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Modelling and Validation of the Composite Shell of a Train Seat

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Summary

The subject of the modelling work and the conducted experiments is the composite shell of a train seat. The activities carried out involved designing the geometry, planning the material structure, and selecting the materials to be used. The shell was built using polymer matrix fibrous composites (i.e. FRP – Fibre Reinforced Polymer – composites), which are lighter than steel and comply with the relevant standards for strength and safety at the same time. This was followed by creating a computational model for the shell and conducting a strength analysis in accordance with the guidelines of the relevant industry standard and strength hypotheses adopted for FRP composites. The calculations were conducted using ANSYS Composite PrepPost software based on the finite element method. The article offers a strength analysis of an optimised composite shell of a train seat. Based on the guidelines obtained as a result of the conducted modelling work, a physical prototype (validation model) of the seat was created. Hot vacuum lamination technology was applied in the production process. The experimental validation of the model, producing a positive result, was conducted using a test stand owned by S.Z.T.K. TAPS – Maciej Kowalski.

Keywords: train seat structure, FRP composite, FEM modelling, experimental validation

1. Introduction

Train seats should meet the requirements of the standards adopted in the areas of fire safety, ergonomics and strength (durability). At the same time, the equipment and features of the rolling stock are among the main elements affecting economic analyses based on the rail vehicle LCC (Life Cycle Cost) methodology. Such analyses take into account not only the costs of purchase but also the costs of later use and operation of any such feature or piece of equipment. The operating and maintenance costs depend largely on the applied structural solutions guaranteeing the required durability and lower weight of the vehicle. The structural elements of train seats made of materials such as steel or plywood make up a significant part of a passenger car's weight. To ensure the optimal level of comfort to passengers and make sure that the product is suitably designed, manufacturers cover train seats with a layer of flexible polyurethane (PU) foam and upholstery. The seat structure has additional elements, such as armrests or tables, fixed to it. Figure 1 shows an example of an XCR-type train seat designed by S.Z.T.K. TAPS – Maciej Kowalski for regional rail operators.

Fig. 1. Example of an XCR-type train seat manufactured by S.Z.T.K. TAPS – Maciej Kowalski with description of particular sections [photo: https://taps.com.pl]

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The purpose of the article is to present the concept of a new, lighter seat structure compliant with the relevant strength requirements. With elements loaded, when specific strength (the ratio between strength and density) is of the essence, polymer matrix composites work really well as they ensure a high level of strength at a low level of density. A resource valued especially in the manufacturing of FRP composites is epoxy resin because of its amorphous structure, non-toxicity, and minimum shrinkage in thermosetting, as well as excellent adhesion to most materials, such as metal, glass and ceramics. The material properties of FRP composites and the dedicated lamination technologies make it possible to design a new structural solution for train seats – in the form of a support shell. Such a structure will reduce the seat weight by about 30–40% (authors' own estimations) compared to the common plywood-based solutions. In the boat-building, railway and construction industries, composite elements of complex shapes are manufactured in a single lamination process. For instance, using the vacuum infusion technology, it is possible to produce even extra-large structural elements of bridges [9]. One of the noteworthy available manufacturing methods is the hot vacuum lamination technology developed by S.Z.T.K. TAPS – Maciej Kowalski, involving connecting pre-pregs – glass fabrics pre-impregnated with resin powder [7, 8, 10].

The guidelines for designing the shape of train seats define the adopted and commonly applied dimensions and curves described in the relevant standard [4], developed based on many years of tests conducted in the area of ergonomics and passenger comfort. The geometry of a train seat comes with two basic dimensions, where the backrest height should be at least 770 mm, and the seat depth – at least 450 mm [4]. The curvature radii in particular parts of a seat ensure the right profile of the curvatures of the backrest and of the lumbar support of the spine.

A train seat's shape is determined by the geometry of its structure.

The design of train seat structures should also take into account the technical solutions for the assembly of seat features (table and armrests) and for the integration of the seat itself with the structure of the passenger car. In the case of FRP composite structures, it is important to arrange for the right area of integration of assembly elements and the composite structure in order to avoid the initiation and propagation of destruction mechanisms, such as delamination, fibre shearing or epoxy matrix cracking [3].

2. The strength criteria for FRP composites

In the case of composites, given the material inhomogeneity, the damage mechanics is more complex compared to homogeneous materials, which are also isotropic at the same time. The anisotropy of composites makes the direction and the development of damage dependent not only on the load, the geometry, and the boundary conditions, but also on the structure of the material. In the case of FRP composites, damage progresses with the involvement of at least a few mechanisms. The material layer may become damaged because of fibres breaking while tension or as a result of their buckling during compression. The layer may also become damaged if the matrix becomes damaged as a result of shear stresses occurring in the layer's plane or perpendicularly to the direction of fibre arrangement. The layer between the fibres and the matrix may also be damaged. Of course, the layer can also become damaged as a result of a combination of all or some of the processes discussed here.

The impact of the mechanical properties of material layers on the properties of an entire composite laminate is described by the classical lamination theory, also known as the classical theory of laminated shells [2]. This utilises a model composed of layers of certain thickness and direction of fibre arrangement. Laminates are therefore modelled as orthotropic and linearly elastic materials. The fibreglass fabric reinforced FRP composites with fibre orientation of 0/90 correspond to a homogeneous orthotropic material with three orthotropic directions 1, 2, 3 coinciding respectively with fibre orientation and layer thickness. Each layer is described by means of 9 elastic dimensionless material properties (material constants):

E_i – Young's modulus towards i,
ν_{ij} – Poisson's ratio in the plane ij, where ij = 12, 23, 31,
G_{ij} – Shear modulus in the plane ij, where ij = 12, 23, 31,

and 9 strength dimensionless material properties (material constants):

R_{it}, R_{ic} – tensile and compressive strength for the main orthotropic directions, where i = 1, 2, 3,
Sij – shear strength in the plane ij, where ij = 12, 23, 31.

The strength of FRP composites subjected to multi-axial loading is determined on the basis of various adopted failure (damage) criteria, including: the maximum stress criterion, the Tsai-Wu criterion, the Hashin criterion, the Tsai-Hill criterion, the Hoffman criterion, and others. The stress criteria are based on the failure index concept, which determines the effective (non-damaged) part of the cross section of the tested material. The parameter assumes values within the range of <0,1>, where 0 means a defect-free state, and 1 means a point in time when the material is damaged [5]. The paper's authors have decided to use the following criteria identifying the occurring material failure mechanisms: the maximum stress criterion and the Hashin criterion. In both cases, it is necessary to determine the stresses occurring in the tested composite material using stress tensor elements: σ_i, σ_{ij}, where $i, j = 1,2,3$. In the case of the Hashin criterion, the following F components are calculated [6]:

- fibre tension towards 1 for $\sigma_1 > 0$:

$$F_1 = \left[\left(\frac{\sigma_1}{R_{1t}} \right)^2 + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 + \left(\frac{\sigma_{13}}{S_{13}} \right)^2 \right] \quad (1)$$

- fibre compression towards 1, $\sigma_1 < 0$:

$$F_2 = \left[\left(\frac{\sigma_1}{R_{1c}} \right)^2 + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 + \left(\frac{\sigma_{13}}{S_{13}} \right)^2 \right] \quad (2)$$

- fibre tension towards 2, $\sigma_2 < 0$:

$$F_3 = \left[\left(\frac{\sigma_2}{R_{2t}} \right)^2 + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 + \left(\frac{\sigma_{23}}{S_{23}} \right)^2 \right] \quad (3)$$

- fibre compression towards 2, $\sigma_2 < 0$:

$$F_4 = \left[\left(\frac{\sigma_2}{R_{2c}} \right)^2 + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 + \left(\frac{\sigma_{23}}{S_{23}} \right)^2 \right] \quad (4)$$

- matrix tension, $\sigma_3 > 0$:

$$F_5 = \left[\left(\frac{\sigma_3}{R_{3t}} \right)^2 + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 + \left(\frac{\sigma_{13}}{S_{13}} \right)^2 + \left(\frac{\sigma_{23}}{S_{23}} \right)^2 \right] \quad (5)$$

- matrix compression, $\sigma_3 > 0$:

$$F_6 = \left[\left(\frac{\sigma_3}{R_{3c}} \right)^2 + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 + \left(\frac{\sigma_{13}}{S_{13}} \right)^2 + \left(\frac{\sigma_{23}}{S_{23}} \right)^2 \right] \quad (6)$$

where: σ_i, σ_{ij}, $i, j = 1,2,3$ – stress tensor elements.

The R_i failure index for the Hashin criterion, determining the layer's stress intensity level, is calculated according to the following formula:

$$R_i = \sqrt{F_i}, \; i = 1, 2, \ldots, 6 \quad (7)$$

In the case of the maximum stress criterion, the components F_i and F_{ij} are calculated for each stress tensor element [11]:

$$F_i = \begin{cases} \dfrac{\sigma_i}{R_{it}} \text{ for } \sigma_i > 0 \\ -\dfrac{\sigma_i}{R_{ic}} \text{ for } \sigma_i < 0 \end{cases}, \; i = 1, 2, 3 \quad (8)$$

$$F_{ij} = \frac{\left| \sigma_{ij} \right|}{S_{ij}}, \; ij = 12, 23, 31 \quad (9)$$

The R_i failure index values for the maximum stress criterion, determining the layer's stress intensity level, equal the values of the components F_i and F_{ij}:

$$R_i = F_i, \; R_{ij} = F_{ij}, \; i = 1, 2, \ldots, 6 \quad (10)$$

Moreover, the following assumption is made:

$$R_4 = R_{12}, \; R_5 = R_{23}, \; R_6 = R_{31} \quad (11)$$

The value of the R_i failure index for the analysed layers is determined by the composite structure reliability level. The value of this parameter may not exceed 1 in any of the described stress states. Otherwise the composite layer may become damaged, or the entire structure may even become completely destroyed.

3. Manufacturing and experimental testing of the validation model

Based on the adopted guidelines originating from modelling work, a prototype (validation model) of a train seat's support shell on a scale of 1:1 was created. S.Z.T.K. TAPS – Maciej Kowalski's machine stand was used to connect epoxy/glass pre-pregs (Figures 2, 3) made fire-retardant by means of "flake graphite" particles applying the method of hot vacuum lamination. Flake graphite makes the shell black in colour.

Next, the validation model, weighing 6 kg, was subjected to a strength test to verify the computational model. The conditions of load application, compliant with the relevant standard [4], were reproduced using S.Z.T.K. TAPS – Maciej Kowalski's strength testing machine. The tested object was placed on the frame of the test stand, and then loaded in two separate tests with two forces: P_1 (outwards) and P_2 (inwards) with the loading point 50 mm away from the upper edge of the backrest of the seat's composite support shell (Fig. 4, 5a). The load was exerted by the movement of the piston towards the stamp (Fig. 5b) to the permissible value adopted by S.Z.T.K. TAPS – Maciej Kowalski, i.e. $F_{1max} = P_{2max} = 1500$ N. This type of load was chosen as most demanding for the structure. Due to combination of force acting with large arm, significant value of bending moment appears. Despite, the norm defines another cases of loading, they are applied for complete seat and act on elements of construction like armrest, table or footrest. Also values of forces and bending moments in those cases are respectively smaller.

a) b) c) d)

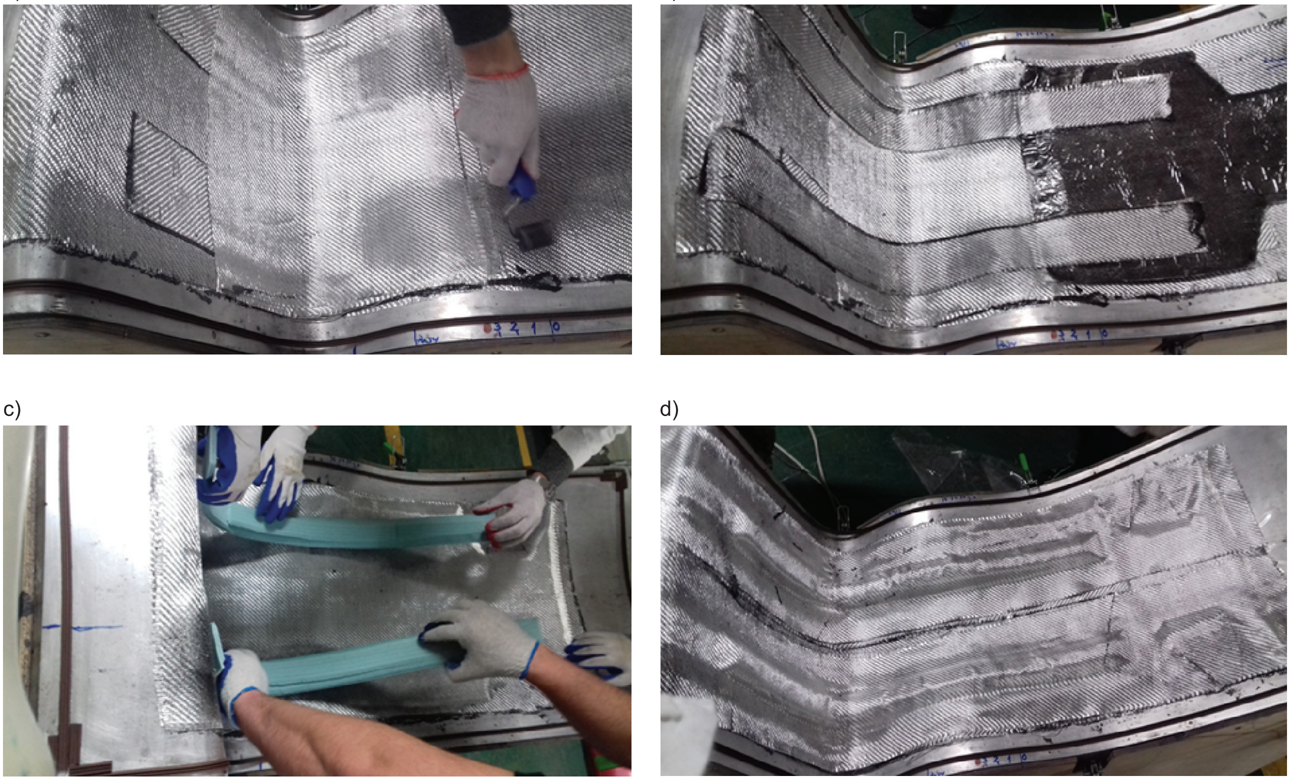

Fig. 2. Examples of stages of laying composite pre-pregs in a mould; a) external layers and layers within the lumbar zone b) polyurethane foam in the headrest zone (black colour) and the first layers forming ribs, c) polyurethane inserts shaping the rib, d) surface layers – end of the laying process [photos by: authors]

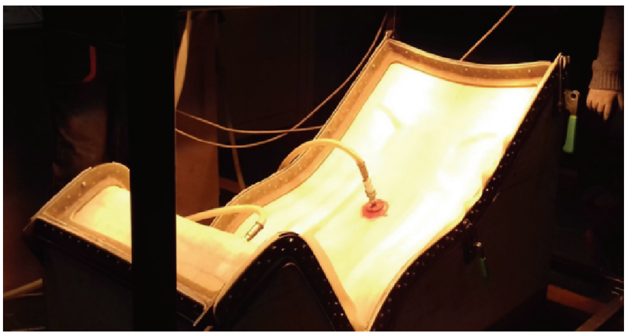

Fig. 3. The stand design for hot vacuum lamination of train seat composite shells [photos by: authors]

General practice for this kind of structure is a check most demanding load case for the supporting composite shell of seat. Depending on the way the load was applied, the backrest moved from 120 mm for P_{1max} and 75 mm for P_{2max}, without any permanent deformation after the load was removed. Force measurements were made in steps of 10 N. The displacements were measured with a measure tape with an accuracy of 1 mm. Based on the obtained findings of the experiment, it was found that the designed composite structure of the support shell complied with the requirements set by the relevant standard [4].

Fig. 4. Point of force application (50 mm below the upper edge of backrest) during strength test

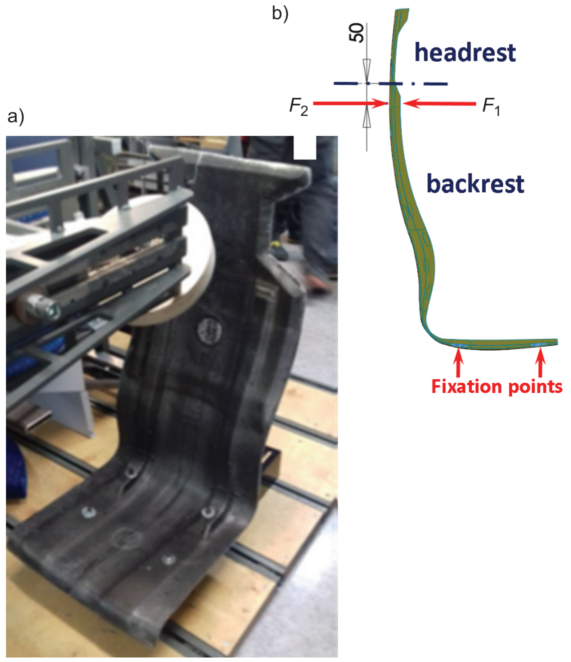

Fig. 5. Seat shell validation model: a) the shell mounted on the test stand and force application punch, b) boundary condition [authors' own work]

In the course of further optimisation carried out to reduce the weight of the composite structure of the seat's shell, it was decided to modify the structure further by cutting a set of holes in the least stressed zones (Fig. 6). After the holes were cut, the shell weighed 5.2 kg and passed the test strength successfully. Results of numerical analysis for such hollowed version of seat shell will be also presented.

Fig. 6. A train seat composite support shell with holes cut through [photo by: authors]

4. Numerical simulation of the strength test

Before the prototype was created, a numerical (computational) model of the train seat composite support shell was developed. It included a geometry model, material properties, and boundary conditions according to the relevant standard [4]. The calculations were conducted using *ANSYS Composite PrepPost* software based on the finite element method. Before the final structural solution for the composite shell was designed, the stage of modelling involved many optimisation attempts, where the variables involved were the fibreglass fabric grammage, the arrangement and the number of composite layers, stiffening elements, and technological issues.

The spatial geometry of the seat support shell model was based on an original proprietary design of a train seat by S.Z.T.K. TAPS – Maciej Kowalski. The final geometry of the model is a result of a couple of stages of optimisation of computational models validated by means of experimental models. The thickness of the geometry model depends on the adopted composite layers (epoxy resin laminated fibreglass fabric with fibre orientation of 0/90) and a PU foam inserts (Fig. 7a). The thickness differs depending on the seat part (zone) and the number of composite layers (3 to 34). The assumption made was that the thickness of a single composite layer was 0.8 mm. The number of featured composite layers depends on the structure's behaviour under the set load. The largest number of layers is found in the zone between the backrest and the seating, exposed to intense stress values. In addition, the shell was reinforced by means of two stiffening ribs shaped by PU foam inserts. The ribs were shaped in a way to make it possible for fabrics to be arranged freely during manufacturing and to prevent the concentration of stresses (Fig. 7b-d). The design of the model of the seat's support shell geometry also took into account the manner in which the table and armrests were fixed to the seat. This involved using commercially available fastening elements (KVT Bighead) with a high effective surface area, designed for FRP composite shell structures (Fig. 8).

The computational model was constructed using four-node shell elements in a three-dimensional space (Fig. 9a). The adopted system of coordinates 123 represents the orthotropic properties of the FRP composite, where axes 1 and 2 coincide with the model's planes, and axis 3 defines the thickness of the composite layers (Fig. 9b). The model was subjected to the permissible load P_{1max} of 1,500 N, generating the greatest system displacements. The support conditions and the force application method are show in Figure 9c.

The calculations were made using the material constants for FRP composites, determined empiri-

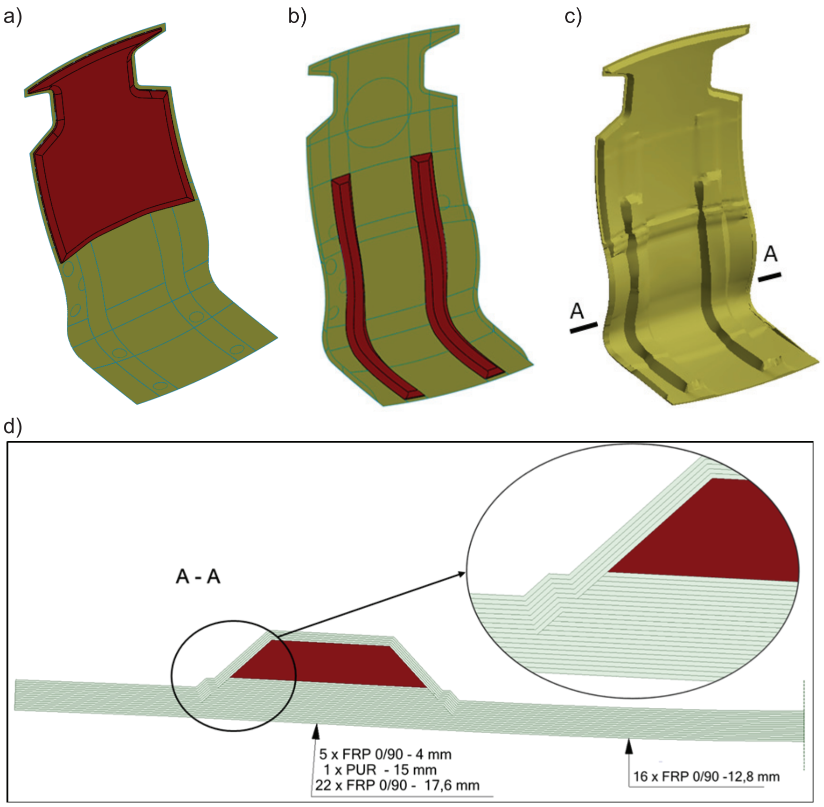

Fig. 7. The structure of the support shell of a train seat: a) PU foam layer in the upper zone of the backrest, b) PU foam inserts shaping the ribs, c) the final geometry of the model, d) ½ of the cross section of the lumbar zone with the arrangement of the layers [authors' own work]

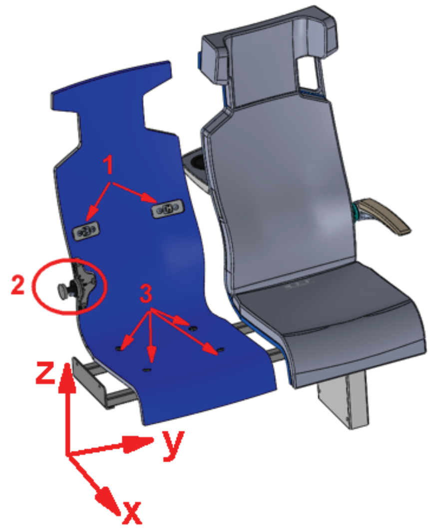

Fig. 8. Attachment products of the equipment fixed to the seat's shell: 1) table, 2) armrest, 3) visible points of fixing to the train car's structure [authors' own work]

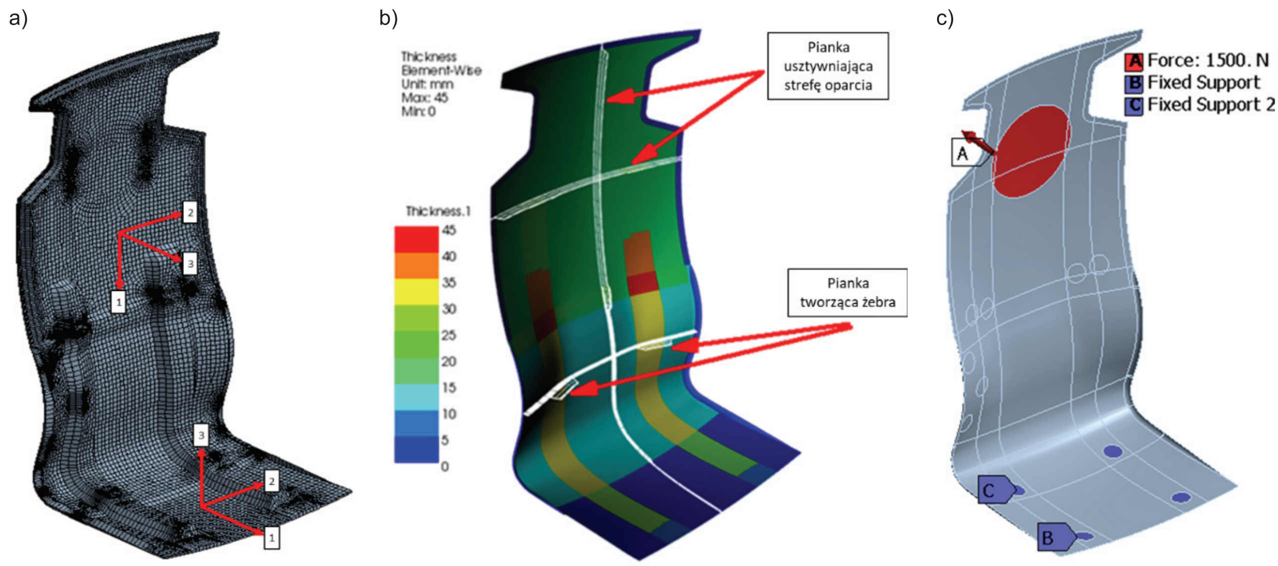

Fig. 9. A numerical model of the train seat's support shell: a) a finite element mesh with marked orthotropic directions of composite layers, b) a thickness distribution chart with colour markings, c) boundary conditions [authors' own work]

cally based on the authors' own tests (standard tensile, compressive, and shear strength tests). The seat's structure features fabrics with a fibre orientation of 0/90, which is why it was assumed that the particular material properties of the FRP composites used were equal (Table 1). The calculations also included the material properties of Airex T90 PU foam, based on the manufacturer's specifications (Table 2) [1].

Table 1

Material properties of FRP composite for the modelling of the seat support shell

Index (parameter) [MPa]		Value
Young's modulus	$E_1 = E_2$	7350
	E_3	1750
Shear modulus	G_{12}	3040
	$G_{23} = G_{13}$	2,040
Poisson's ratio [–]	υ_{12}	0.28
	$\upsilon_{13} = \upsilon_{23}$	0.4
Tensile strength	$R_{1t} = R_{2t}$	256
	R_{3t}	31
Compressive strength	$R_{1c} = R_{2c}$	195
	R_{3c}	100
Shear strength	S_{12}	50
	$S_{23} = S_{13}$	35

[Authors' own work].

The results of the strength test of the 1:1 scaled train seat composite shell showed that the maximum values of the displacement of the outermost point of the headrest exceeded 135 mm only slightly (Fig. 10), meaning they remained within the range permissible under the relevant standard [4]. In addition, a strength analysis of the applied FRP composite was performed based on selected strength criteria, i.e. the maximum stress criterion and the Hashin criterion. The results of the analysis were provided in the form of R_i failure index distribution charts (Fig.11).

Table 2

Material properties of Airex T90 PU foam used in the modelling of the seat support shell [11]

Index (parameter) [MPa]	Value
Young's modulus	65
Shear modulus	44
Poisson's ratio [–]	0.3
Tensile strength	1.5
Compressive strength	0.8

[Authors' own work].

In the analysed model, the greatest level of material stress intensity, causing the fibres to stretch, occurs near the points of fixing to the frame, and the maximum value of the failure index according to the Hashin criterion is equal to 0.63. The next zone with an increased level of stress, where R_i amounts to approximately 0.3, is the zone between the seating and the backrest. It is an area where the maximum bending moment occurs under the set load. When $R_i < 1$, it means that the analysed model was not destroyed.

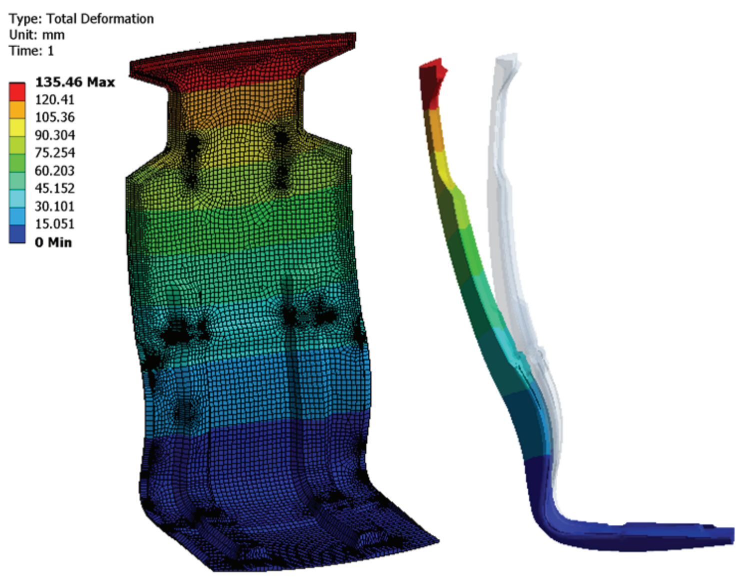

Fig. 10. Total displacements of the shell model [authors' own work]

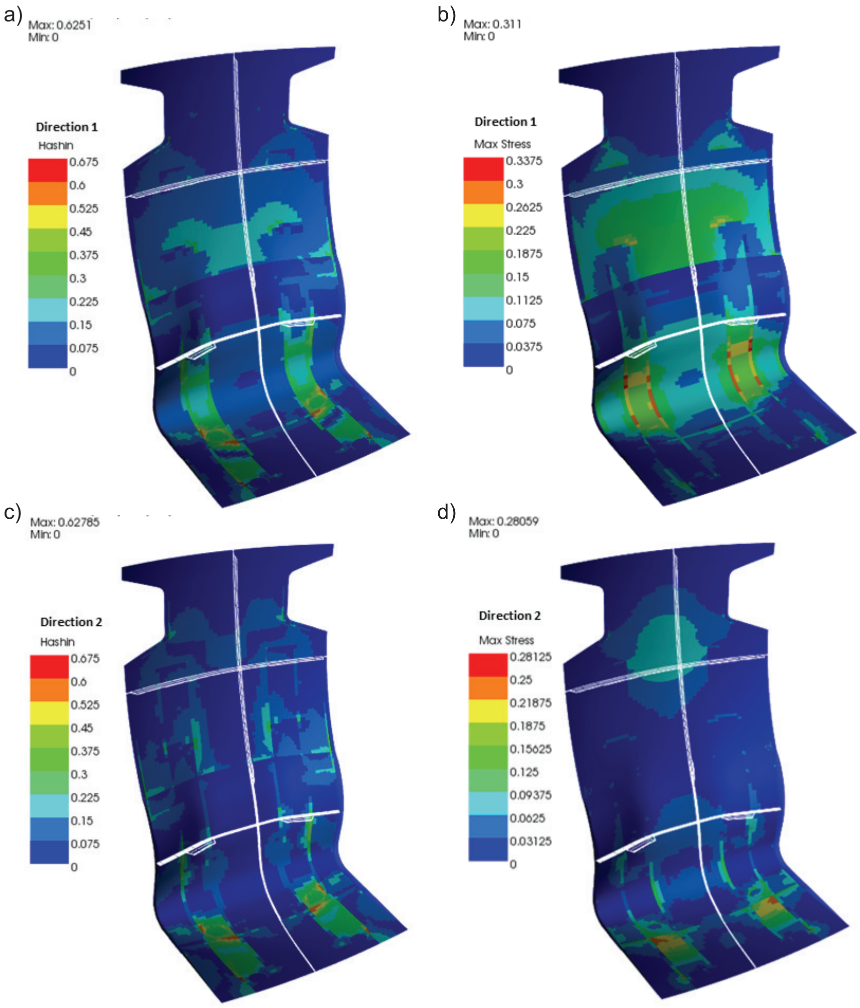

Fig. 11. Distribution of the R_i failure index for the composite shell model for two selected orthotropic directions 1 and 2 and for two strength criteria: a and c) the Hashin criterion, b) and d) the maximum stress criterion [authors' own work]

Similar values of stress intensity and Hashin criterion are obtained for modified type of seat shell. The hollowed version of geometry (shown in figure 12) exhibit 11 mm larger displacements. Values of the failure index *Ri* are well below 1. The highest failure index for Hashin criterion is equal 0.6 and 0.618, respectively for orthotropic direction 1 and 2. In case of maximum stress criterion this values are equal 0.32 and 0.316.

Maximal differences of failure index between two presented types of seats are smaller than 0.04 and concern maximum stresses criterion. Small differences in values and also in distribution of failure index confirm, that modified structure is capable to withstand load equal to 1500 N. The results of the analysis are shown in the form of R_i failure index distribution charts (Fig.13).

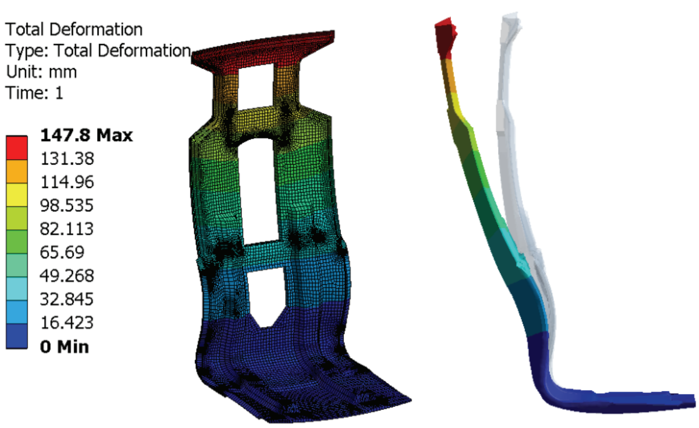

Fig. 12. Total displacements of the shell model [authors' own work]

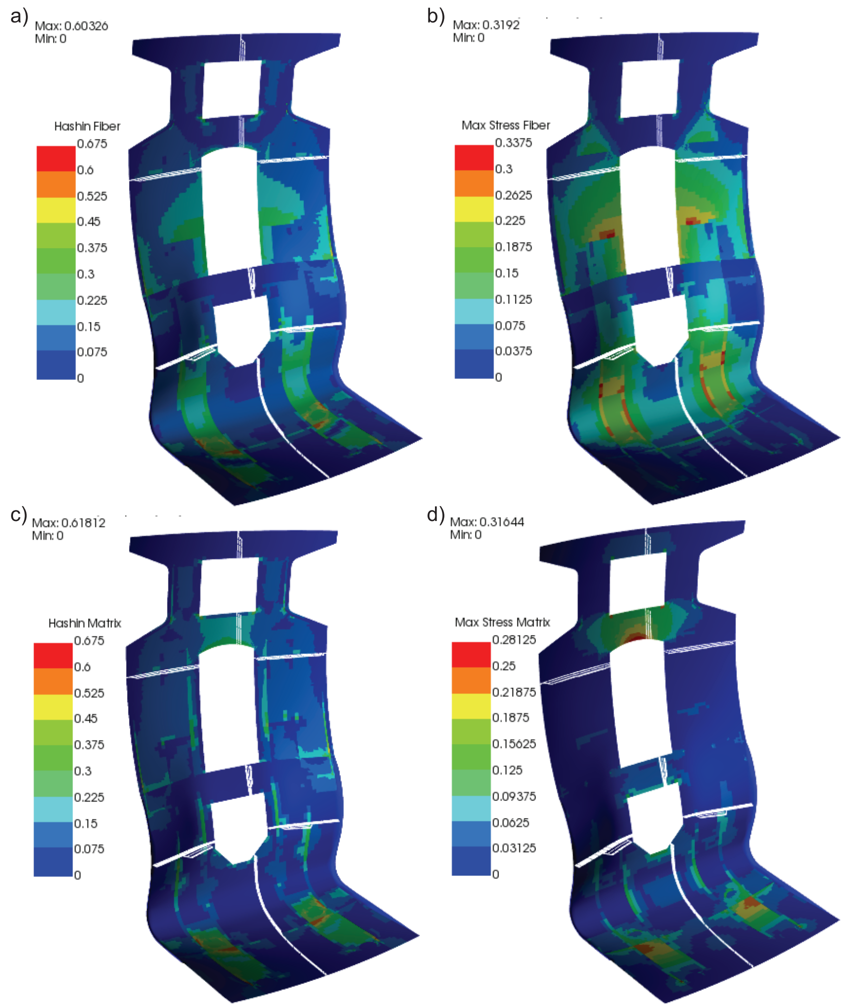

Fig. 13. Distribution of the R_i failure index for the composite shell model for two selected orthotropic directions 1 and 2 and for two strength criteria: a and c) the Hashin criterion, b and d) the maximum stress criterion [authors' own work]

5. Conclusion

The article describes a composite support shell of a train seat, composed of epoxy-fibreglass composite pre-pregs and PU foam inserts. The modelling work and experiments carried out imply a consistency between the numerical model of the seat shell model with the validation model, in the event of operating of the critical load. A special methodology of modelling and strength analysis has been developed for the purpose of conceptual work and quick prototyping of composite structural elements of train seats. Experimental verification, in turn, will make it possible to maintain the desired quality in terms of strength and safety. The presented framework of modelling work and experimental tests may contribute to the appearance of light and durable shell-type seats made of innovative materials based on FRP composites in rail vehicles. The proposed procedure of design and numerical optimization of the composite support structure showed the ability to reduce the number of prototypes. Moreover, the selected composite reduced weight of the train seat by about 30–40% compared to the common plywood-based solutions.

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