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INFLUENCE OF RVE GEOMETRICAL PARAMETERS ON ELASTIC RESPONSE OF WOVEN FLAX-EPOXY COMPOSITE MATERIALS

In the case of polymer composites reinforced with natural fiber woven fabrics, microstructural calculations are extremely difficult to perform due to their characteristic variability, among others their mechanical properties. The aforementioned scientific problem has not been thoroughly investigated, hence the purpose of this work was to assess the possibilities of predicting the properties of a composite reinforced with flax woven fabric by micromechanical calculations using the Mori-Tanaka and the double inclusion homogenization models. In addition, the second important utilitarian problem that was undertaken in the work was assessment of the impact of the size of the representative volume element (RVE) on the obtained results. The analyses were carried out for composites based on epoxy resin reinforced with flax fabrics: plain, 2x2 twill and 3x1 twill types. Based on the performed calculations, it was found that the obtained results depend on the type of weave in the fabric used, the size of the RVE, the number of yarn bands in the RVE and the appropriately selected homogenization method. Guidelines useful for evaluating the optimal RVE size depending on the type of weave were formulated.

Keywords: RVE, natural fiber composites, Digimat, flax, FEM, homogenization

WPŁYW PARAMETRÓW GEOMETRYCZNYCH W REO NA WŁAŚCIWOŚCI SPRĘŻYSTE MATERIAŁÓW KOMPOZYTOWYCH ŻYWICA EPOKSYDOWA-TKANINA LNIANA

W przypadku kompozytów polimerowych zbrojonych tkaninami z włókien naturalnych przeprowadzanie obliczeń mikrostrukturalnych jest wyjątkowo trudne do wykonania z uwagi na charakterystyczną dla nich zmienność, m.in. właściwości mechanicznych. Wspomniany problem naukowy nie jest dokładnie zbadany, stąd celem niniejszej pracy była ocena możliwości prognozowania właściwości kompozytu wzmacnianego tkaniną lnianą poprzez obliczenia mikromechaniczne z wykorzystaniem modelu homogenizacji Mori-Tanaka oraz Double Inclusion. Ponadto drugim istotnym problemem utylitarnym, który podjęto w pracy, była ocena wpływu wielkości reprezentatywnego elementu objętościowego (REO) na uzyskane wyniki. Analizy przeprowadzono dla kompozytów o osnowie żywicy epoksydowej zbrojnej tkaninami lnianymi o splocie: płóciennym, skośnym 2x2 oraz skośnym 3x1. Na podstawie przeprowadzonych obliczeń stwierdzono, że uzyskane wyniki zależą od rodzaju splotu w zastosowanej tkaninie, wielkości REO, ilości pasm przędzy w REO oraz odpowiednio dobranej metody homogenizacji. Sformułowano wskazówki przydatne do oceny optymalnego wymiaru REO w zależności od rodzaju splotu.

Słowa kluczowe: REO, kompozyty wypełnione włóknami naturalnymi, Digimat, len, MES, homogenizacja

INTRODUCTION

In the process of modeling composite structures, it is very often impossible to perform calculations for the entire structure due to limitations in the performance of computers and the relatively long calculation time. Therefore, it is desirable to describe the whole structure with a much smaller area that remains large enough to be constitutively valid. This area, which is small enough on the one hand, and large enough on the other, is referred to as the representative volume element (RVE). Basically, applications assume that the RVE exists and that its size is predetermined. However, determining the size of the RVE is often one of the main questions to be answered. This problem has not been sufficiently discussed in the literature, with notable exceptions [1, 2].

After a positive answer to the question about the definition of the RVE, a procedure for determining its size should be introduced. There have been several attempts in the literature to develop a procedure to establish a representative volume [3-5]. An objective method of determining the RVE size was also proposed in the work of Gitman et al. [6]. This method is based on combined statistical analysis of the numerically modeled responses of the material.

There are several definitions of the RVE in the literature that are used by scientists for various purposes:

- The RVE is an area that is structurally completely typical of the entire mixture. In addition, the RVE contains enough inclusions so that apparent integer modules are independent of the surface force and displacement values as long as these values are macroscopically homogeneous [7].
- The RVE is a material model to be used to determine the appropriate effective properties for a homogenized macroscopic model. The RVE should be large enough to contain enough information about the microstructure; however, it should be much smaller than the macroscopic body (this is known as the micro-meso-macro principle) [8].
- The RVE is defined as the minimum volume of the sample on the laboratory scale so that the results obtained from this sample can still be considered representative of the continuum [9].
- The RVE size should be large enough to the individual reinforcing element size to define all the parameters such as stress and strain. In turn, this size should also be small enough not to dominate the macroscopic heterogeneity [10].

Studies on the properties of composites based on methods analyzing the problem of the representative volume element (RVE) are referred to as homogenization methods. The main model that gave the prototype for the formulation of commonly used analytical homogenization methods was the Eshelby model [11]. The assumptions of this model focus on determining the solution to the problem of a single inclusion of material placed in the matrix, which is subjected to a uniform external load.

A commonly used model based on Eshelby's approximate solution is the Mori-Tanaka model [12]. This model assumes that the strain concentration tensor for a single inclusion is equal to the strain concentration tensor of all the inclusions at the average size of their deformation in relation to the average size of the matrix deformation. The analyzed area of the material is interpreted as infinite and it is assumed that the average matrix deformations in the analyzed RVE can be considered as deformations for the entire area of the matrix occurrence in the macroscopic dimension. This model is formulated as follows [12-14]:

$$B^{\varepsilon} = H^{\varepsilon}(I, C_0, C_1) \tag{1}$$

where: B^{ε} – strain concentration tensor of all the inclusions, H^{ε} – strain concentration tensor for a single inclusion, C_0 – matrix stiffness, C_1 – inclusion stiffness, I – inclusion.

An alternative, commonly used model of homogenization formulated by Nemat et. al. [15] is referred to as the double inclusion model. The main assumption of this model is the fact that each inclusion of a certain stiffness is covered with a matrix, and outside this system there is a reference center. This model is formulated as follows [13, 15, 16]:

$$B^{\varepsilon} = \left[(1-\zeta(v_1))(B_l^{\varepsilon})^{-1} + (1-\zeta(v_1))(B_u^{\varepsilon})^{-1}\right] \tag{2}$$

where: B^{ε} – strain concentration tensor of all the inclusions, B_l^{ε} – strain tensor for the Mori-Tanaka model, $\zeta(v_1)$ – interpolation function, B_u^{ε} – strain tensor for the inverse of the Mori-Tanaka model.

It should be noted that in addition to the analytical homogenization models presented above, numerical homogenization methods are increasingly used [17, 18]. The main limitations of this type of analysis are the requirement to have very efficient computational units, and the occurrence of fairly frequent errors during calculations. Therefore, the Mori-Tanaka and double inclusion homogenization models are still the mainly and most willingly used models in micromechanical analysis of composite materials.

The growing focus on combating the problem of managing and processing plastic waste and their derivatives in the form of composites with synthetic fillers encourages the development of technologies for the production of new composite materials based on natural resources. In the case of polymer composites with a Duroplast matrix, glass or carbon fibers are commonly used as reinforcement in the form of mats or fabrics. Progress in the development of the possibility of using plant-derived fibers as a filler in the polymer matrix gives measurable benefits in supporting the reduction of polymer waste and their derivatives.

In the case of plant fibers, due to their large supply in the environment, their cost as a raw material is relatively low. These materials have a much lower density compared to synthetic fibers, while maintaining high strength and density. Moreover, they are fully renewable, and their production does not require a lot of energy input. In turn, the utilization/combustion stage of plant-derived fibers does not generate toxic waste/fumes. There are also some disadvantages of this type of fillers. These fibers are characterized by lower durability compared to synthetic fibers and a lower degradation temperature, which may limit the selection of polymers for the matrix. What is more, an important problem of this type of fillers is the large variability of properties, which may depend even on the cultivation conditions, harvest times, storage method and processing methods [19-22]. In [23], it was noticed that the value of the modulus of elasticity decreases with increasing humidity of the fibers, and augments with increasing temperature. It was also proved [24] that natural fibers harvested 5 days after the right time of harvest had about 15% lower mechanical properties. Furthermore, in publication [25], it was noted that hand-picked flax fibers have 20% better mechanical properties than mechanically harvested fibers.

Basically, the production of plant-based filler composites focuses on using short fibers oriented randomly in a polymer matrix. Natural fibers such as flax and hemp can also be used to make composites in the form of long fibers, as roving, yarn, knitwear, nonwovens, and fabrics with a 2D and 3D structure [26]. The construction of fabrics made of vegetable fibers intended for the reinforcement of composites significantly influences the choice of the composite formation method and its properties [27-31].

In [30] it was shown that the structural parameters of yarn, flax and hemp fabric affect the properties of the obtained composites. The type of fiber used to make the yarn, the spinning sequence and the level of twisting affect the mechanical properties of the fabric. Lowering the density of the yarn or fabric results in a decrease in its properties and consequently, the properties of the composite. On the other hand, a lower fabric density should have a positive effect on better adhesive properties between the polymer fiber-matrix phases, improving the properties of composites.

In the work of Goutianos et al. [31], the effect of the type of flax fiber reinforcement in the form of unidirectional tapes, biaxial plain weaves, unidirectional fabrics and non-crimp fabrics on the properties of the obtained composites was examined. It was found that composites containing reinforcement with long fibers can have even several times better mechanical properties compared to composites filled with non-woven flax fibers, and the type of fabric significantly affects the mechanical properties of composites. In addition, it was proved that the level of yarn twist is an important parameter when preparing this type of reinforcement. Unlike yarns commonly used in textile applications, yarns used in polymer composites should have a low twist level, reducing the negative impact of fiber misalignment and improving the degree of fabric supersaturation.

In the case of composite materials, in particular those reinforced with natural fiber fabrics, their microscopic properties significantly affect the macroscopic properties. Modern methods of describing microstructural phenomena based on micromechanical homogenization models can allow a better and faster understanding of material behavior on the macroscopic scale. DIGIMAT MF software allows the use of the above-mentioned methods. In this software, the calculation algorithm uses Mori-Tanaka and double inclusion homogenization models. In the case of polymer composites reinforced with natural fiber fabrics, microstructural calculations are very difficult to perform due to their characteristic variability, among others mechanical properties. The aforementioned scientific problem has not been thoroughly investigated, hence the purpose of this work was to assess the possibilities of predicting the properties of a composite reinforced with flax fabric by micromechanical calculations using the Mori--Tanaka and double inclusion homogenization models. Additionally, the second important utilitarian problem that was analyzed in the paper was the assessment of the impact of the size of the representative volume element (RVE) on the obtained results.

METHODS

The proposed method of conduct assumes that the distribution of fibers in the yarn is uniform, and that the yarn distribution in the composite is also homogeneous. Adopting such assumptions allows the problem to be approached within the micromechanical theory of heterogeneous periodic materials [32].

Using Digimat MF software porosity, areal density, fiber volume fraction and Young's modulus, calculations for a flax epoxy composite with different fabric weave pattern were made.

The first stage of the calculations was to determine the properties of flax yarn based on the parameters contained in Table 1. Yarn is considered as a set of individual fibers arranged in one direction. Calculations related to predicting yarn properties required input of the actual fiber properties from literature data. The yarn was designed and then calculations were made using Digimat software. The results obtained for the yarn are included in Table 2. These data were used for the next calculations for all the investigated cases of fabric weave patterns.

TABLE 1. **Properties of flax fiber [33]**
TABELA 1. **Właściwości włókien lnianych [33]**

Yarn linear density [Tex]	250
Fiber diameter [μm]	20
Fiber volume fraction (Yarn)	0.545
Yarn cross section (H/W) [mm]	0.35/1.2
Warp count	7 ends/cm
Weft count	7 ends/cm

TABLE 2. **Results of numerical calculations for yarn**
TABELA 2. **Wyniki obliczeń dla przędzy**

Axial Young's modulus [MPa]	8209.9
In-plane Young's modulus [MPa]	6741.2
In-plane Poisson's ratio	0.4156
Transverse Poisson's ratio	0.3436
Transverse shear modulus [MPa]	2446.7
Axial Young's modulus [MPa]	8209.9

The second stage of calculations was to obtain the parameters of the fabric with a given weave pattern based on the properties of yarn after homogenization. It was assumed that the distribution of reinforcement in the composite is regular; therefore, it was possible to determine the RVE. Calculations for various RVE sizes using Digimat MF software were made. The input data used in the calculations are presented in Table 3.

Two different homogenization schemes were used: Mori-Tanaka and double inclusion. A number of characteristic parameters were determined such as porosity, areal density, fiber volume fraction and Young's modulus, depending on the RVE size. The results of the calculations were referred to the experimental results contained in [36], which concerned the study of the 2x2 twill flax-epoxy composite (Table 4). In the next part of the work, the calculation for two additional types of weave pattern: plain and 3x1 twill were presented.

TABLE 3. **Mechanical properties of used materials**
TABELA 3. **Właściwości mechaniczne zastosowanych materiałów**

	Kinetix R240 [34]	**Flax fiber [35]**
Young's modulus E [MPa]	3650	12000
tensile strength f_{uT} [MPa]	83.3	-
compressive strength f_{uC} [MPa]	98	-
Density [g/cm^3]	1.1	1.5
Poisson ratio	0.4	0.3

TABLE 4. **Material properties of flax-epoxy composite [36]**
TABELA 4. **Właściwości kompozytu żywica epoksydowa-tkanina lniana [36]**

Young's modulus (tensile) E_T [MPa]	6030
Tensile strength f_{uT} [MPa]	45.4
Tensile elongation ε_{uT} [%]	3.1
Young's modulus (compression) E_C [MPa]	4199
Compressive strength f_{uC} [MPa]	38.5

a) b)

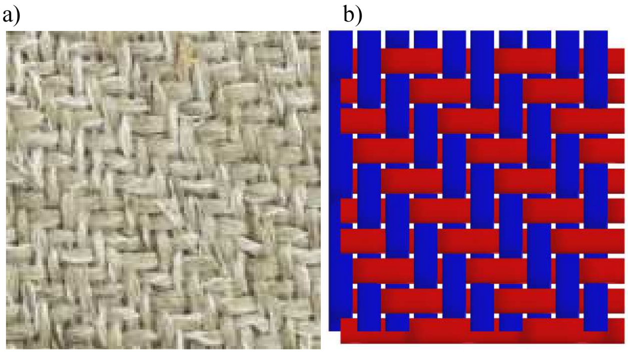

Fig. 1. Sample view of Biotex Flax 400 g/m^2 2x2 twill fabric [33] (a) and fabric visualization (b)

Rys. 1. Przykładowy widok tkaniny lnianej Biotex Flax 400 g/m^2 twill 2x2 [33] (a), wizualizacja tkaniny (b)

The calculated results are presented in the form of graphs of the dependence of individual parameters on the RVE size. Since the thickness of the RVE was the same in each case (0.7 mm), only its surface area was taken into account. An exemplary visualization of the fabric weave pattern in the created numerical model compared to the real fabric is shown in Figure 1.

RESULTS FOR 2X2 TWILL FABRIC EPOXY COMPOSITE

Two yarns warp and two yarns weft (2x2 RVE) is the smallest RVE analyzed in the case of 2x2 twill fabric (although this is not a geometrically correct RVE for this type of weave pattern). Then the amount of yarn in the warp and yarn in the weft was increased proportionally. The list of calculated parameters depending on the RVE size is presented in Table 5.

Depending on the number of yarns used in the RVE, different values of the analyzed parameters were obtained. For two yarns weft and two yarns warp, the results were significantly different from those obtained for the larger RVE size (Fig. 2).

An RVE of this size probably does not meet the premises regarding the basic properties of an RVE, namely that increasing the size of the RVE does not change the value of the obtained results.

The calculations made based on two different homogenization schemes show differences in the Young's modulus E (Fig. 3). When determining porosity, fiber volume fraction or areal density, there are no such differences (Fig. 2). The calculations showed relative stabilization of the results for an RVE 6x6 (six yarns weft and six yarns warp).

For the 2x2 twill fabric type, it should be noted that the calculations for four yarns weft and four yarns warp in the RVE give results for which increasing the RVE size does not cause significant changes in the obtained values. In the case of the calculations of the Young's modulus, an additional factor that affects the results is the homogenization scheme. The double inclusion method allows a Young's modulus value about 0.31% higher than the Mori-Tanaka method to be obtained.

TABLE 5. **Results of numerical calculations for Biotex Flax 400 g/m^2 2x2 twill-epoxy composite**
TABELA 5. **Wyniki obliczeń dla kompozytu żywica epoksydowa-tkanina lniana Biotex Flax 400 g/m^2 o splocie skośnym 2x2**

Warp x weft	**RVE area [mm^2]**	**Mori-Tanaka (M-T)**				**Double inclusion (DI)**			
		Areal density [g/m^2]	**Porosity**	**Fiber volume fraction V_f**	**E [MPa]**	**Areal density [g/m^2]**	**Porosity**	**Fiber volume fraction V_f**	**E [MPa]**
2x2	8.122	393.058	0.3139	0.3737	6107.6	393.058	0.3139	0.3737	6131.2
3x3	18.318	388.038	0.3227	0.3698	6113.5	388.038	0.3227	0.3698	6133.7
4x4	32.604	385.529	0.3271	0.3665	6116.7	385.529	0.3271	0.3665	6135.3
5x5	50.979	384.023	0.3297	0.3651	6118.7	384.023	0.3297	0.3651	6136.3
6x6	73.444	385.529	0.3271	0.3665	6116.7	385.529	0.3271	0.3665	6135.3
7x7	99.800	386.604	0.3252	0.3675	6115.3	386.604	0.3252	0.3675	6134.6
8x8	130.416	385.529	0.3270	0.3660	6116.7	385.529	0.3270	0.3660	6135.8
9x9	165.122	384.69	0.3285	0.3650	6117.8	384.690	0.3285	0.3650	6135.8
10x10	203.918	385.529	0.327	0.3660	6116.7	385.529	0.3270	0.3660	6135.3

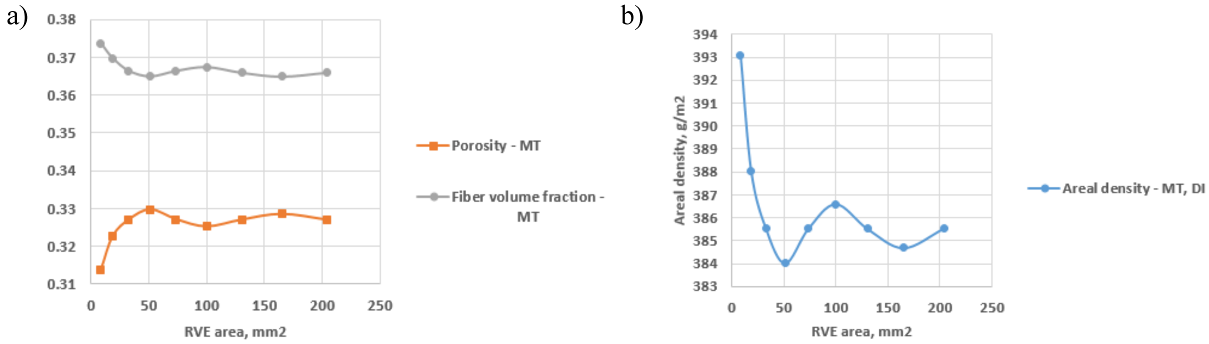

Fig. 2. Porosity, fiber volume fraction (a) and areal density (b) as a function of RVE area; calculations for Biotex Flax 400 g/m^2 2x2 twill-epoxy composite

Rys. 2. Przepuszczalność, udział objętościowy włókien (a) i gramatura (b) jako funkcja powierzchni RVE; wyniki obliczeń dla kompozytu żywica epoksydowa-tkanina lniana Biotex Flax 400 g/m^2 o splocie skośnym 2x2

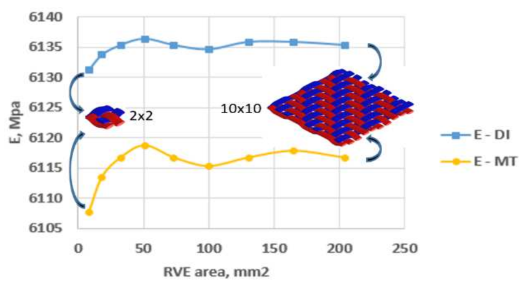

Fig. 3. Young's modulus E as a function of RVE size (DI – double inclusion homogenization scheme, MT – Mori-Tanaka homogenization scheme); calculations for Biotex Flax 400 g/m^2 2x2 twill-epoxy composite

Rys. 3. Moduł Younga E jako funkcja rozmiaru RVE (DI – homogenizacja Double Inclusion, MT – homogenizacja Mori-Tanaka); obliczenia dla kompozytu żywica epoksydowa-tkanina lniana Biotex Flax 400 g/m^2 o splocie skośnym 2x2

RESULTS FOR PLAIN FABRIC EPOXY COMPOSITES

For comparative purposes, similar analyses were carried out for a plain weave pattern (Fig. 4). The analyzed plain weave pattern shows greater variability in the obtained results compared to the twill weave pattern. In addition, the result is affected by an even or odd number of yarns in the RVE area (Table 6).

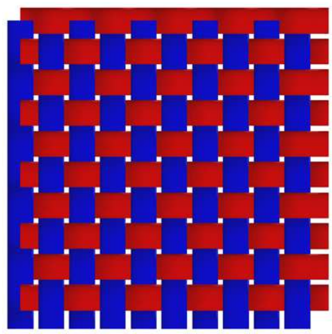

Fig. 4. Fabric visualization; plain fabric

Rys. 4. Wizualizacja tkaniny; splot płócienny

In the case of plain fabric, the calculation results clearly depend on whether the number of yarns in the RVE is even or odd (Figs. 5 and 6). For an even number of yarns, the results regarding areal density and fiber volume fraction V_f, Young's modulus E (only for the Mori-Tanaka homogenization scheme) or porosity remain constant.

TABLE 6. **Results of numerical calculations for flax 400 g/m^2 plain-epoxy composite**
TABELA 6. **Wyniki obliczeń dla kompozytu żywica epoksydowa-tkanina lniana 400 g/m^2 o splocie płóciennym**

Warp x weft	RVE area [mm^2]	Mori-Tanaka (M-T)				Double inclusion (DI)			
		Areal density [g/m^2]	Porosity	Fiber volume fraction V_f	E [MPa]	Areal density [g/m^2]	Porosity	Fiber volume fraction V_f	E [MPa]
2x2	8.122	393.058	0.3139	0.3737	6107.6	393.058	0.3139	0.3737	6131.2
3x3	18.318	388.038	0.3227	0.3689	6113.5	388.038	0.3227	0.3689	6133.7
4x4	32.604	393.058	0.3139	0.3737	6107.6	393.058	0.3139	0.3737	6131.2
5x5	50.979	390.046	0.3192	0.3708	6111.1	390.046	0.3192	0.3708	6132.0
6x6	73.444	393.058	0.3139	0.3737	6107.6	393.058	0.3139	0.3737	6131.2
7x7	99.800	390.906	0.3177	0.3716	6110.0	390.906	0.3177	0.3716	6132.0
8x8	130.416	393.058	0.3139	0.3737	6107.6	393.058	0.3139	0.3737	6131.0
9x9	165.122	391.385	0.3169	0.3721	6109.5	391.385	0.3169	0.3721	6132.0
10x10	203.918	393.058	0.3139	0.3737	6107.6	393.058	0.3139	0.3737	6131.0

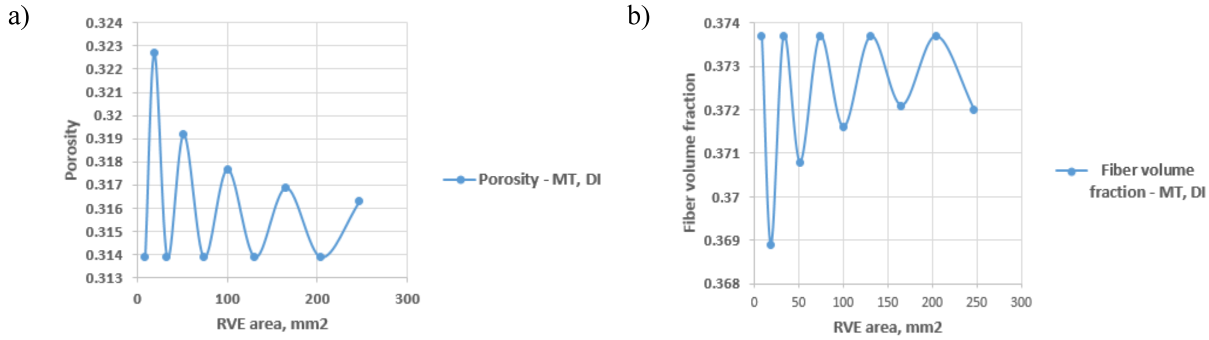

Fig. 5. Porosity: a) fiber volume fraction, b) as a function of RVE area; calculations for flax 400 g/m^2 plain-epoxy composite

Rys. 5. Przepuszczalność: a) zawartość objętościowa włókien, b) jako funkcja powierzchni REO; obliczenia dla kompozytu żywica epoksydowa--tkanina lniana o splocie płóciennym 400 g/m^2

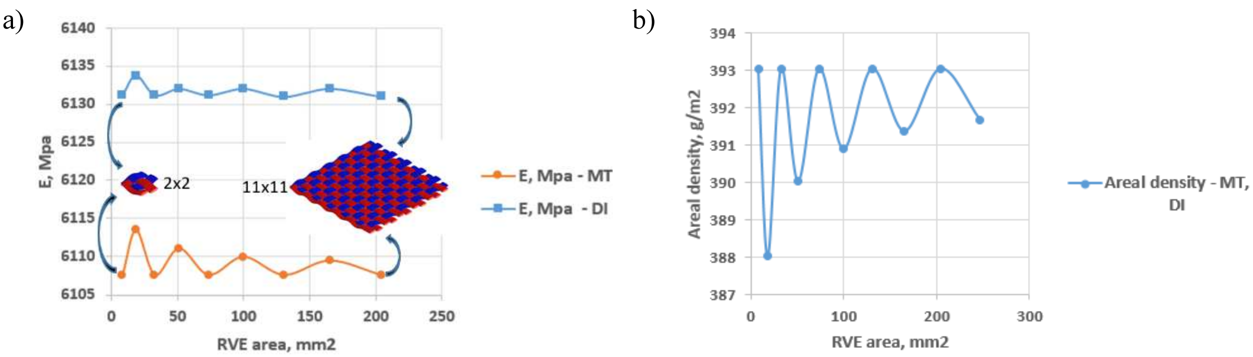

Fig. 6. Young's modulus E as a function of RVE size (DI – double inclusion homogenization scheme, MT – Mori-Tanaka homogenization scheme) (a); areal density as a function of RVE size (b); calculations for flax 400 g/m^2 plain-epoxy composite

Rys. 6. Moduł Younga E jako funkcja rozmiaru REO (DI – homogenizacja Double Inclusion, MT – homogenizacja Mori-Tanaka) (a); gramatura jako funkcja rozmiaru REO (b); obliczenia dla kompozytu żywica epoksydowa-tkanina lniana o splocie płóciennym 400 g/m^2

For an odd number of yarns, the calculation results show high variability – the smaller the greater the RVE. Theoretically, there is also an RVE size for which the results from a cell (RVE) with an odd and even number of yarns will be equal (Fig. 7). To determine the size of this cell, in each case a function describing the respective parameter values for an odd number of yarns was determined (Fig. 7a).

The form of each function is shown in Table 7. In the case of Young's modulus calculations by the double inclusion homogenization method, there is no such relationship. As the number of yarns in the RVE was increased, the results for an even number of yarns differ more (Fig. 7b).

Using an odd number of yarns, relative stability was obtained for an RVE with five yarns weft and five yarns warp (the results slightly decrease as the RVE increases).

The double inclusion homogenization scheme allows a Young's modulus about 0.39% higher compared to the Mori-Tanaka homogenization scheme to be obtained (for the largest RVE analyzed).

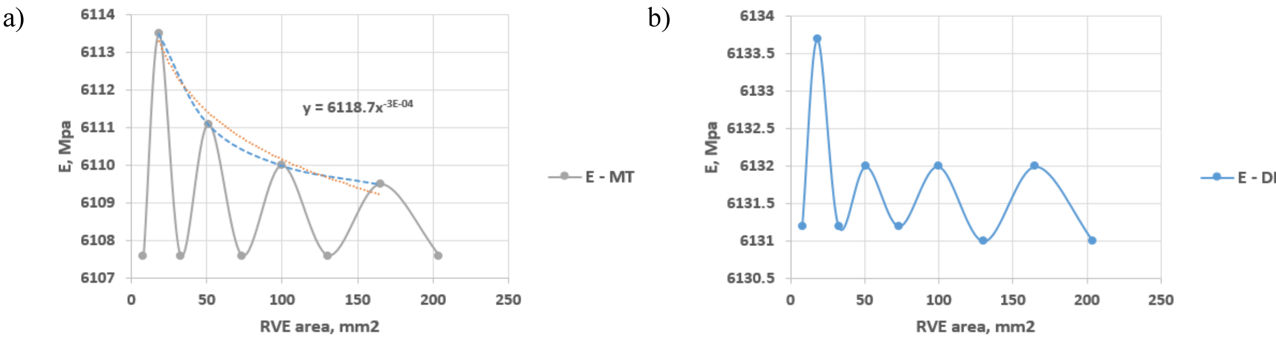

Fig. 7. Young's modulus E as a function of RVE size; Mori-Tanaka homogenization scheme (a); double inclusion homogenization scheme (b); calculations for flax 400 g/m^2 plain-epoxy composite

Rys. 7. Moduł Younga E jako funkcja rozmiaru REO; homogenizacja Mori-Tanaka (a); homogenizacja Double Inclusion (b); obliczenia dla kompozytu żywica epoksydowa-tkanina lniana o splocie płóciennym 400 g/m^2

TABLE 7. **Form of mathematical function for odd number of yarns in RVE**
TABELA 7. **Postać funkcji dla nieparzystej liczby pasm przędzy w REO**

	Mori-Tanaka (M-T)			Double inclusion (DI)		
	Formula	R^2	**RVE area [mm^2]**	**Formula**	R^2	**RVE area [mm^2]**
Areal density	$y = 384.27\ x^{0.0036}$	0.9659	534.0	$y = 384.27\ x^{0.0036}$	0.9659	534.0
Fiber volume fraction	$y = 0.3656\ x^{0.0033}$	0.9284	763.0	$y = 0.3656\ x^{0.0033}$	0.9284	763.0
Young Modulus	$y = 6118.7\ x^{-3E-04}$	0.9756	425.0	-	-	-
Porosity	$y = 0.3295\ x^{-0.008}$	0.9691	435.0	$y = 0.3295\ x^{-0.008}$	0.9691	435.0

RESULTS FOR 3X1 TWILL FABRIC EPOXY COMPOSITES

In the next part of the work, similar analyses were performed for flax 3x1 twill fabric (Fig. 8). The results of the calculations are presented in Table 8.

For the 3x1 twill fabric, different results were obtained depending on the RVE size and the homogenization scheme. Both homogenization methods when calculating the areal density, fiber volume fraction or porosity show the same results for the smallest and largest RVE analyzed, while they differ significantly for the mean RVE area (Fig. 9a, 9b, 10a). For porosity this difference is 1.24%, for the fiber volume fraction 0.55%, for areal density it is 0.49%.

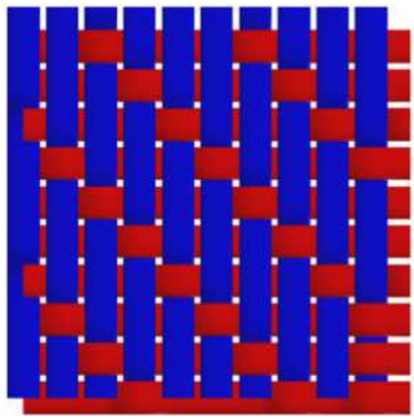

Fig. 8. Fabric visualization; 3x1 twill

Rys. 8. Wizualizacja tkaniny; splot skośny 3x1

TABLE 8. **Results of numerical calculations for flax 400 g/m^2 3x1 twill-epoxy composite**
TABELA 8. **Wyniki obliczeń dla kompozytu żywica epoksydowa-tkanina lniana 400 g/m^2 o splocie skośnym 3x1**

Warp x weft	RVE area [mm^2]	Mori-Tanaka (M-T)				Double inclusion (DI)			
		Areal density [g/m^2]	**Porosity**	**Fiber volume fraction V_f**	E **[MPa]**	**Areal density [g/m^2]**	**Porosity**	**Fiber volume fraction V_f**	E **[MPa]**
4x4	32.604	385.53	0.3271	0.3665	6116.7	385.529	0.3271	0.3665	6135.3
5x5	50.979	384.02	0.3297	0.3651	6118.7	384.023	0.3297	0.3651	6136.3
6x6	73.444	385.53	0.3271	0.3665	6116.7	384.69	0.3280	0.3665	6135.8
7x7	99.800	386.60	0.3252	0.3675	6115.3	385.37	0.3270	0.3660	6135.4
8x8	130.416	387.41	0.3230	0.3680	6116.7	385.53	0.3270	0.3660	6135.3
9x9	165.122	384.69	0.3280	0.3650	6117.8	384.69	0.3280	0.3650	6135.8
10x10	203.918	385.52	0.3270	0.3660	6114.5	385.52	0.3270	0.3660	6133.3

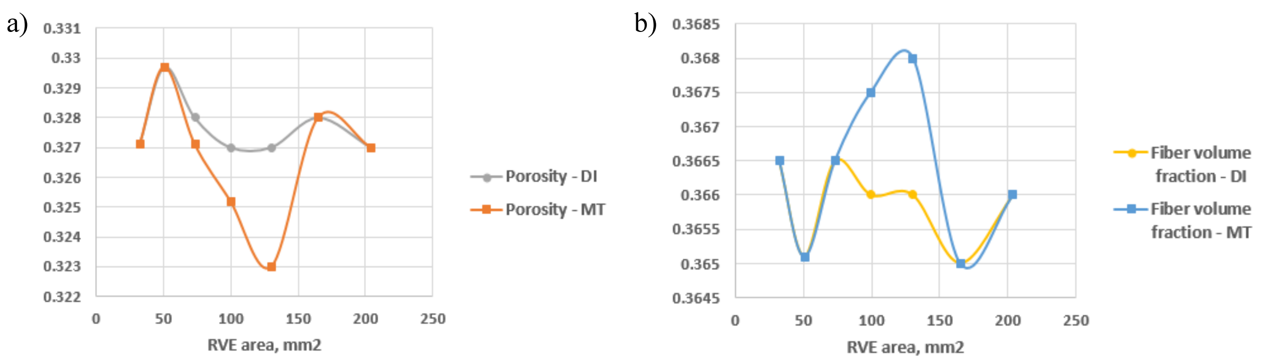

Fig. 9. Porosity (a); fiber volume fraction (b) as a function of RVE area; calculations for flax 400 g/m^2 3x1 twill-epoxy composite

Rys. 9. Przepuszczalność (a); zawartość objętościowa włókien (b) jako funkcja powierzchni REO; obliczenia dla kompozytu tkanina lniana-żywica epoksydowa 400 g/m^2 o splocie skośnym 3x1

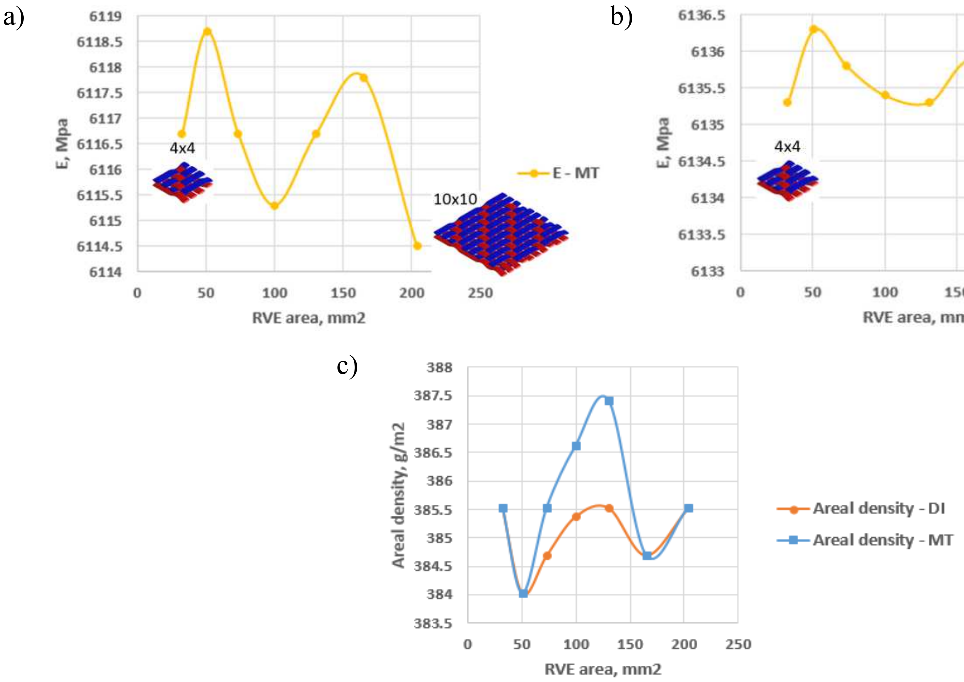

Fig. 10. Young's modulus E as a function of RVE size (DI – double inclusion homogenization scheme, MT – Mori-Tanaka homogenization scheme) (a, b); areal density as a function of RVE size (c); calculations for flax 400 g/m^2 3x1 twill-epoxy composite

Rys. 10. Moduł Younga E jako funkcja rozmiaru REO (DI – homogenizacja Double Inclusion, MT – homogenizacja Mori-Tanaka) (a, b); gramatura jako funkcja rozmiaru REO (c); obliczenia dla kompozytu tkanina lniana-żywica epoksydowa 400 g/m^2 o splocie skośnym 3x1

The double inclusion homogenization scheme allows a Young's modulus about 0.31% higher compared to the Mori-Tanaka method for the largest RVE analyzed to be obtained (Fig. 10b, 10c).

CONCLUSIONS

1. The performed tests indicate a large dependence of the obtained results on the type of weave pattern of the reinforcing fabric, the size of the RVE, the amount of yarn in the RVE and in some cases on the homogenization scheme.
2. Depending on the homogenization scheme and the fabric weave pattern, a different nature of changes in the calculated values is obtained.
3. In the case of plain weave fabrics, the difference of the results obtained for a 2x2 RVE (two yarns warp and two yarns weft) compared to a 3x3 RVE (three yarns warp, three yarns weft) for porosity amounts to 2.8%, fiber volume fraction 1.3%, areal density 1.29% and Young's modulus 0.1% (MT), and 0.04% (DI). The Young's modulus is also affected by the homogenization scheme. Therefore, special attention should be given to selection of the RVE size but also to the number of yarns in the model under consideration depending on the type of fabric.
4. For plain fabric and the Mori-Tanaka homogenization scheme, the same results are obtained for an even number of yarns, regardless of the RVE size. In this case, theoretically there is a size of RVE for which we obtain the same values of the tested parameters for an even and odd number of yarns in the RVE, equal to the results obtained for the 2x2 RVE (two yarns warp two yarns weft).
5. For the same fabric and the double inclusion homogenization scheme, no similarity was observed. Therefore, in this case it is difficult to determine the optimal RVE size.
6. In the case of 2x2 twill fabric, it should be noted that the results of calculations based on the RVE with four yarns weft and four yarns warp give results for which increasing the RVE causes small changes in the obtained values.
7. For twill 3x1 fabric, greater stability of the porosity, fiber volume fraction, Young's modulus and areal density for the double inclusion homogenization scheme was obtained.
8. Based on the obtained results, the recommended RVE size for a plain fabric reinforced composite is 2x2 RVE (two yarns weft and two yarns warp) and each RVE with an even number of warp and weft strands. For a 2x2 twill fabric reinforced composite the recommended RVE size is 4x4 RVE; for a 3x1 twill fabric reinforced composite the recommended RVE size is four yarns weft and four yarns warp (RVE 4x4). In this case, the change (increase in RVE size) causes a change in the obtained results.

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