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COST-EFFECTIVE PARTITIONING AND MODELING OF POLYMER
COMPOSITE SHELL- AND SANDWICH STRUCTURES IN THE
CONCEPT PHASE

PHD THESIS BOOKLET

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The doctoral thesis review and the minutes of the defense can be viewed at the Dean's Office of the Faculty of Mechanical Engineering of the Budapest University of Technology and Economics.

1. Introduction

The future of the automotive industry faces many challenges due to increasingly strict regulations on emissions, energy consumption, and component recyclability, as well as the need to maintain cost efficiency. Weight reduction is the main driver, which can significantly impact achieving these goals through innovative component design and appropriate material selection, as around 85% of energy consumption in a vehicle's life cycle occurs during the operating phase. Another important impact of weight reduction for electric and hybrid vehicles is that it increases the range between forced stops or when switching to internal combustion mode. In addition, vehicles must meet increasingly stringent safety and crashworthiness requirements, as well as customer needs in terms of affordability and comfort features (aesthetics, ergonomics, noise, vibrations). Meeting these goals is a major challenge and does not come without compromise. Approaches to weight reduction can be divided into: a) optimized structural design and topology of vehicle components, b) incorporation of advanced lightweight composite materials. Due to their low density but high stiffness and strength, polymer composite materials are increasingly present in automotive applications outside the aerospace industry. Although the aerospace industry has a decades-long advantage in design methods for fiber-reinforced polymers, applying these methods in the automotive industry can be problematic due to the significantly different production volumes, the technology used, and the development time. In the aerospace industry, the transition from metallic materials to fiber-reinforced polymers was facilitated by lower production volumes and a market environment that favors lightweight solutions due to fuel costs and payload. The automotive industry has long been reluctant to use these materials due to cycle time, repeatability, and high material costs, even though they offer outstanding benefits, design freedom, and component integration potential.

Examining the design chain of vehicle chassis development, it can be stated that the concept phase is the first and most important in terms of raw materials and manufacturing processes. The concept phase sets boundary conditions for later design phases and limits later decision options. In general, about 80% of the price of the finished product is decided in the early concept phase; the same is true for the structure's weight. In the concept phase, the following questions arise in order to create a weight- and cost-optimized structure: What manufacturing process should we use? Should the goal be as homogenized as possible in terms of material use, or should there be a high degree of material diversity in the structure? Where is the optimum between an integrating – larger, more complex components – and a differentiating – partitioned into components – design strategy? Answering such important questions in the early concept phase with limited experience in high-volume composite manufacturing increases the risk in terms of the weight and cost of the structure. Therefore, there is a great demand for design methods that help choose materials, manufacturing processes, or even provide guidance on the optimal partitioning of components.

Partitioning into manageable components has always been a fundamental concept in engineering design. Still, the emergence of composite structures in the automotive industry

has brought them to the forefront due to the high volume of production and cost sensitivity of the automotive industry. In the last few years, papers have shown that partitioning a composite structure can benefit overall cost since the main cost element of high-volume composite production is the cost of raw materials. The key to cost efficiency is to achieve better material utilization by dividing the structure and thus reducing the scrap material and waste from cut-outs. Due to the high cost-sensitivity and the outstanding weight reduction potential of fiber-reinforced polymer composites, a slight increase in the total weight due to the partitioning is acceptable if it is beneficial in terms of the overall cost.

However, if we add joints to the structure, they also affect the mechanical behavior. In the case of automotive polymer composites, adhesive bonding is the most common joining method. In my thesis, I examine composite sandwich structures containing adhesive joints.

The research aims to develop a design method that seeks to minimize the manufacturing cost of a composite shell structure with complex geometry, as well as to create a method for reliable modeling of the composite shell and its bonded joints in the concept phase for the effective analysis of the design variants of partitioning. This includes the definition of measures characterizing the complexity of the composite shell geometry and their application. By developing the design method, I aim to provide practical assistance to experts in vehicle body design, which can facilitate the determination of the position of the bonding lines in the structure. Such an application does not currently exist, but it would be an effective tool for design engineers, especially when a new vehicle architecture is required due to the transition from internal combustion engine drive to electric or other alternative fuel drive.

2. Literature review and objectives

The main problem with using composite materials in mass production is the higher production costs compared to traditional metal structures; therefore, in addition to innovations in materials science, there are other approaches to optimizing product production costs.

In the literature, typically using a bottom-up cost estimation approach, it has been shown that the production of larger and more complex composite parts can be made more cost-effective by partitioning them into several parts and then connecting the individual parts using a suitable bonding method, e.g., adhesive joints. It has been shown that the joining cost only has a minor impact on the total production cost and that partitioning the part can reduce the geometric complexity of the parts to be manufactured, thereby reducing scrap and tooling costs. The tooling cost was proportional to a geometric complexity factor. This method was later developed by combining partitioning and material selection. In addition, an analysis method was presented to examine a shell structure's cost and mechanical performance when partitioned into several parts. These methods calculate the complexity of the parts with prior knowledge of the manufacturing direction since the partitioning has

to be done manually. It is also necessary to automatically determine the optimal manufacturing direction of an arbitrary shell structure in an optimization framework to automate this.

My goal is to develop a method that can automatically determine the optimal manufacturing direction of a composite shell structure. This allows for the automatic calculation of the complexity factor of an arbitrary shell structure, which is a further step towards a method that aims at cost-effective partitioning.

The impact of partitioning a composite structure on its mechanical performance and manufacturing costs has also been studied in the literature. There are publications analyzing different partitioning concepts, but these concepts were created manually based on engineering considerations.

I have not found an optimization method for partitioning composite shell geometry into parts in the literature; therefore, I aim to develop a generalized method that works for arbitrary shell geometry and searches for a cost-effective partitioning of the shell geometry into parts.

Regarding the mechanical modeling of polymer composite vehicle body structures, a literature review shows that extensive studies are available with analytical models and simulation methods to understand the mechanical behavior of sandwich structures and their adhesive joints. Analytical methods often only work with beam or plate geometries and idealized boundary conditions. However, finite element models are too detailed and can only be used effectively at the specimen scale. In recent years, product development has aimed to maximize virtualization, thus minimizing prototype manufacturing and reducing design costs. This indicates the need to develop a modeling method for sandwich panels and their adhesive joints that assists the design process in the concept phase so that the structure can be modeled at the full vehicle scale but provides reliable results.

My goal is to develop a new efficient modeling method that can be applied to full vehicle scale for heterogeneous sandwich core materials containing resin walls and to analyze the deformation behavior of bonded joints of sandwich materials. This new method allows us to quickly and easily test different partitioning concepts and joint geometries with sufficient accuracy, thus becoming an effective tool in simulation-driven product development.

3. Materials and methods

In this chapter, I present the materials and the applied testing methods. The results of the measurements performed on the various test specimens will later provide input data for the numerical calculations and serve to validate the calculation models.

3.1 Materials

Composite face-sheets of sandwich structure

- QE-1232 quadraxial glass fabric, areal weight 1232 g/m² (Saertex GmbH),
- Distitron VE220 vinyl ester resin, viscosity at room temperature 270-380 mPas (Polynt Group S.p.A.),
- Lay-up: 3 x [-45/90/45/0],
- Thickness: 2,5 mm.

Core material of the sandwich structure

- Airex T90.100 closed-cell PET foam (3A Composites Core Materials – Airex AG),
- Core thickness: 25 mm,
- Total thickness of sandwich structure: 30 mm.

Manufacturing technology

- vacuum infusion,
- vacuum pressure: 0,8 bar.

Adhesive material of bonded joints

- AcraLock SA 10-100A two-component adhesive, working time 70 min (Engineered Bonding Solutions LLC)

3.2 Methods

Below, I describe the test methods used during the experiments, the equipment used, and the most important machine settings. The tests were performed at room temperature (22±2 °C) and 46±2% relative humidity. The measurements were made on a Zwick Z020 universal materials testing machine in the Department of Polymer Technology of the BUTE laboratory, with a maximum load capacity of 20 kN.

Tensile test of composite face-sheet

The tensile modulus and Poisson's ratio of the layers of the composite face-sheet were determined by displacement-controlled tensile testing. In addition to recording the force and crosshead displacement, the specimen's strain was also measured with two uniaxial strain gauges placed one above the other on one surface of the specimen within the measuring length. The test speed was 2 mm/min. The measurement was carried out until failure. The specimen type was the Type 2 specimen without end-tabs as described in the ISO 527 - 4 standard, with dimensions of 250x25 mm.

Tensile testing of adhesive and vinyl ester resin

For subsequent calculations, the elastic modulus and tensile strength of the vinyl ester resin and methacrylate adhesive are also required, and these were also determined by

tensile testing. The test specimen type for these materials is type 5A, as specified in the ISO 527 - 2 standard. The thickness of the test specimen is 2 mm. The test speed was 1 mm/min.

Shear test of composite face-sheet

The in-plane shear modulus of the composite face-sheet was determined by a V-notch shear test, the so-called Iosipescu test. The measurement was performed according to the ASTM D5379 standard. The test speed was 2 mm/min. The measurement was carried out until failure.

Bending tests of sandwich structure

To determine the stiffness of the sandwich structure, I performed a four-point bending test according to the recommendations of the ASTM - D7249 standard. The test speed was 6 mm/min. The measurement was carried out until failure. The length of the test specimen was 660 mm, its width was 60 mm, the external support distance of the bending was 500 mm, and in the case of four-point bending, the internal support distance was 166 mm.

To examine the failure of the sandwich panel, I also performed a three-point bending test. The measurement was carried out according to the recommendations of the ASTM - C393 standard. The dimensions of the test specimen, the external support distance, and the test speed are the same as in the case of four-point bending.

4. Summary of research work

In this chapter, I present the results of my research work with experimental tests and finite element simulations.

4.1 Determining the optimal manufacturing direction of a composite part

To determine geometric features relevant to manufacturing technology, I developed an application in the Python environment, the input of which is a shell geometry with a finite element mesh.

I am looking for the optimal manufacturing direction for composite shell structures that can be manufactured in one step with a conventional tool, i.e., without moving inserts. A part that can be manufactured in one step with a tool without a moving insert means that there is a direction from which the shell geometry is free of undercuts. Such parts can be manufactured using hand lamination, vacuum infusion, resin transfer molding (RTM), or light resin transfer molding (Light-RTM) technologies. Of course, the parameters of the manufacturing cost function and the cycle time are different in these manufacturing

technologies, but the geometry is characterized, and the optimal direction is determined in the same way.

When examining composite structures, I used the complexity factor C_c as the main metric, which quantifies the deviation of the geometry from a flat plate, which is the ratio of the total surface area of the component to its area projected onto a given plane.

In my case, the total surface area of the part (A_c) is the sum of the areas of the individual triangular elements that make up the geometric model; the denominator (A_p) is the area of the perpendicular projection of the geometry in the manufacturing direction ("shadow"). It is clear from the definition that $C_c \geq 1$, and equality occurs when $A_c = A_p$, which means an entirely flat part. The smaller the value of C_c , the less the shape of the part deviates from a flat plate, the less complex and expensive the tooling required for manufacturing, and the less the manufacturing waste. The method plots the value of the complexity factor in a spherical coordinate system for any shell geometry in the branch diagram I developed.

During the traditional design process, the manufacturing direction is determined by the expert technologist. If we want to automatically quantify the complexity of a part in the process of partitioning it into components, an automated determination of this direction is essential. For this, I introduced a metric characterizing undercut, which I denoted as U_s . The basis of the method is that I project projection rays from different directions of space onto the examined shell geometry, and then I count how many times the projection rays intersect the surface model. The method also handles degenerate cases when the outer and inner surfaces of the surface model are visible from a given projection direction. Similarly to the C_c value, $U_s \geq 1$ for any geometry.

The method for choosing the manufacturing direction is to select the direction corresponding to the minimum of the metrics determined so far. I examined the results of minimizing the $C_c \cdot U_s$ product for different geometries. I concluded that this metric can be generalized to give the correct direction according to engineering considerations.

I conducted a case study on a composite seat shell. It is a glass fiber-reinforced, unsaturated polyester resin (UP resin) matrix composite manufactured using RTM technology.

I evaluated the shell as a single part, and with two different partitioning versions. I calculated the C_c values for each part from the original shell's optimal orientation and the smaller parts' optimal orientation. To estimate the manufacturing costs, I used a bottom-up cost estimation for the material and tool costs. In the cost model, the material cost depends on the geometric complexity because it affects the amount of manufacturing waste, and the tool cost depends on the tool volume, which is determined by the product of the surface area of the part projected onto the plane in the manufacturing direction and its height in that direction.

The results show that partitioning the shell geometry results in parts with lower complexity, which means lower material costs. The optimal manufacturing direction of each

part also results in lower material costs than the production direction of the seat treated as a single part. Examining the tooling costs, I found that there is a partitioning variant in which the sum of the tooling costs of the individual parts is less than the tooling cost of the seat treated as a single part.

4.2 Cost-effective partitioning of a composite vehicle body

Since partitioning large, complex geometric shell structures into parts can be advantageous in terms of manufacturing costs, I developed a method to determine cost-effective partitioning into parts.

The analysis of shell structures is possible through their elementary components. To find effective combinations, the shell must first be divided into components. The algorithm suitable for handling the division is the K-means clustering algorithm. After the partitioning into elementary components, these can be combined in the next step, thus obtaining parts suitable for manufacturing. In my work, I used a hierarchical, bottom-up clustering, which considers various limiting conditions such as manufacturability, size, and manufacturing cost. To characterize the 3D geometry of the shell structure, I examine a shell geometry meshed with triangular elements.

Figure 1 illustrates the steps of the method. First, I define the mesh and transform it into a graph-based representation. In this step, I calculate the normal vectors of the triangular elements. I segment the geometry based on the normal vectors of the triangular elements using K-means clustering, where the similarity of the normal vectors in clustering is the cosine distance. I create connected geometric components from the resulting cluster elements. I decompose the components into elementary units and combine them using a bottom-up hierarchical clustering algorithm if the combination results in lower manufacturing costs. The algorithm takes into account various cost functions and their constraints. In addition, I perform a similarity analysis to determine which parts can be manufactured with the same tool. The similarity analysis is performed by using the ICP (Iterative Closest Point) algorithm.

I demonstrate the method on a composite bus body structure using the cost function of the RTM manufacturing technology. The cost model used is a bottom-up model, in which I took into account the costs of each stage of the manufacturing process: investment, material, tooling, and operating costs.

Applying the manufacturing cost function is necessary to determine the cost-effective partitioning. If a commercial software product is introduced to the market using the developed method in industrial applications, each composite factory should provide its own cost model to achieve optimal results.

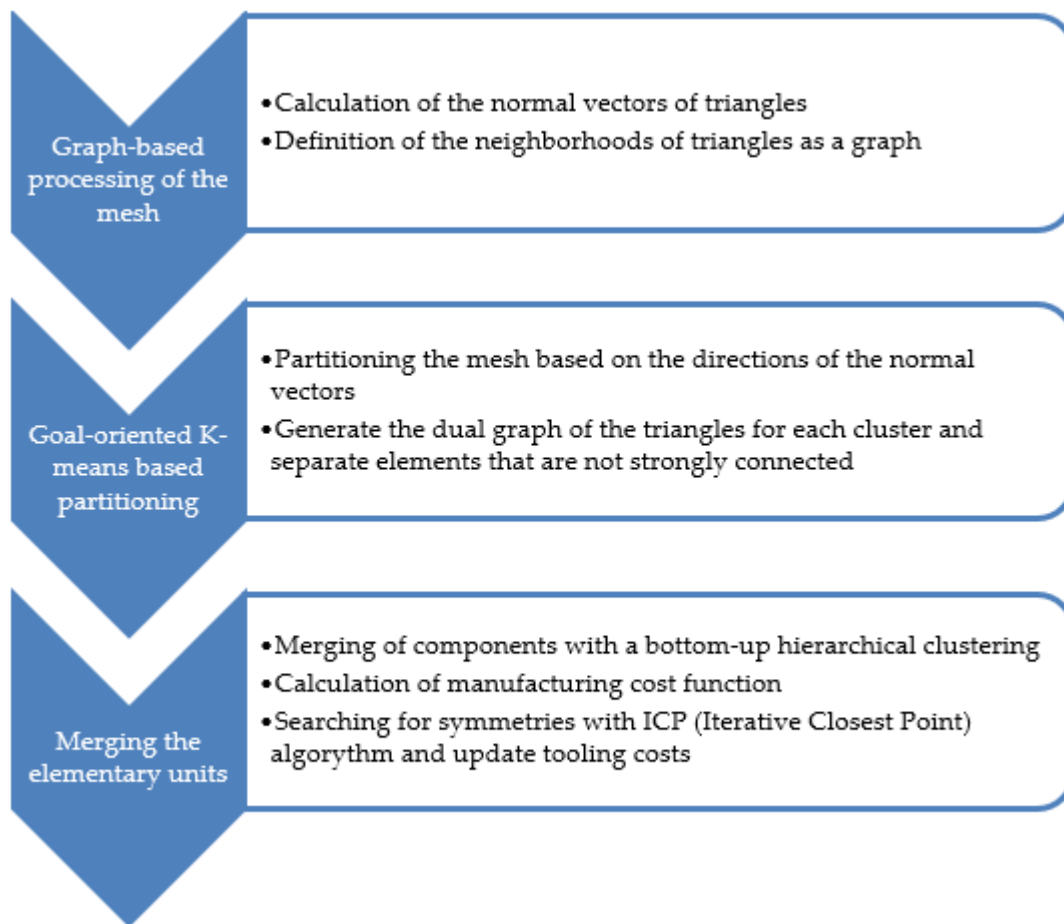


Figure 1. Flowchart showing the steps for cost-effective partitioning of composite shell structures

Examining the individual types of costs, I found that the total manufacturing cost decreases monotonically as the elementary units are combined and then increases again as the individual parts are further combined. The significant increase in tool costs can explain this increase. Thus, the method is suitable for determining the partitioning with the minimum cost.

I also used the ICP algorithm (Iterative Closest Point) in the method, which makes it possible to identify parts that can be manufactured with the same tools so with this extension of the algorithm, symmetrical parts can be taken into account, which results in further savings in terms of tool costs.

4.3 Mechanical modeling of polymer sandwich structures of a vehicle body in the concept phase

In the concept phase of the design, in addition to examining the cost-effective partitioning, it is also important to investigate the mechanical performance of the body structure, for which finite element analysis is an effective tool. However, to effectively

evaluate different design variants, a modeling method is needed to provide reliable results applicable to the full vehicle scale but with a low computational capacity requirement. By examining a polymer sandwich structure for the bus industry, I developed a method for characterizing the deformation behavior and predicting failure.

Using the material parameters determined by tensile- and shear tests of the face-sheet of the sandwich panel under investigation, the tensile test of the resin, and the tensile modulus of the foam manufacturer's data sheet, I created a finite element model, which is built up of volume elements where the foam also includes the resin walls. I demonstrated by the 4-point bending test of the model according to the ASTM - D7249 standard that the presence of the resin walls causes a 16% increase in stiffness. By performing a virtual tensile and shear test of the foam without face-sheets but containing resin walls, I determined the equivalent tensile- and shear moduli for the heterogeneous foam structure, and I also demonstrated that the equivalent tensile modulus of the heterogeneous foam can be determined by combining the direct and inverse rules of mixtures.

In the next step, I modeled the entire sandwich panel with laminated shell elements, homogenizing the heterogeneous foam core and taking into account the previously defined equivalent elastic parameters; I also performed 4-point bending on the laminated shell model and obtained a 3% difference in the calculated deformation compared to the detailed reference model, while the calculation required two orders of magnitude less simulation time.

I developed a dynamic simulation model based on the detailed finite element model to investigate the failure. I applied a maximum stress-based failure model to the foam core and the resin walls. I compared the results of the 3-point bending test of the model according to the ASTM – C393 standard with the results of the experimental test, with which I achieved good agreement, and using the failure force and deflection value, I determined the shear strength applicable to the failure prediction for the homogenized foam core with the 3-point bending test of the laminated shell model. This gave the strength-modifying effect of the resin walls, and thus, I developed a method that can effectively analyze different design variants in the concept phase of development.

In summary, the modeling method, which aims to analyze a complex core sandwich panel structure on a full-vehicle scale efficiently, consists of the following steps:

1. determination of the stiffness parameters of face-sheets by measurement,
2. finite element modeling with laminated shell elements,
 - a. homogenization of an inhomogeneous core material containing resin walls with an orthotropic material model,
3. bending test of a detailed finite element model built from volume elements at the specimen scale, determination of failure force and deflection,
 - a. the core has a heterogeneous structure, contains resin walls,
 - b. application of a failure model to foam and resin materials,
4. determination of the shear stress of the homogenized core associated with failure deflection in the model built in point 2.

With the shell model developed using the above procedure, it is possible to examine different design variants on a full vehicle scale with quick and simple modeling and low computational capacity requirements while obtaining highly reliable results for characterizing mechanical behavior.

4.4 Efficient modeling of adhesive joints of sandwich structures in the concept phase

To investigate the design variants of the vehicle body built from polymer sandwich panels, it is essential to be able to effectively model the mechanical behavior of various adhesive joint constructions on a full vehicle scale. I have developed a method for effectively modeling the deformation behavior of sandwich panels containing adhesive joints.

The basic principle of the applied solution is that I connect geometrically coincident node pairs at the edges of the shell models representing the individual components, which are connected by adhesives in reality, with a general element describing stiffness.

Separate virtual tests for typical bonding geometries can determine the stiffness matrix parameters. The reference model is a detailed finite element model (consisting of volume elements) of a simpler geometry validated by mechanical tests. The same geometry as the reference should also be developed as a shell model, and the matrix elements should be determined by a parameter search so that the responses of the structure - i.e., the displacements measured at a representative point - match the reference as closely as possible under typical loads (e.g., 3-way tension and 3-way bending).

I used the design of experiments (DoE) method to find the parameters. I evaluated the points of the parameter field that were considered possible according to an appropriate random distribution. I determined the input parameter combinations using the Modified Extensible Lattice Sequence (MELS) algorithm. MELS creates a quasi-random combination sequence that covers the parameter field evenly on average, minimizing congestion and empty space. Due to this property, the method is a good space filler and is well-suited for covering the entire parameter space and establishing approximate relationships. The extensibility property means that the method is able to supplement an existing data set in such a way that the space is evenly covered optimally in the case of data generated according to previous MELS. These properties make it ideal for the current application. The process is illustrated in Figure 2.

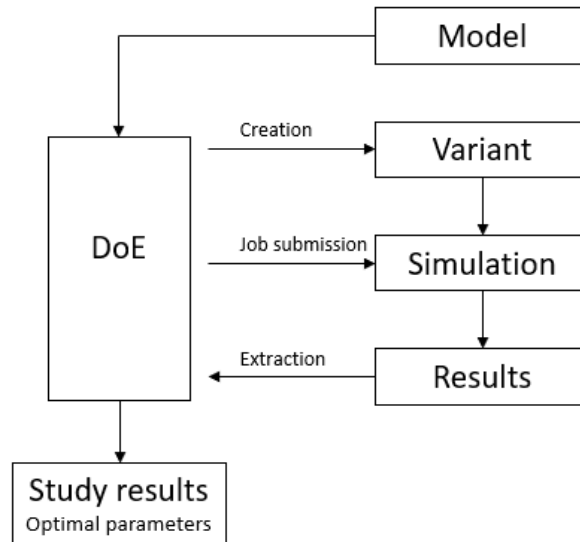


Figure 2. Finding stiffness parameters using the design of experiments

The test was performed with two different glued joint constructions of the sandwich panel used in the previous chapter on three reference geometries: bar, plate, and frame geometry, which models a simplified bus body.

I have shown that by tuning the parameters of the stiffness matrix, the stiffness-increasing effect of the joints cannot be taken into account, so I have introduced a parameter called E_{aux} , which is the elastic modulus of the isotropic elements modeled in the width of the joints in the finite element simulation. Thus, by using five parameters – the stiffnesses S_x , S_y , S_z in the x , y , and z directions, the rotational stiffness around the y axis S_{xz} , and an additional stiffness parameter labeled E_{aux} , which homogenizes the joint – the error in the deformation behavior can be reduced to less than 3% compared to the detailed reference model, but the analysis requires an order of magnitude less computational capacity, which I have illustrated with the torsional stiffness analysis of a bus body.

5. Theses

The manufacturing direction of polymer composite parts manufactured by resin transfer molding, vacuum infusion, or hand lamination with a traditional tool without a moving insert, i.e., the direction of the parting plane of the tool, affects the tool and material costs. To minimize the manufacturing costs, the optimal manufacturing direction of the part must be determined. I have developed a method for determining the optimal direction, which is formulated in the following thesis.

Thesis 1.

The optimal manufacturing direction in terms of manufacturing costs for polymer composite parts with shell geometry that can be manufactured in one step with a tool without moving inserts can be determined using the following procedure if the bottom-up cost model is applied to the manufacturing costs:

- Processing the discretized geometry – with finite element mesh – reading of nodal coordinates and element definitions,
- determination of the geometric complexity factor from literature for the component as a function of the possible 3D directions,
- determining the undercut factor developed by me for the component depending on the possible 3D directions,
- determining the optimal direction by finding the minimum of the product of the two factors [1].

The manufacturing costs of polymer composite vehicle body structures with large and complex geometries manufactured by resin transfer molding, vacuum infusion, and hand lamination can be reduced by partitioning the structure and using structural joints between the individual parts because the effect of lowering the tool- and raw material costs of smaller and less complex parts is greater than the cost increase resulting from the use of adhesive joints. I was the first to develop a method for determining cost-effective partitioning from the point of view of manufacturing costs, which I formulated in the following thesis.

Thesis 2.

The cost-effective partitioning of a polymer composite vehicle body structure can be determined using the following procedure:

- Graph-based processing of discretized shell geometry – consisting of triangular elements: generation of a dual graph based on the triangular elements and their relationships,
- using K-means clustering, the geometry is divided into elementary units based on the normal vectors of the triangle elements and the relationships between the triangle groups,
- merging elementary units by hierarchical clustering in several steps in such a way that the manufacturing cost function decreases in the merging steps,
- identification of symmetries during the merging process using the ICP (Iterative Closest Point) algorithm due to the additional cost-saving effect of manufacturing symmetrical parts with the same tool.

The method partitions an arbitrary shell geometry into parts that can be manufactured in one step with a tool without moving inserts and searches for the minimum of the bottom-up manufacturing cost function. [2].

In the concept phase of vehicle body design, it is of great importance to be able to perform the strength verification of design variants quickly, with low computational capacity, but with sufficient accuracy. In the case of polymer sandwich vehicle bodies, the resin walls in the foam core, which are created as a result of the manufacturing process, significantly influence the stiffness and strength properties of the sandwich structure, but their finite element modeling is only possible if the foam core is modeled with volume elements, which significantly slows down the strength verification of the entire vehicle body due to the workload of modeling and the significant increase in calculation time. I have developed a method for efficiently modeling polymer sandwich vehicle bodies – applicable on a full vehicle scale – which I have formulated in the following thesis.

Thesis 3.

The mechanical behavior of the heterogeneous core of polymer composite sandwich panels containing resin walls can be effectively modeled with layered shell elements, a homogeneous orthotropic material model, the stiffness parameters of which can be determined by homogenizing the heterogeneous core material: the tensile modulus by a combination of the straight and inverse rules of mixtures, the shear modulus by a shear test of the detailed finite element model containing the resin walls. The limit stress applicable to the prediction of failure can be determined by a dynamic simulation of the heterogeneous core sandwich panel containing element failure model, from which the strength modification factor of the resin wall for the core failure can be obtained. With this modeling method, a finite element calculation requires two orders of magnitude less computational time, while its accuracy in terms of the calculated deformation differs by only 3% compared to a detailed finite element model. In the detailed finite element model, the foam core and the resin walls are modeled with volume elements according to their geometry and are considered separately with a linear, isotropic material model, which is valid in the range of normal operating loads of vehicle body structure.

I have verified my statement with bending tests and finite element simulations of a sandwich panel consisting of QE-1232 glass fiber reinforced Distitron VE220 vinyl ester matrix face-sheets and Airex T90.100 closed-cell PET foam [3, 4].

In the concept phase of vehicle body design, it is essential to be able to analyze the mechanical behavior of design variants that implement the partitioning into different parts, taking into account various types of joints quickly, with low computational capacity but with sufficient accuracy. I have developed a method for efficiently modeling polymer

sandwich vehicle bodies containing adhesive joints at full vehicle scale, which I have formulated in the following thesis.

Thesis 4.

The deformation behavior of polymer sandwich vehicle bodies containing adhesive joints can be effectively modeled according to the following method: the sandwich panel is characterized by laminated shell elements, and the joints are characterized by a matrix element describing general stiffness, the parameters of which are determined by the MELS (Modified Extensible Lattice Sequence) method of design of experiments, for which the reference is provided by a 3D finite element model validated by mechanical tests. By using the following five parameters instead of the 21 independent parameters of the stiffness matrix representing the joint, the accuracy of the calculated deformation differs by less than 3% compared to the 3D finite element model while requiring an order of magnitude less computational time: the stiffnesses S_x , S_y , S_z in the x , y , and z directions, the rotational stiffness around the y axis S_{xz} , and an additional stiffness parameter denoted E_{aux} , which homogenizes the joint. The method can be applied to structures and materials whose deformation behavior can be modeled linearly in the range of normal operating loads of the vehicle body structure. [5-9].

I have verified my statement with experimental tests and finite element simulations of a sandwich panel consisting of QE-1232 glass fiber reinforced Distitron VE220 vinyl ester matrix face-sheets and Airex T90.100 closed-cell PET foam bonded with Acralock SA 10 HV adhesive. I have determined the parameters of the raw materials of the sandwich structure by tensile- and shear tests. I have analyzed the deformation behavior of the sandwich panel by bending tests.

6. List of own publications

- [1] **Takács L.**, Szabó F.: Automated determination of the optimal manufacturing direction of polymer composite shell structures. IOP Conference Series: Materials Science and Engineering, **1246**, 012026 (2022).
- [2] **Takács L.**, Szabó F.: Kompozit szerkezetek optimális részekre bontása a gyártási költségek minimalizálására. Polimerek, **10**, 362-368 (2024).
- [3] **Takács L.**, Kovács L., Olajos T.: Numerical tool with mean-stress correction for fatigue life estimation of composite plates. Engineering Failure Analysis, **111**, 104456 (2020). IF=2,203; Q2
- [4] **Takács L.**, Szabó F.: Modeling the deformation behavior of polymer sandwich structures with inhomogenous core. IOP Conference Series: Materials Science and Engineering, **903**, 012024 (2020).
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- [6] **Takács L.**, Kiss Z.: Cost-effective partitioning of a composite bus structure from the perspective of adhesive joints. in '18th European Conference on Composite Materials. Athens', Vol. 18, 8p (2018).
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- [8] **Takács L.**, Szabó F.: Experimental and numerical failure analysis of adhesive joint of glass fiber reinforced polymer composite. Periodica Polytechnica Mechanical Engineering, **64**, 88-95 (2020).
- [9] **Takács L.**, Szabó F.: An effective method of modeling the deformation behavior of polymer sandwich structures with adhesive joints. Applied Composite Materials, **28**, 1959-1978 (2021). IF=2,199; Q2