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COMPRESSION STUDIES OF MULTI-LAYERED COMPOSITE MATERIALS FOR THE PURPOSE OF VERIFYING COMPOSITE PANELS MODEL USED IN THE RENOVATION PROCESS OF THE FREIGHT WAGON'S HULL

BADANIA PORÓWNAWCZE WIELOWARSTWOWYCH MATERIAŁÓW KOMPOZYTOWYCH NA POTRZEBY WERYFIKACJI MODELU PANELI KOMPOZYTOWYCH STOSOWANYCH DO RENOWACJI POSZYCIA WAGONÓW TOWAROWYCH*

The paper presents the procedure sequence for modelling multilayer composite materials using PLM Siemens NX software. Virtual studies were referring to three-point and four-point flexural test of composite material samples. Composite materials containing fiber reinforced epoxy resin composites were considered. Within the carried out research, a virtual experiment to test composite samples composed of 5, 7 and 10 layers was conducted. Then the virtual model was matched to the results obtained during the stationary tests. As a result of matching the composite material model to the real model, correct results of the virtual bending experiment of composite samples were obtained. The presented procedure sequence for modelling composite material was used to analyse the MES of the scaled side of the freight wagon. The modification consisted in the use of composite panels as reinforcing elements of the wagon's hull from inside to extend its life. The presented modelling approach enabled the initial strength verification of the modified side of the freight wagon's hull.

Keywords: *composite materials, FEM method, modelling, flexural test.*

W pracy przedstawiono sposób postępowania przy modelowaniu wielowarstwowych materiałów kompozytowych z zastosowaniem oprogramowania PLM Siemens NX. Badania wirtualne odnosiły się do próby trójpunktowego i czteropunktowego zginania próbek kompozytowych. Rozważano materiały kompozytowe będące kompozycją żywicy epoksydowej ze wzmocnieniem włóknistym. W ramach prowadzonych badań przeprowadzono wirtualny eksperyment badania próbek kompozytowych będących kompozycją złożoną z 5, 7 i 10 warstw. Następnie dopasowano wirtualny model do wyników otrzymanych na drodze badań stanowiskowych. W wyniku dopasowania modelu materiału kompozytowego uzyskano poprawne wyniki wirtualnego eksperymentu zginania próbek kompozytowych. Zaprezentowany tok postępowania odnośnie modelowania materiału kompozytowego zastosowano do analizy MES pomniejszonego fragmentu zmodyfikowanej burty bocznej wagonu. Modyfikacja polegała na zastosowaniu paneli kompozytowych jako elementów wzmacniających poszycie wewnętrzne wagonu mających na celu wydłużenie jego czasu eksploatacji. Przedstawiony sposób modelowania umożliwił wstępną weryfikację wytrzymałościową zmodyfikowanego fragmentu burty bocznej wagonu towarowego.

Słowa kluczowe: *materiały kompozytowe, metoda MES, modelowanie, próba zginania.*

1. Introduction

The inevitability of using composite materials as construction materials forces engineers to use numerical models describing their structure and properties. Microscale non-homogeneous materials, such as composites, may also be considered on a macro scale as the homogeneous material. To determine the properties of the resultant material a mixture based rule is usually applied, which takes into consideration the volume of components in total volume. It is also possible to use methods based on the approximation of heterogeneous bodies or on the basis of virtual work [1, 2, 14, 15, 17, 26].

In models based on the classical composite materials theory (lamination theory), it is assumed that the laminate consists of layers bonded together in an unbreakable way and the joints have an infinitesimal thickness (they have a thickness close to 0) and do not allow shear between layers. This means that the deformations in thickness of the composite are continuous and no layer can move relative to another. A composite as an integrity forms macroscopically one layer with values of properties that are the resultant of values of the layers forming it. In order to determine the durability of a laminate composite, it is necessary to know the stresses in each individual layer. For this purpose, Hooke's law is used, taking into consideration the determined

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** deformation values. The criteria for the destruction of composite materials are also commonly used [3, 11, 12, 17, 29].

Composite properties and accuracy of the models used can be verified during the experiments. These experiments can be carried out using destructive methods as well as nondestructive methods. During the destructive tests in the structure of the composite material, undesirable and irreversible changes may occur. This aspect often disqualifies a particular method in the research process. In case of non-destructive testing, the examined object will not be damaged so that key information will not be lost and can be obtained. In the research process of composite materials, the key values are displacement and stress [3, 11, 12, 17, 27].

Both destructive and nondestructive methods are used to verify the results of numerical tests. In that process methods based on resistance and optical strain, bending and impact methods are used. In addition, non-destructive methods are used to analyze the occurrence of defects in the composite structure. More sophisticated methods include thermal imaging, ultrasonic, radiological and visual methods can be defined. [11, 13, 26, 27, 29].

Modelling and verification of components made of fibrous composite materials can be supported by numerical analysis using the finite element method. There are two basic approaches during the process of modelling laminate with MES. In the first case, the internal structure of the examined object the number of layers is taken into consideration. We also consider the type and weave of the reinforcement and the degree of resin impregnation. The properties of the various components of the laminate, that is the properties of the matrix and the individual strands of the fabric, are also taken into consideration. Applying this method leads to building models with a large number of variables and a large number of degrees of freedom. Due to the complexity of the problem and limited computing power, this method is used in the analysis of relatively small elements characterized by uncomplicated geometric form. Regarding larger elements of greater complexity, the calculation is based on the analysis of the properties of the composite slice. At this stage, attributes of the replacement material are determined, which is then applied to the entire model. In this case, the model is created using solid elements with properties of the composite material. As a result, the solids are given with special replacement properties, which are characteristic to the previously studied section, without penetrating the internal structure of the composite material. [2, 10, 12, 16, 20, 23, 25, 26].

Two methods are used to describe the structure of a composite material using a finite element mesh. In the first of them, the 2D surface elements mechanical parameters and a virtual thickness parameter are given. In the second method, 3D spatial elements are used for which the thickness is known. Then it is divided into the number of layers for which the properties of the laminate are applied. Both methods take into consideration the volume constituents of the components and the number of layers and their orientation relative to each other. Material constants are determined by experiment or supplied by the manufacturer of the material [2, 10, 12, 16, 19, 20, 23, 25, 26, 28].

The main objective of the conducted research was the verification of numerical strength calculations regarding the analysis of composite panels used to renovate the hull of freight wagons. In the first step, the simplest MES models were tested to verify the convergence of numerical and experimental results. Experimental tests performed on a strength machine were used to compare and verify the results. These were strength tests conducted to composite samples subjected to three-point and four-point bending tests. Experimental FEM models were then developed. Verification of the results allowed for fitting (modification) of FEM numerical models to obtain convergent results. At the next stage, a strength verification was carried out on panels mounted on the side of the freight wagon's hull. It was planned that the numerical results would be verified on a test bench constructed to study the behaviour of the composite panels on the freight wagon's hull. For this purpose, a FEM numerical analysis was carried out which allowed us to initially estimate the expected stresses and displacements, and to identify where the sensors for the experimental analysis would be fixed. In the next step, a strength analysis on a specially built test bench using resistance strain gauges and displacement sensors was carried out. Based on the experience gained during the numerical modelling and with respect to simple strength tests, the FEM models of the freight wagon hull's sidewall was fitted to produce convergent results to those obtained in test bench tests. Matched models are the basis for further research carried out within the framework of the project.

2. The results of experiments of samples made of a composite material

The experiments of composite samples consisted of two types of bending strength tests:

- four-point bending strength test of carbon fiber reinforced by epoxy resin,
- strength test of carbon fiber reinforced by epoxy resin samples performed in triple point bending test.

Experimental research was carried out by the Technical-Humanistic Academy in Bielsko-Biała as part of a research project, the authors of this paper carried out numerical analyzes using the finite element method.

Figure 1 shows the load and support scheme of the tested samples for four-point bending tests. Whereas Figure 2 shows the load and support scheme of the examined samples for the three-point bending tests.

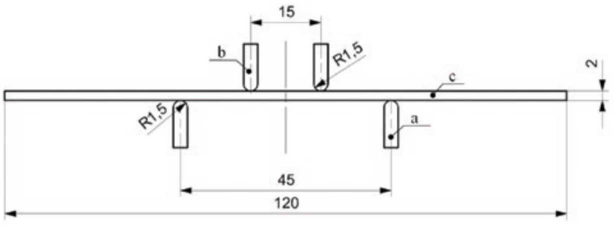

Fig. 1. Scheme of load and support of samples used in four-point bending tests: a – support, b – punch, c – test sample

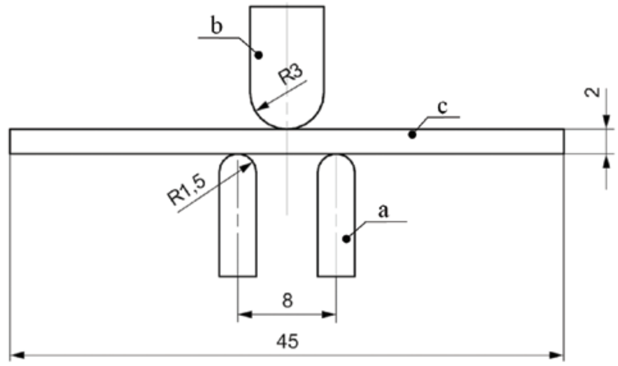

Fig. 2. Scheme of load and support of samples used in three-point bending tests: a – support, b – punch, c – test sample

The strength tests of laminates subjected to a four-point bending test were performed for samples of dimensions of 120 mm x 20 mm x 2 mm. The strength tests of laminates subjected to the three-point bending test concerned samples of dimensions of 45 mm x 4 mm x 2 mm. The thickness of the samples was in the range of 2 to 2.25 mm and the width was in the range of 20 to 20.15 mm. The experi-

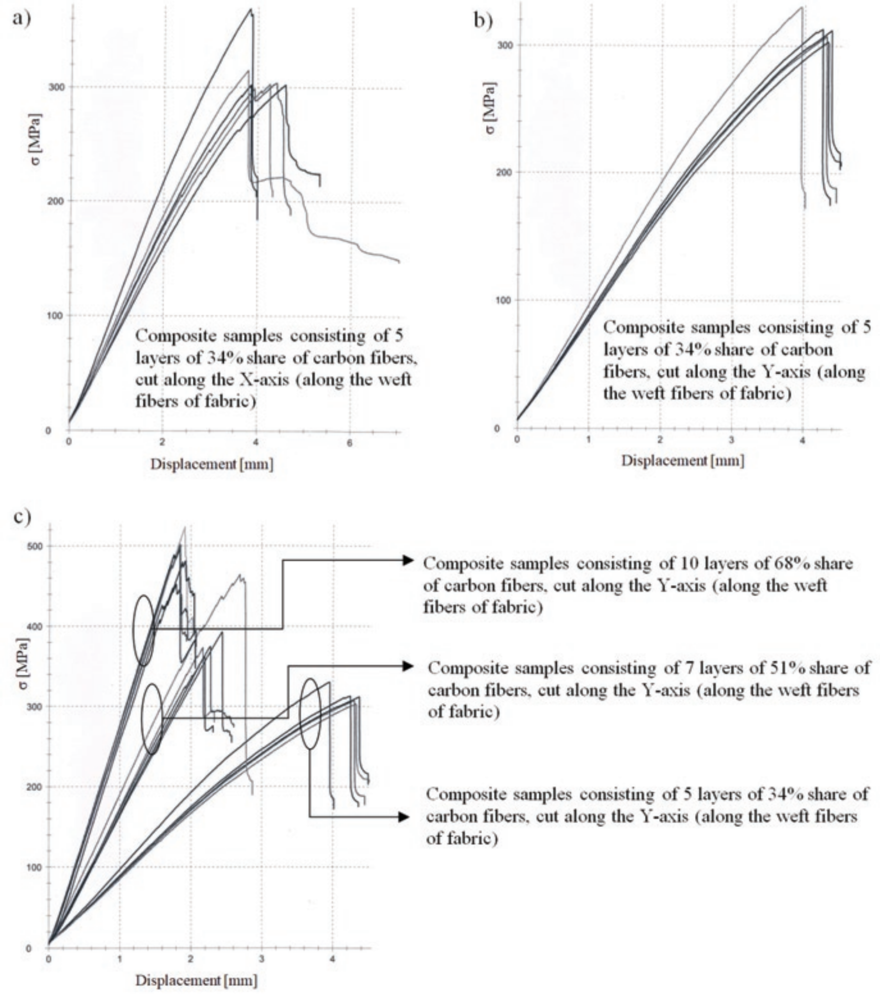

Fig. 3. Examples of results of experimental testes of composite samples in relation to the four-point bending method

mental tests on the testing machine in both cases were performed for samples cut from composite panels made of epoxy resin and fabric with the plain type of weave. Composite panels have been made in the serial production process by infusion method, which guarantees the assumed reinforcement-matrix ratio. Three panels of carbon fiber volume (34%, 51% and 68%) were chosen for the study. The coefficient of a volume of warp fibers to weft fibers was equal to 0.5. Samples were cut in three directions: in the direction of alignment of the warp fibers of the carbon fabric, in the direction of the direction of the weft of the carbon fiber weft and at an angle of 45 ° to the carbon fiber warp yarns. The analyzes also concerned samples of composite panels consisting of a composite of epoxy resin and carbon fibers arranged in one direction, made in 3 variants of carbon fiber volumetric share percentage (38%, 51% and 68%). In this case, the samples were cut in the direction of fiber orientation and at an angle of 90 ° with respect to the orientation of the fibers in the layer. All layers, within the structure of the composite material of the sample, had the same orientation. These bending tests were carried out in accordance with test standard ASTM D 6272-02 at a load velocity (punch velocity) of 2 mm / min.

Fig. 3 illustrates the experimental results of composite samples of the four-point bending test. Figs. 3a and 3b show bending results of composite samples composed of 5 layers, where each layer is a combination of epoxy resin and carbon fiber with plain weave, assuming a 34% carbon fiber content in the composite structure. Figure 3a shows the results of the tests of samples cut along the axis aligned to the carbon fabric weft direction, in Figure 3b the results of the tests are presented of the samples cut along the axis in accordance with the axis of alignment of the carbon fiber matrix. In Fig. 3c, the results of the tests were compiled for composite samples composed of 5, 7 and 10 layers, where each layer was a combination of epoxy resin and carbon fiber with a plain weave, assuming respectively for a number of layers of 34%, 51% and 68% of carbon fiber in the composite structure. By analyzing the presented results, in the case of samples cut along the weft fabric, the stress values were approximately 10% higher than those of the identical composite material cut along the fiber matrix, of the composite at the same displacement of the punches, could be seen. On the other hand, with reference to the results of the studies of 5, 7 and 10 layers of composite samples with respectively 34%, 51% and 68% of volume of carbon fiber, with the increase in the number of layers and the percentage of fibers in the composite structure, the value of archived stresses in the sample increases, for the same displacement value of the stamps could be seen. In Fig. 3c, three separate areas of strength characteristics can be observed depending on the number of layers and percentage infill of fibers.

3. Virtual modelling of three-point and four-point bending tests using finite element method

For representing the three-point and four-point bend test, the models of test benches with the test samples were developed in the PLM Siemens NX10 system. The created solid models were subjected to a discretization process by applying a finite element mesh to individual parts. In the next step, boundary conditions were defined in such a way, that virtual tests were as much comparable as the research on the real test stand.

In the models prepared for FEM analysis, the following boundary conditions were defined (Figures 4 and 5): fixing of the supports, surface to surface contact between the test sample and the supports and

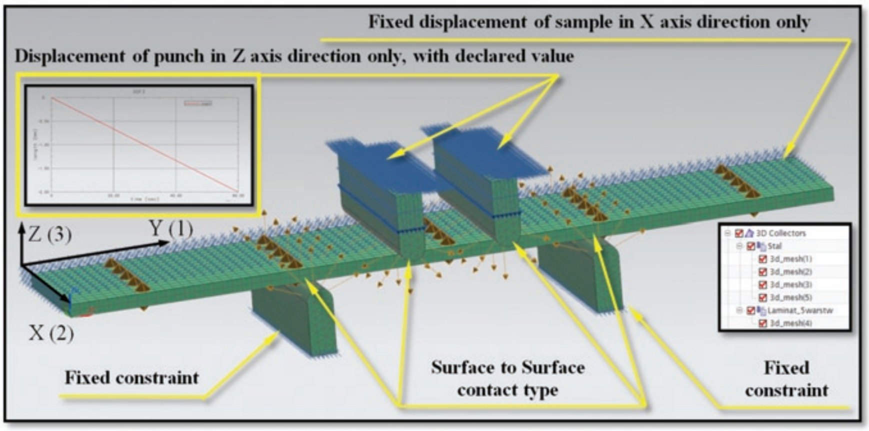

Fig. 4. FEM model with defined boundary conditions and loads for four-point bending strength tests

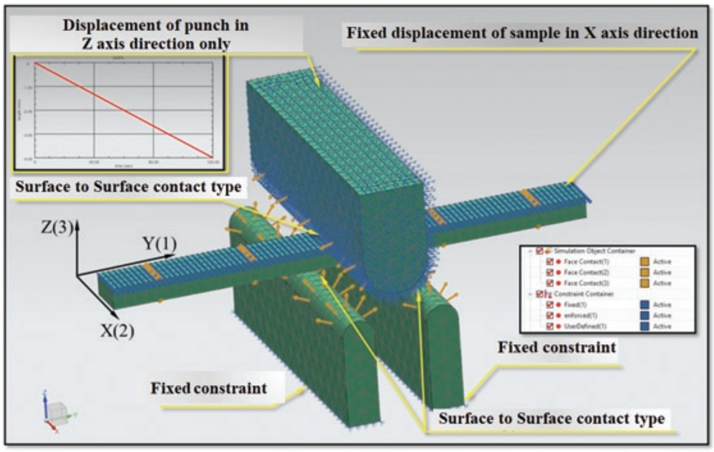

Fig. 5. FEM model with defined boundary conditions and loads for three-point bending strength tests

stamps, fixing of one degree of freedom of the sample for removing the possibility of moving along the X axis, forcing the displacement of punches only along the Z axis. The type of contact used enables the displacement of the discretized samples, supports and punches relative to each other - which is a necessary condition in order to correctly characterize the displacement of the testing sample. In the virtual experiment, the load was defined as the displacement of the stamps in the direction of the Z axis at a speed of 2 mm / min. The applied displacement represents the movement of the actual punches of the testing machine.

The next stage of the research was to map material form of samples made of composite materials subjected to strength tests on the endurance machine. Virtual studies included strength analyzes using finite element method, epoxy resin and carbon fiber composite samples, straight weave and epoxy resin and unidirectional carbon fiber composites. The composite material consisting of 5, 7 and 10 layers were considered.

To define the composite material in PLM Siemens NX 10 software the first layer is described first. Based on the manufacturer's data in relation to used warp and fiber types the following basic layers of laminate composite material were defined: 34_Woven_2W_90, 38_Woven_1W, 51_Woven_2W_90, 51_Woven_1W, 68_Woven_2W_90, 68_Woven_1W.

In the assumed designations values of 34, 38, 51 and 68 determine the volume ratio of carbon fiber to epoxy resin. Mean percentage of carbon fiber in one layer of composite material is respectively 34%, 38%, 51% and 68%. Woven_2W_90 denotes the use of a fabric with a plain weave in which the weft and warp yarns are woven in two directions at an angle of 90 °. The name Woven_1W means the use of carbon fiber weft in one direction. Table 1 summarizes the basic parameters for single components, and Table 2 shows the basic parameters for individual layers of composite material.

The next step in the modelling of the composite material is the reproduction of the composition of the composite material of the tested samples. The following compositions (composite material structures) are defined: SL-0_90-34-5layers, SL-45_45-34-5layers, SL-0_1W(Y)-38-5layers, SL-90_1W(X)-38-5layers, SL-0_90-51-7layers, SL-45_45-51-7layers, SL-0_1W(Y)-51-7layers, SL-90_1W(X)-51-7layers, SL-0_90-68-10layers, SL-45_45-68-10layers, SL-0_1W(Y)-68-10layers, SL-90_1W(X)-68-10layers. A total amount of 12 composite material compositions were defined.

Table 1. Summary of basic parameters of components of a single layer of composite material

Epoxy resin	Carbon Fiber HTA40
Density – 1300 kg/m^3	Density – 1770 kg/m^3
Younge modulus – 3000 MPa	Younge modulus – 240000 MPa
Poission's ratio – 0,37	Poission's ratio – 0,22

Table 2. Summary of basic parameters with respect to exemplary single layers of composite material

34_Woven_2W_90 layer	38_Woven_1W layer
Matrix material – epoxy resin	Matrix material – epoxy resin
Volumetric share of matrix material – 0,66	Volumetric share of matrix material – 0,62
Matrix warp yarn material – carbon fiber	Matrix warp yarn material – carbon fiber
Weft fiber material – carbon fiber	Volumetric share of fiber – 0,38
Volumetric share of fiber – 0,34	Younge modulus E_1 – 93060 MPa
The coefficient of volume of warp fibers to weft fibers – 0,5	Younge modulus E_2 – 4802 MPa
The angle of alignment of the fibers relative to each other – 90°	Younge modulus E_3 – 4802 MPa
Younge modulus E_1 – 44240 MPa	Poission's ratio ν_{12} – 0,313
Younge modulus E_2 – 44240 MPa	Poission's ratio ν_{13} – 0,313
Younge modulus E_3 – 3000 MPa	Poission's ratio ν_{23} – 0,37
Poission's ratio ν_{12} – 0,032	Shear modulus G_{12} – 1754 MPa
Poission's ratio ν_{13} – 0,345	Shear modulus G_{13} – 1754 MPa
Poission's ratio ν_{23} – 0,345	Shear modulus G_{23} – 1095 MPa
Shear modulus G_{12} – 1649 MPa	Density – 1479 kg/m^3
Shear modulus G_{13} – 1047 MPa	
Shear modulus G_{23} – 879 MPa	
Density – 1460 kg/m^3	

The general way of describing composite material structures using Woven_2W_90 layers can be written as follows: SL-A_B-C-D. In the used method of writing, the SL symbol means that a given structure is formed as a solid laminate structure, A symbol denotes a measure of the angle of laying of the matrix fibers of the layer relative to the main direction of fiber orientation, B denotes the value of the angle of position of the weft yarn relative to the main direction of the yarn (angle between the fibers the warp and the warp in the layer always equals 90 °), C denotes the percentage of fibers in the layer, D denotes the number of layers in the structure. In this case, of Woven_1W composite structure, the following name can be written as SL-E_F (G) -HI, where E denotes the angle of unidirectional yarns in the layer relative to the main fiber orientation, F denotes the use of unidirectional fibers, G denotes the reference method of placing the fibers in the layer to the absolute coordinate system of the model, H denotes the percentage of fibers in the layer, I denotes the number of layers of the laminate composition.

Virtual strength tests of composite samples using the finite element method were performed to match the virtual model to the real object. This adjustment is necessary to implement the correct model's

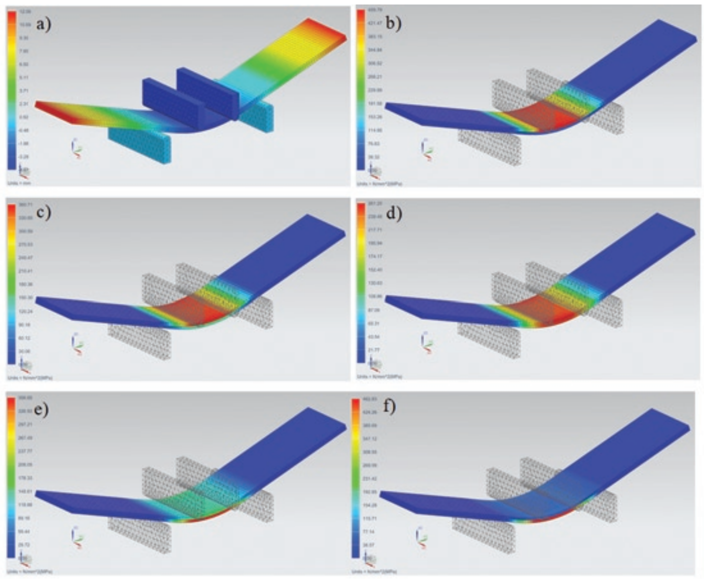

Fig. 6. Exemplary results of a virtual experiment (four-point bending test) using finite element method for SL-0_90-34-5 composite material: a) map of displacement, b) map of reduced stress in first layer, c) map of reduced stress map in second layer, d) map of reduced stress in the third layer, e) map of reduced stress in the fourth layer, f) map of reduced stress in the fifth layer

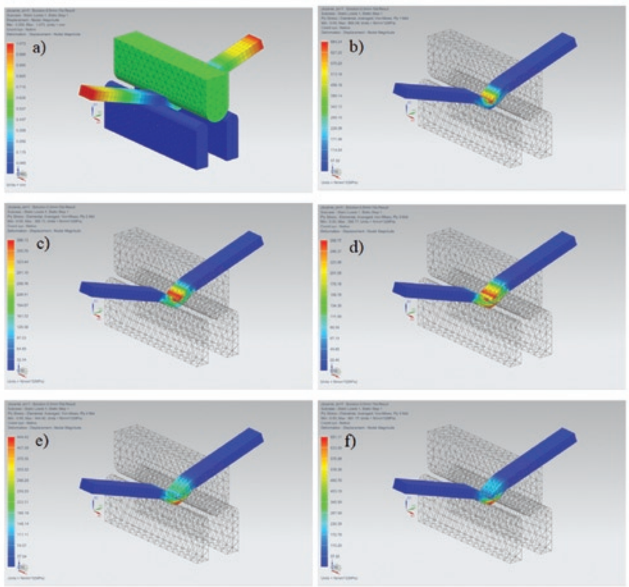

Fig. 7. Exemplary results of a virtual experiment (three-point bending test) using finite element method for SL-0_90-34-5layers composite material: a) map of displacement, b) map of reduced stress in first layer, c) map of reduced stress map in second layer, d) map of reduced stress in the third layer, e) map of reduced stress in the fourth layer, f) map of reduced stress in the fifth layer

Table 3. Examples of the results of virtual experiment on analyzed samples (four-point bending test)

Material symbol	Displ. of the sample [mm]	Layer nr 1 (σ [MPa])			Middle layer nr 3, 4 or 5 (σ [MPa])			Last layer nr 5, 7 or 10 (σ [MPa])		
	z_{max}; z_{min}	σ_{red}	σ_{11max}	σ_{11min}	σ_{red}	σ_{11max}	σ_{11min}	σ_{red}	σ_{11max}	σ_{11min}
SL-1, t_1	12,1; -4,6	460	48,9	-482,7	261	254,4	-261	463	472	-55,3
SL-2, t_2	7,2; -2,9	420	30,7	-442,8	225	221,8	-224,9	419	424,5	-33,7
SL-3, t_3	5,6; -2,3	455	22	-480	257	207,5	-257,2	450	454,2	-26,4

Table 4. Comparison of the FEM analysis results and the four-point bend test of the composite material SL-0_90-34-5 (volumetric share of the fabric 34%)

Punch displacement [mm]	Time [s]	The maximum value of stress (FEM analysis)	Stress values (bending test)		Relative error
			Range	Mean	
		[MPa]	[MPa]		
0,5	15	55	40 – 50	45	18%
1,0	30	112	80 – 100	90	19%
1,5	45	169	125 – 142	133,5	21%
2,0	60	228	165 – 195	180	21%
2,5	75	287	205 – 238	221,5	23%
3,0	90	347	218 – 270	244	29%

Table 5. Comparison of the results of the FEM analysis and four-point bending test for the composite material SL-0_90-51-7layers (volumetric share of the fabric 51%)

Punch displacement [mm]	Time [s]	The maximum value of stress (FEM analysis)	Stress values (bending test)		Relative error
			Range	Mean	
		[MPa]	[MPa]		
0,5	15	83	80 – 95	87,5	5%
1,0	30	167	165 – 190	177,5	6%
1,5	45	252	245 – 290	267,5	6%
2,0	60	339	320 – 380	350	3%

properties on other models made of composite materials used in specific constructional solutions. The virtual model was matched to the real object by changing parameters, such as finite element size, finite element mesh fit to the geometry of model of the sample and Young modulus.

The boundary conditions and the form of loads were defined in the created model. That enabled the achievement of correct deformities of the test sample according to the actual deformation distribution of the real sample during the four-point bending test (Figure 6) and the three-point bend (Figure 7). Based on the virtual bending of samples made of the composite material experiment, the values of displacement, deformation and stresses were calculated for each layer.

Figures 6 and 7 show the results of the analysis using the finite element method of the adjusted composite material, which was a composition of five layers, labelled as SL-0_90-34-5. The Figures illustrate the maps of displacement of the sample (a), the maps of reduced stress, presented in layers 1 (b), 2 (c), 3 (d), 4 (e) 5 (f).

Table 6. Comparison of the results of the FEM analysis and four-point bending test for the composite material SL-0_90-68-10layers (volumetric share of the fabric 68%)

Punch displacement [mm]	Time [s]	The maximum value of stress (FEM analysis)	Stress values (bending test)		Relative error
			Range	Mean	
		[MPa]	[MPa]		
0,5	15	113	120 – 140	130	15%
1,0	30	227	260 – 270	265	17%
1,5	45	343	390 – 420	405	18%

The results of the virtual experiment were also maps of the values of all the stress components (11 (YY), 22 (XX), 33 (ZZ), 12 (YX), 13 (YZ), 23 (XZ) - according to the global coordinate system showed on Figure 4), and deformation, which allows to precisely determine the influence of used load and boundary conditions on the applied composite material of the test sample.

Tables 4 - 6 summarizes the comparison results based on the FEM analysis and four-point bending test. The match was achieved for the composite material SL-0_90-51-7layers (the volumetric share of the fabric 51%). In this case, the maximum relative error was 6%. In case of composite material SL-0_90-68-10 layers (68% volumetric share of the fabric) the maximum relative error was 18%. Compared to the composite material SL-0_90-34-5 (volumetric share of the fabric 34%), a maximum error of 29% was obtained. However, it should be noticed that the material SL-0_90-34-5 was characterized by a large non-linearity of the stress characteristic in the sample as a function of the displacement of the punch in the range of displacements larger than 2 mm. In all the analyzed cases the FEM model includes the same match degree of mesh to the geometrical form of the sample and the other elements of the model, the same size of the finite element, and the same material properties.

4. Application of the composite material model for the strength analysis of the scaled freight wagon hull's sidewall

As part of the research [4 – 9, 18, 21, 22, 24] conducted by the research team in the scope of the project aimed at extending the life of freight wagons, the use of internal lining of the wagon hull in the form of the fiber reinforced composite panels was considered. The life of the wagon depends on the condition of its hull, which is made of metal sheet. Damages of the sidewall of the wagon can be caused by: the mechanical impact of the load carried on the wagon, the mechanical impact of the actuators of the loading and unloading machines and the chemical impact of the aggressive substances contained in the transported cargo. As a result of the mentioned effects, plastic deformation and local defects can occur in the sheet of metal. These hazards regarding the operation of freight wagons were the basis for the selection of fiber reinforced composites. Epoxy resin was used as the matrix, while glass fiber and carbon fiber were considered as reinforcing material.

Due to the need of carrying out a test of a modified version of the wagon's hull plating, the sidewall of the 418V dumper wagon (Fig. 8) was isolated. The method of isolation was selected to ensure the possibility of building a physical of test bench (Fig. 9 and Fig. 11) and to improve conducting of the numerical strength analysis and their validation.

For the purposes of the research, a test stand was designed and built, of which the basic elements are shown in Figure 9. The test stand consists of a support frame 1 to which the side sidewall 2 has been attached. A hydraulic cylinder 3 was attached to the lower part of the frame, which interacts with force on the analyzed part of the sidewall. A changeable pressure element is mounted to the actuator's piston rod 4 and presses against the side plating. Changing the length and width of this element allows for different types of load to be considered (point, surface). A control system has also been developed which allows for a smooth adjustment of the force in the range of 0 to 30 kN. In addition, the actuator can be moved smoothly in the XZ plane, which allows the load to be generated in different areas of the considered sidewall.

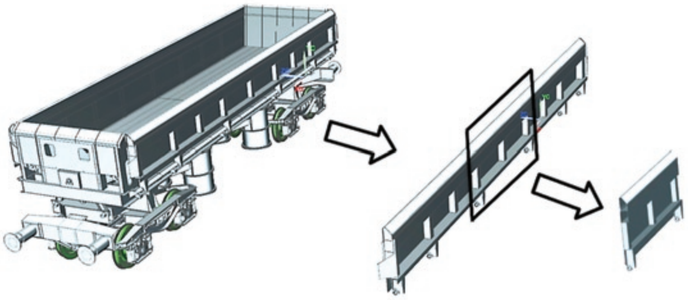

Fig. 8. Selected part of analyzed freight wagon's hull [6]

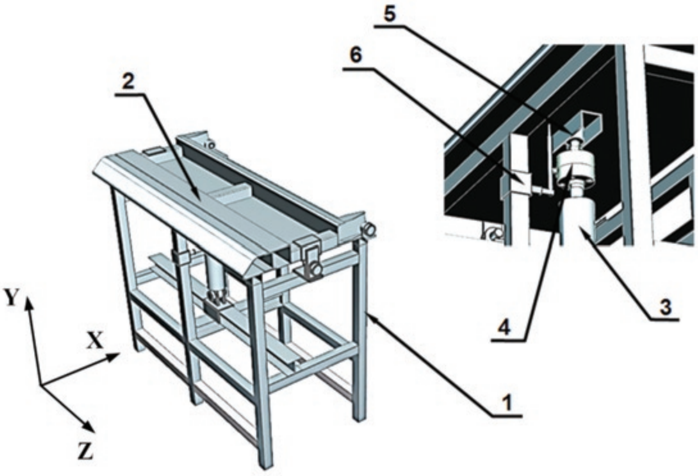

Fig. 9. CAD model of test bench [6]

The developed research bench was equipped with a system of sensors necessary to carry out the planned test cycle. It was assumed that the state of stresses and displacements on the sidewall before and after mounting the composite panels would be analyzed. For measuring the deformations a resistance strain gauges with a resistance of 120 Ω were used. For force measurement, a force transducer (HB2 U2B) was used, which was mounted on the piston rod of the hydraulic cylinder. A displacement transducer (HBM WA-T) was used to measure the displacement of the sidewall by which the displacement of the test area of the sidewall during the test was measured.

For the data acquisition and visualization of the results, a measuring circuit was developed and constructed (Figure 10). Signals from strain gauges were sent via the CANHED multi-channel amplifier to the computer on which the CATMAN data acquisition software was installed. This application is used to visualize and acquire measurement data. The obtained data packets were saved in a format com-

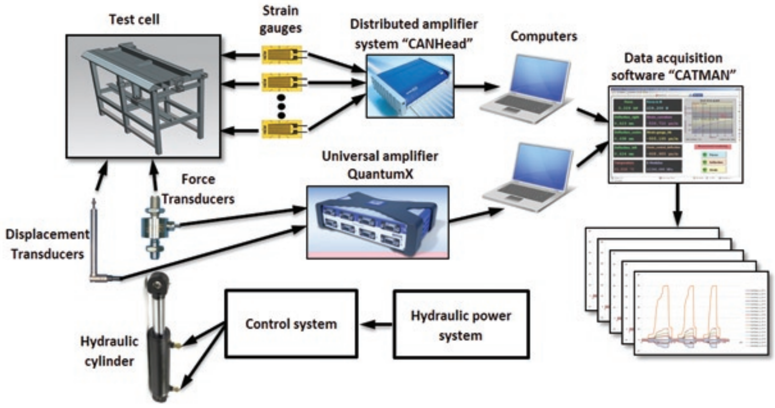

Fig. 10. Measuring circuit of a developed test bench[6]

patible with MS Excel software, and graphs were then generated for the analyzed quantities. Analogously, force and displacement values were measured and analyzed. Signals from the displacement transducer and force transducer were transmitted through the QuantumX multichannel amplifier to a computer and saved with a CATMAN software.

Firstly, the MES analysis of the scaled sidewall of the wagon's hull was performed to determine the places where significant stress values should be expected regarding the actual object.

Then, strain gauges were placed on the test bench (Fig. 12) and the wagon sidewall model was adjusted to the actual object [6].

The adjustment process of the wagon's sidewall FEM model consisted in the applying of such modifications in the model so that the results were consistent with the results obtained by experimental studies (strain gauges). The conformed numerical model of the hull's sidewall of the wagon became the basis for numerical analysis using the FEM method of the upgraded part of the freight wagon. In this case, composite panels (Fig. 13) were added to the FEM model and the stresses and displacements were calculated for the whole set of objects of the scaled sidewall. Numerical tests were performed in PLM Siemens NX software. In the first step, a mesh of finite elements was generated regarding the steel parts of the sidewall of the wagon. In this case, CTETRA finite elements (10 nodes tetragonal finite elements) were used. A finite element mesh was then defined for composite panels. In this case, finite elements of the CHEXA type (8 hexagonal finite elements) were used. All the finite elements of the wagon's plating mesh were assigned a steel type material. On the other hand, in the case of mounted composite panels, the previously described method of modelling multilayer composite materials was used. Two composite materials have been included in the numerical study. The first composite material was defined as an epoxy resin and carbon fiber fabric, while the other was an epoxy resin and glass fiber fabric composite. Regarding to both composite materials a composition consisting of four layers was used. The basic properties of both compositions are shown in Table 7.

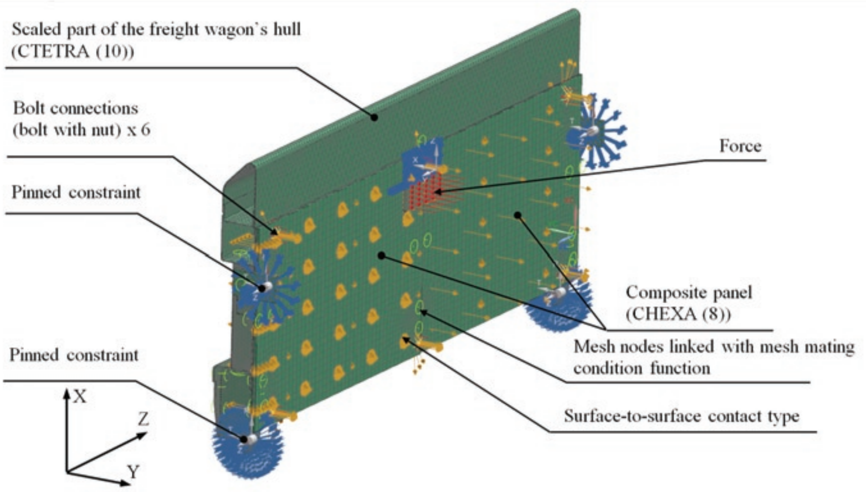

Fig. 13. Sidewall model of the wagon with mounted composite panels prepared for FEM analysis

Fig. 11. CAD model and actual layout of test bench

Regarding the composition, the following parameters are defined: the main direction of fiber orientation according to the Z axis of the global coordinate system, the direction of layering according to the Y axis, the thickness of the single layer equal to 1 [mm] and the angle of laying of the layer within the defined composition equal to 0 °.

In order to represent the problem, the following boundary conditions were defined:

- „pinned constraint" – this type of constraint was used to imitate the method of fixing the sidewall,
- „mesh mating condition" linking mesh nodes function – by which the elements of the wagon's hull are connected to each other permanently,
- „surface-to-surface" contact type – by which the nature of the interactions between the elements that come into contact by load existing in the system (between the wagon's hull plates and the composite panels) was defined,
- „bolt connections" – by which the method of fixing composite panels to the wagon's hull plates was imitated.

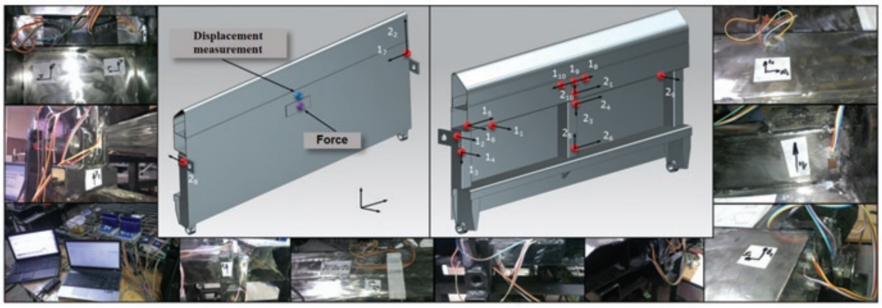

Fig. 12. Measurement points on the analyzed sidewall

Table 7. Summary of basic properties of the composite material layer consisting of epoxy resin and carbon fiber and fiberglass

Carbon fiber layer	Glassfiber layer
composite matrix material - epoxy resin	composite matrix material - epoxy resin
volume ratio of composite matrix material - 0.47	volume ratio of composite matrix material - 0.45
fabric matrix material - carbon fiber	fabric matrix material - glassfiber
fabric weft material - carbon fiber	fabric weft material - glassfiber
volume ratio of fiber - 0.53	volume ratio of fiber - 0.55
weight of warp and weft fibers – 0,5	weight of warp and weft fibers – 0,53
alignment angle between fibers – 90°	alignment angle between fibers – 90°
Young's modulus E_1 - 67220 MPa	Young's modulus E_1 - 24250 MPa
Young's modulus E_2 - 67220 MPa	Young's modulus E_2 - 22230 MPa
Young's modulus E_3 - 3000 MPa	Young's modulus E_3 - 3000 MPa
Poission's ratio ν_{12} – 0,027	Poission's ratio ν_{12} – 0,079
Poission's ratio ν_{13} – 0,33	Poission's ratio ν_{13} – 0,32
Poission's ratio ν_{23} – 0,33	Poission's ratio ν_{23} – 0,326
hear modulus G_{12} – 2283 MPa	shear modulus G_{12} – 2329 MPa
shear modulus G_{13} – 1110 MPa	shear modulus G_{13} – 1118 MPa
shear modulus G_{23} – 1189 MPa	shear modulus G_{23} – 1443 MPa
density – 1547 kg/m^3	density – 1982 kg/m^3

Based on such prepared model, a series of strength tests was performed using the finite element method. Table 8 summarizes the results of FEM analysis regarding the scaled side wall of the wagon with mounted composite panels. Based on the results obtained, it can be assumed that composite material panels made of epoxy resin and glass or carbon fiber will not be destroyed as a result of the load coming from the cargo carried by the freight wagon.

For economic reasons, a scaled part of the sidewall of the wagon with mounted panels made of composite material consisting of epoxy resin and glass fibers was subjected to experimental verification. Due to the highest stress values in this area, Fig. 15 shows the stress distribution, regarding the matched model, on the outer side of the freight wagon's hull. In contrast, Fig. 16 shows the results of measurements using strain gauges, where the strain gauge number 21 was highlighted, which recorded the highest values of stresses in the analyzed system with the applied force of 15 kN. It can be noticed that the application of reinforcement on the inner surface of the wagon's hull in the form of composite panels caused the reduction of the component stresses on the sidewall of the wagon in the Z-Z direction from about 76 MPa to about 60 MPa. Adjustment of the FEM model to the stationary test results was made by modification of the finite element size, the method of matching the finite elements mesh to the geometric form of the model, and the value of the Young modulus.

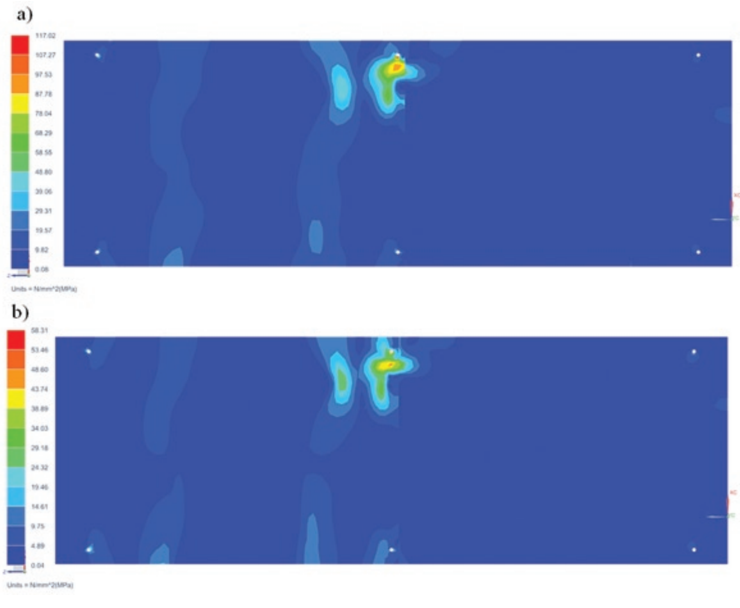

Fig. 14. Stress distribution occurring in panels made of composite material (layer 1), which is a composition of epoxy resin and carbon fibers (a) and glass fibers (b)

Table 8. Comparison of the FEM analysis results regarding the model of scaled sidewall of the wagon with mounted composite panels for the load of 15 kN of force applied

Layer number	Maximum values of reduced stresses in composite panels (carbon fiber) [MPa]	Maximum values of reduced stresses in composite panels (glass fiber) [MPa]
1	117,02	58,31
2	53,94	28,64
3	49,48	47,05
4	109,16	87,99

5. Conclusions

The developed model based on the acoustic method (ATH) is suitable for use in non-destructive testing of composite panels used in freight wagons.

The best match of the virtual model to the results of analysis carried out on the actual samples was achieved for seven-layered composite material with 51% of fabric content.

The tests carried out at the test bench shown in Figure 9 correlate sufficiently with the tests carried out on the actual object which was the sidewall of the wagon.

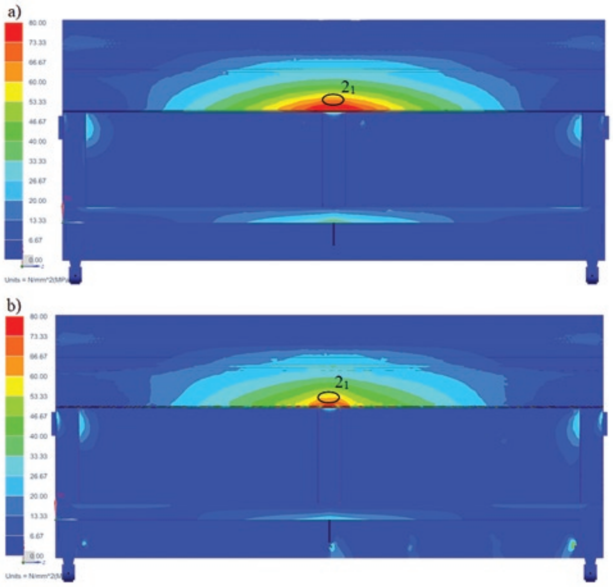

Fig. 15. Stress distribution in Z-Z direction on the sidewall of the scaled freight wagon's hull: without reinforcement (a), reinforced in the form of fiberglass composite panels (b)

The diagrams in Fig. 16 show that the placement of the reinforcement on the sidewall of the freight wagon's hull in the form of a 4mm composite panel will reduce the stresses on the by about 20%.

The computer-assisted modelling technique for modelling the three-point and four-point bending of composite samples, presented in this paper, allows to prepare, perform and obtain correct results of the virtual bending experiment of multilayer composite samples.

The suggested way of describing the composite material allows it to be modeled in the form of a composition of any number of layers. Particular attention should be paid to the possibility of creating and testing samples made of a composite material whose individual layers may be composed of different fabrics and resin types. In addition, each of the layers in the composite material composition may have a different angular position relative to the global coordinate system, which implies obtaining various strength properties of the sample in different directions.

The main purpose of using the inner lining of a freight wagon's hull in the form of composite panels was to protect it from mechanical and chemical damage. However, the protective "coating" applied in form of the proper composite material composition and the number of composite layers may also act as a reinforcement to the wagon's hull. This is very important from the point of view of servicing of already damaged wagons(reduced sheet thickness due to corrosion). This would allow a dramatic reduction in the number of operations involved in cutting damaged sheet metal from the wagon's hull and inserting a new one.

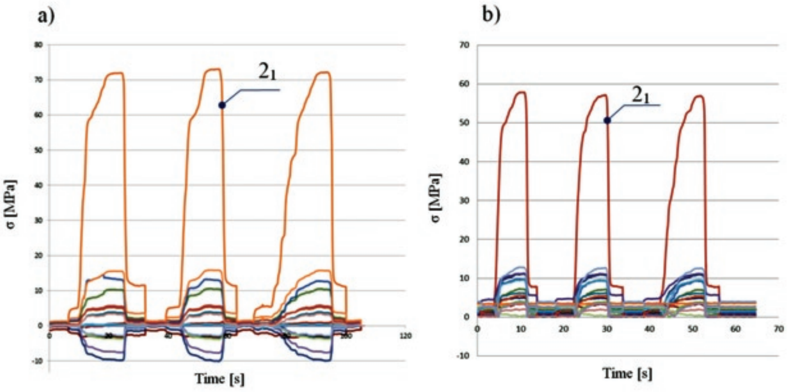

Fig. 16. Results of test bench measurements of the scaled sidewall of the freight wagon: without reinforcement (a), with reinforcement in the form of fiberglass composite panels with a thickness of 4 mm (b)

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