direction) plays the main role in the stress homogeneity. Indeed, the graphs show that for all the examined cases, the unidirectional type presents the best homogeneity while the 2.5D interlock shows the worst one: for the same fiber volume percentage (39.6%) for all the textures, it is the unidirectional one that presents the highest E_{xx} while the 2.5D interlock presents the lowest value.

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