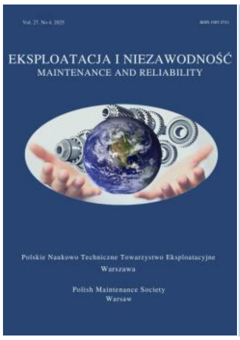

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Multi-objective optimization of the deck structure of the lightweight micro-vehicle for improved reliability and desired comfort and stability while driving

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Highlights

- Novel approach to design of main deck of e-scooter.
- Actual distribution of loads on deck.
- A comparison of two optimization techniques.
- Optimal thickness of deck.
- Low-maintenance and reliable design.

Abstract

Electric kick scooters represent a viable alternative to reduce emissions associated with the use of cars. However, several obstacles hinder the widespread adoption of e-scooters, primarily stemming from their high mass, short range, and challenges in navigating uphill routes. The LEONARDO project aims to develop an innovative, 10 kg microvehicle with high torque, similar to a monowheel, while maintaining the ease of riding. To achieve this goal, heavy and complex suspension components were eschewed. In order to maintain ride comfort and stability, it was necessary to design a scooter deck with a specific susceptibility, but one that provided a high level of vehicle reliability.
The article presents a novel approach to the design of a microvehicle deck. The methodology and the results of measuring operational loads are presented, which were used to develop a design that meets the assumed level of reliability, comfort and stability. The study employs a comparative analysis of two distinct optimization algorithms, each accounting for varying load scenarios and multiple objectives.

Keywords

safety, reliability, multi-objective optimization, riding comfort, riding stability

1. Introduction

Electric kick scooters' popularity is constantly growing in Europe thanks to their ease of use in the urban environment. This form of micromobility stands as an interesting solution to (e-)bicycles [1–4] for decreasing passenger cars' emissions [5]; even though electric, these latter vehicles are associated with environmental issues [6][7] that cannot be currently solved due to the energy mix of the European Union (it is expected that 40% of the electricity will be generated from renewable sources by 2030). While it is foreseen that e-scooters sales will augment of approximately 25% per year [8], their spread is currently obstructed by the difficulties in employing them for other purposes than last-mile travels: their mass, often higher than 15 kg, generates difficulties in carrying them onboard more traditional means of transportation (e.g., in a trunk of a car or

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on the train). At the same time, the ride time is typically less than an hour as reported by Ma et al. [9] because of the limited energy stored in the battery packs. Also, due to the small wheels, it is not feasible to cover specific urban tracks, as high-slope routes. Following innovation trends in the field of micromobility [10], the LEONARDO project (microvehicle fOr staNd-alone and shaReD mObility) aims to create a microvehicle by hybridizing a scooter and a unicycle. The idea is to achieve high torque with a large diameter wheel while maintaining the ease of use of a scooter. Large-diameter wheels also make the user less sensitive to vibrations transmitted by road irregularities [11]. Additionally, the new vehicle aims to be lightweight—under 10 kg—while ensuring high reliability and simplified maintenance.

Achieving a low-maintenance and reliable design necessitates minimizing mechanical complexity. A key decision in the LEONARDO project is the elimination of traditional suspension elements, which are typically present on the rear (and sometimes front) wheels of conventional scooters. This approach not only reduces weight but also simplifies serviceability, making the vehicle easier to maintain over its operational lifespan. However, removing suspensions requires careful optimization of the deck, ensuring it provides both structural strength and riding comfort.

Decks for the circulating scooters are typically obtained from aluminum beams, which are extremely strong per se but also stiff: simulation-based research by Cano-Moreno et al. [12] demonstrated that employing less stiff suspensions improves riding comfort while also decreasing overall mass and maintenance requirements. These outcomes have been experimentally confirmed by Gulino et al. [13] by excluding the suspension elements of a kick scooter: testing several types of decks in terms of material on a track, the authors determined that less stiff decks promote the riding comfort (defined in accordance with ISO 2631).

When considering durability, engineers have a number of tools to assist in the verification of basic design assumptions. One of the most popular is FEA [14]. It allows a thorough analysis of the stiffness of the whole device and an estimate of its durability from a strength point of view, but the stiffness information is not used to assess ride comfort. Experimental studies based on acceleration measurements are used to determine comfort levels [11,15]. Various modelling methods are also used [16], but these are mainly parametric analyses in Matlab/Simulink [17] or simulations based on multi-body systems [18,19]. However, these types of studies do not provide information on the loads occurring between the driver and the deck, nor do they provide stress analyses of the deck structure.

Building upon the findings of Gulino et al. [13] the present study focuses on determining the forces acting on the deck as a function of its material. These indices, expressed as a function of the stiffness of the deck, provide essential information for piloting a multi-objective numerical optimization of the deck design to ensure that the final structure not only provides a stable and comfortable driving environment, but is also lightweight, highly reliable and easy to maintain.

The main objective of the paper was therefore to develop an effective multi-variant numerical-experimental method for optimizing the board, considering the actual course of operational loads acting on the structure, different load patterns and different types of materials. The practical aim of the work was to reduce the mass of the scooter, simplify the mechanical design for easier maintenance and improve overall durability. This study is the first in scientific literature to propose a comprehensive multi-objective optimization framework for the deck design of an electric scooter. The novelty lies in its systematic integration of ride comfort, stability, and maintenance simplification within the design process. Unlike existing designs that rely on traditional suspensions, this approach emphasizes low-maintenance architecture without compromising reliability. The findings will provide valuable guidelines for the development of next generation micromobility solutions, offering an optimal balance between durability, comfort, and serviceability.

2. Materials and methods

2.1. Experimental test campaign

The present section describes the decks employed in the experimental campaigns, as well as the testing environments and the devised data acquisition scheme.

2.1.1. Decks

A commercially available e-kick scooter with an aluminum deck has been dismounted for the exclusion of the suspension mechanisms and the replacement of its original aluminum deck with four different types of deck:

- a 15 mm thick deck consisting of three vacuum resin-bonded bamboo layers;
- a deck made of eight maple sheets with an additional non-slip grip, with a total thickness of 12.5 mm;
- a composite deck made of a 18 mm thick PVC core and two 2 mm thick fiberglass skins on the upper/lower faces;
- a 12.5 mm thick deck made up of three fir sheets.

2.1.2. Closed circuit and obstacle for the tests

The stiffness of the decks was measured experimentally by three-point bending tests. To derive information regarding the forces discharging on the different types of deck, two different testing environments have been defined with diverse purposes:

1. Closed circuit - the 200 m long track, closed to the traffic, characterized by a set of pavement discontinuities that can be typically found in an urban road environment (e.g., rough asphalt, manholes, ramps); it also comprises a straight road segment where a speed of 20 km/h can be easily reached. Each lap on the closed circuit has been performed at a speed ranging from 13 km/h and 20 km/h, slowing down in correspondence of acute curves but always remaining within these limits. At least five repetitions of the test considering a single deck have been performed, in accordance with the description by Gulino et al. [13].
2. Obstacle - artificial bump sited in an ideal road segment. The obstacle is obtained by fixing two 15 mm thick sheet of a plywood on a straight path with smooth surface, for a total height of 30 mm. This type of test is developed to minimize external disturbances: the track is straight (no random irregularities given by the different curving path), it has no pavement discontinuities, and the position of the rider on the deck in the segments both before and after the obstacle is highly repeatable. The speed in correspondence of the obstacle is 20 km/h. 10 repetitions of the test with the obstacle have been performed considering a single deck. Fig. 1 depicts the obstacle.

Since the closed circuit tests provide information regarding the cyclic loading conditions for the deck, the related results can be employed for structural verification of the deck in dynamic conditions (fatigue sizing - the primary concern is the reliability of the system over an extended period of utilization). Conversely, the obstacle tests represent shock conditions for the deck, being more appropriate for performing static sizing.

Fig. 1. Reference obstacle.

2.1.3. Data acquisition setup

A primary component of the project entailed the quantification of the loads exerted on the platform. To this end, a bespoke measuring system was utilized. Instrumented shoes have been produced to determine the distribution of weight for the rider in the scenarios reported in Section 3.1.2. The right instrumented shoe is visible in Fig. 2. It consists of one full-bridge strain gauge on the rear of the shoe and one on the front to maximize sensitivity. The strain gauges have been fixed on a rigid wood plate to allow for the complete transmission of forces among shoes and deck. During data processing, the two signals from the two bridges are summed, to provide the overall value of the weight on the right shoe. The same applies to the left shoe.

The distribution of all measured forces by the load cells directly mirror those from the shoe that pass to the deck; since only the vertical component of the resulting force is considered, the insertion of a rigid body is not influent. The rider was asked, after standing onboard the vehicle, to maintain the initial positioning of the feet to avoid force fluctuations throughout the test. This is eased by the short duration of the test. The lateral translation of the shoes is also prevented by means of constraints fixed to the deck, which contact the rigid plate.

Fig. 2. Views of the right instrumented shoe from below (left figure) and side (right figure).

The data from the instrumented shoes are acquired by a National Instrument data acquisition board (model 9291) and refer to the forces discharged on the left and right shoes in the vertical direction. The data are acquired during: 1) one complete lap in the closed circuit, 2) the overcoming of the artificial obstacle. Fig. 3 reports an example of signal acquired for the obstacle test, in the case of deck in fir (maximum stiffness, highest peak force among decks) and bamboo (minimum stiffness, least peak force among decks). The sample rate was set to 100 samples/s.

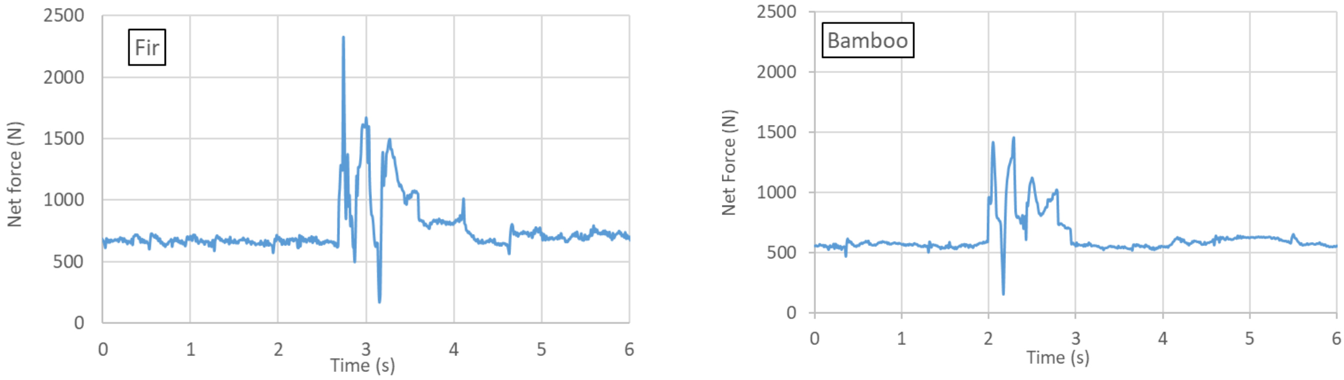

Fig. 3. Example of signals acquired for an obstacle test in the case of deck in fir (left) and bamboo (right).

2.1.4. Results of experiments

To analyze the behavior of the four considered decks in the two diverse testing conditions, data have been suitably processed and reported as a function of the decks' stiffness. Should a proper correlation among these parameters and stiffness be obtained, it could be possible to determine the forces that will discharge on a specific type of deck without conducting tests: even if its behavior has not been analyzed before, this could provide initial indications regarding its static or dynamic sizing.

A first indication regards the overall riding feeling for the user provided by the employment of a specific type of deck. It is however worth specifying that only feelings linked to the forces that discharge on the deck are addressed, not the riding comfort as conversely treated in previous research [13]. Riding feeling discussed here is more directly related to riding stability, rather than comfort.

An indication regarding the overall distribution of forces as a function of time can be obtained by referring to the first and second order moments of the signals, i.e., signal average and Root Mean Square (RMS). These values are linked to the weight of the rider (740 N), which was the same throughout the different acquisitions. A part of the weight discharges in fact on the deck, while another part on the front wheel passing through the handlebar and the steering column. The first has been measured with the kick scooter moving slowly on a smooth surface: it resulted as substantially independent from the employed deck, corresponding to a measured value of 597 N. In the closed circuit tests, the part of the weight discharging on the deck is not constant but sustains variations as a function of the riding conditions (at curves, braking, etc.) that have been maintained as constant as possible during the tests. The trend in the mean RMS among the different repetitions of the acquired signals during closed circuit tests is reported in the left part of Fig. 4; repetitions for the same stiffness represent different laps. The results obtained for this parameter indicate that it definitely depends on the deck stiffness. The difference in terms of RMS between the stiffest and the least stiff decks is around 57%. These variations are linked to the accelerations that the decks sustain especially while moving on asperities of the track. The reported results demonstrate a relevant deviation span among the repetitions with the same deck. Nonetheless, considering the average values of RMS for the different deck types, a value of R^2 equal to 0.998 can be achieved for a logarithmic regression. For what regards the additional indicator of mean average force, the right part of Fig. 4 indicates that the behavior is very similar to that of the RMS and the trend is well represented by a logarithmic regression.

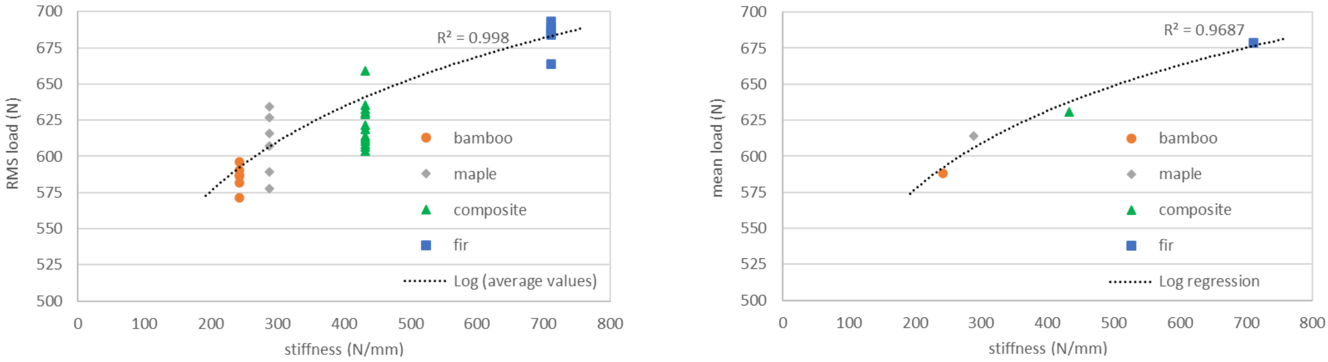

Fig. 4. RMS (left) and mean of averages (right) for the acquired forces during the various tests in the closed circuit, as a function of the deck stiffness.

In addition to the two indicators considered, another variable that influences riding feeling is represented by the amplitude of the forces during the test. Situations where the rider is subjected to a vertical acceleration in accordance with or in opposite directions to the weight were observed. To focus on the number, duration, and amplitude of the force peaks, the number of peaks that overcome a specific threshold in the signal has been investigated. This variable is mainly related to the passage on a discontinuity of the road pavement and the subsequent oscillations of the deck. The number of peaks above the mean value as a function of stiffness has the same trend as shown by both the RMS and the mean force, with a monotonic evolution (Table 1).

In addition, to consider a parameter related to the duration and intensity of peaks, the ratio between the signal area above the threshold value and the number of peaks has been evaluated (Table 1). A low value is desirable. As a function of the stiffness, some oscillations are observed, with the lower values featured by the two decks with higher stiffness.

Another possibility is also to consider fluctuations in forces discharged on each single shoe, i.e., between right and left shoe. Discontinuities in the road surface (manholes, bumps, disconnected asphalt, etc.) generate sudden displacements of the deck. To maintain balance while riding, the rider is forced to constantly modify the weight distribution between the sides. Hence, an additional parameter is defined, i.e., the absolute value of the difference between the RMS for the left shoe and the right shoe (DRMS) whose trend is depicted in Fig. 5. DRMS for the two less stiff decks is significantly higher than the variation for the stiffer ones. This implies that the rider is exposed to instability conditions while employing a more flexible deck, being more prone to continuous adjustments of the weight between the two sides when traveling through pavement discontinuities. These variations are not visible in the RMS of the net force.

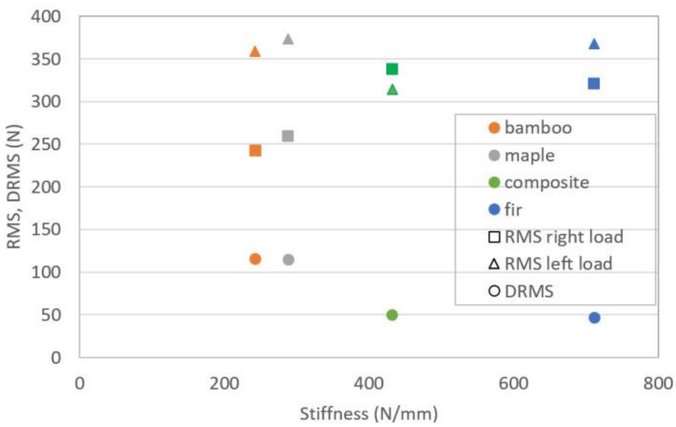

Fig. 5. DRMS for the circuit tests, as a function of the deck stiffness

Apart from a subjective component, feeling surely depends on the route conditions. In the end, several indicators related to riding feeling have been defined. The first three variables decrease as stiffness decreases, with monotonic behavior. This would suggest that a lower stiffness increases riding feeling. This is true for the considered closed circuit for the measurement, representative of a normal urban road with a few pavement discontinuities. The DRMS and the area/peaks parameters suggest that in the case of a discontinuous road, a stiffer deck would be the best alternative.

Regarding the passage on the artificial obstacle, the average value of the maximum load recorded in the tests is reported in Table 1, together with its standard deviation.

Table 1. Properties of the different decks.

	Bamboo	Maple	Composite	Fir
Closed circuit tests				
Stiffness (N/mm)	242	288	432	711
Mean load (N)	588.2	614.2	630.9	678.8
RMS load (N)	591	609	639.2	683.7
Number of peaks over mean value	1070	1116	1147	1287
DRMS (N)	115.5	114.8	50.1	46.6
Area/peaks (reference mean value) (Nh)	0.487	0.562	0.467	0.434
Obstacle tests				
Average value of the maximum load (N)	1496.2	1538.8	1998.5	2348.7
Standard deviation of the maximum load (N)	141.3	107.0	301.8	204.5

Considering the results obtained from the processing of experimental data, the following conclusions can be derived:

1. it is possible to compensate for lack of suspension with the flexibility of the deck of the microvehicle and not to cross mechanical limits of the deck material,
2. less stiff decks give better riding feeling on the roads with a few pavement discontinuities
3. more stiff decks provide better stability i.e. less body weight balancing is required during ride.

2.2. Structural design of the lightweight deck

In this section numerical model of the deck is discussed. Definition of a weighted objective function and set up of multi objective optimization is also showed. Finally results of optimization are presented.

2.2.1. Numerical model of a conceptualized deck

The design of the vehicle must consider the categories of users to whom it is addressed, which in some ways is indicative of the road surface conditions that the vehicle will encounter most during its operative life. It is therefore possible to define at the design stage the desired stiffness for the deck so that the riding feeling and stability will be optimal without the need to implement classical suspension mechanism. These riding properties should not compromise deck reliability. This purpose can be done using composite material with an appropriate layout.

The composite deck, which has a low stiffness compared to traditional metallic decks, is associated with high performance based on the indicators of stability but with lower performances regarding the indicators linked to the riding feeling.

Based on these considerations, it was decided to build the deck of the LEONARDO vehicle in composite. The lay-up will be designed to obtain stiffness similar to that of the bamboo deck used in the experimentations, assuming that e-scooter will be used mainly on the even roads. A second objective is to limit the weight, obviously keeping adequate safety characteristics with regard to the stress and durability. The third benefit, which will appear, so to speak, will be the simplification of servicing procedures and increased reliability of the device. The most efficient way to develop structure meeting the goals is to use numerical analysis tools allowing to conduct proper optimization process. The process was performed in the software environment provided by LSTC company.

The first stage of the optimization process was to create numerical model of the deck and definition of boundary conditions. The shape of the platform of the LEONARDO vehicle differs from that used in the experiments, which consisted of a parallelepiped with constant rectangular cross-section. This is due to the different riding characteristics of the vehicle compared to those of an e-scooter, which involves different construction requirements. The concept design of the vehicle is presented in Fig. 6.

Fig. 6. Concept design of the vehicle.

The mass of the driver was assumed to be 150 kg, uniformly distributed on a suitable area of the deck. This value was about twice the mass of the driver and allowed to account for dynamic overload in static analyses. The adopted value was also consistent with the results of the obstacle test (Fig. 3). Two load cases were analyzed. Static nonlinear analysis with symmetric and asymmetric loading were conducted. The nonlinear solution was chosen to take into account the large deflection of the deck. The idea behind these two cases was to simulate normal use of the vehicle, i.e., the rider is standing on the deck (symmetric conditions) and the situation when rider is starting the ride and stands on one leg only. In both cases the deck was supported at the axles (Fig. 7, Fig. 8)). The core of the deck was made of PVC, while the outer skins were made of several layers of fiber reinforced epoxy-glass composite. The exact number of layers and lay-up was to be defined by optimization procedure. Supports were made of PA6 reinforced by 50% of short glass fibers (Durethan BKV50H3.0). Orthotropic material model, usually used with composite materials, was chosen to describe the layers of the deck external skins. The stack of the composite layers was modelled using classical lamination theory [20][21]. Behavior of core and supports were described by an elastic material model. The material data are presented in Tables 2-3.

Table 2. Material properties of GFRC for skins.

Material	Polyester- fiberglass
Density (kg/m^3)	1634
E_{11} (MPa)	22500
E_{22} (MPa)	5150
G (MPa)	12715
ν_{12}	0.3
R_{11} tensile (MPa)	290
R_{22} tensile (MPa)	42
R_{11} compression (MPa)	315
R_{22} compression (MPa)	105

Table 3. Material properties of Durethan BKV50H3.0 and PVC.

Material	PA6 + 50% glass fibers	PVC
Density (kg/m^3)	1570	80
E (MPa)	1020	100
Poisson ratio ν	0.4	0.3
R tensile (MPa)	140	

The subscript 1 indicates the direction of the fibers, subscript 2 the direction perpendicular to 1 in the plane of the deck. E, G are the normal and the tangential elastic moduli, ν is the Poisson ratio and R is the ultimate stress.

Since the literature on microvehicles has already demonstrated that it is sufficient to reduce the stiffness to increase the riding comfort (11, 12), the damping characteristics of the material was neglected in the simulations for the sake of simplicity.

In the case of symmetric loading, only half of the deck was modelled to reduce calculation time. 8-noded hexagonal elements with reduced integration were used for mesh of a core. The laminate deck skins were meshed with 4-noded thin shell elements with 2x2 in-plane integration points and 5 through-thickness integration points. Layers were connected by node equivalence. It must be mentioned that the location of the mid surface of deck skins remains unchanged for each case for the sake of simplicity. Developed models for symmetric and asymmetric load cases are presented in Fig. 7 and Fig. 8.

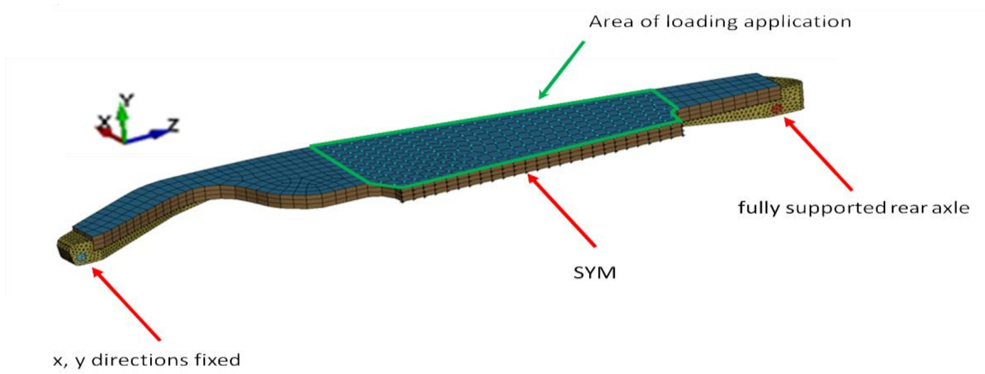

Fig. 7. FE model of the scooter deck for symmetric load case.

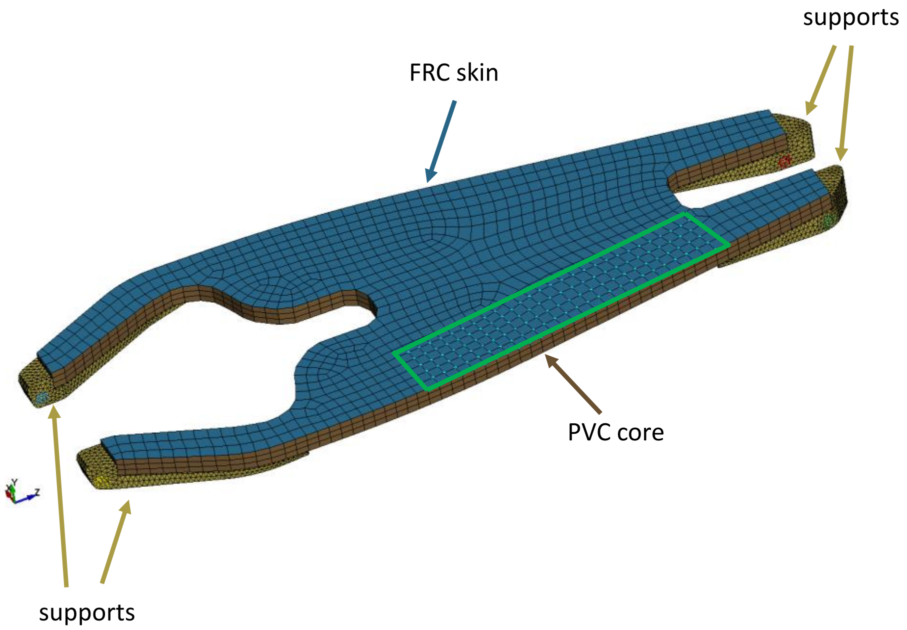

Fig. 8. FE model of the scooter deck for asymmetric load case.

2.2.2. Numerical optimization

Optimization can be defined as a procedure for obtaining the best solution under certain constraints [22]. Mathematical formulation is given by:

$$min\, f_{opt}\,(x) \text{ while } g_j(x) \leq 0; j = 1,2, \dots, m \text{ and } h_k(x) = 0; k = 1,2, \dots, l \quad (1)$$

where f_{opt}, g and h are functions of variables $x_1, \dots x_n$. Function f_{opt} is subject to optimization and functions g, h, are optimization constraints.

A lot of methods exist to solve problem (1). Many of them are described in [23,24]. In the present work, authors decided to use two arbitrary chosen optimization techniques to find optimal lay-up of FRC. The first is the application of genetic algorithms [25–27]. This approach, among other engineering problems, is extensively used for layout optimization of composite structures in conjunction with finite elements computation [28,29]. In the paper an elitist non-dominated sorting genetic algorithm (NSGA-II) is used as a global optimization method [30]. The second approach uses response surface methodology (RSM) [31–33], which is one of the most popular methods used to solve wide range of engineering problems [34].

Problem statement

As it was mentioned, the goal of this study is to find outer layers lay-up with the smallest number of layers (and in effect generating the lowest mass and cost) maintaining stiffness comparable to the bamboo deck and reliability in terms of adequate stress limits. The objective function is formulated in such a way that it contains weighted members depending on the deck's mass, deflection, and stress (2). This kind of interrelated objectives function defines an example of multi-objective optimization based on weighted objective function [35]. Since the process of optimization will also be driven by engineering judgment not included in the algorithm, it can be said that the deck design will be subject to collaborative optimization process [36].

$$f = m \cdot 0.5 + \left| d - \frac{F}{k_{desired}} \right| \cdot 0.15 + \left(\frac{\sigma_{1max} + \sigma_{2max}}{100} \right) \cdot 0.125 \quad (2)$$

where: m – mass of the deck in kg, d – maximum deflection in the symmetric case in mm, $k_{desired}$ – desired stiffness of the deck in N/mm, σ_{1max} – maximum equivalent stress in symmetric case in MPa, σ_{2max} – maximum equivalent stress in asymmetric case in MPa.

The goal of optimization is minimization of the weighted function *f*. Stress limits were defined as design constraints assuring that the optimized deck design will provide both expected riding characteristics and reliability.

The optimization variables were defined as numbers of layers in the upper and lower skins and angles with *z* axis defining main direction (direction 1) of the fiber reinforcement in each layer. To properly incorporate the results from the symmetric model, an alternating stacking sequence of composite layers was assumed.

The whole process of evaluation of deck stiffness consists of the following steps conducted for every single configuration (Fig. 9):

1. parametric generation of the FE models representing sandwich deck reinforced with different lay-up GFRC
2. analysis of two different scenarios:
   - symmetric loading
   - asymmetric loading
3. evaluation of the results
4. selection of the most effective GFRC layout.

Step 3 is different for the genetic algorithm and RSM.

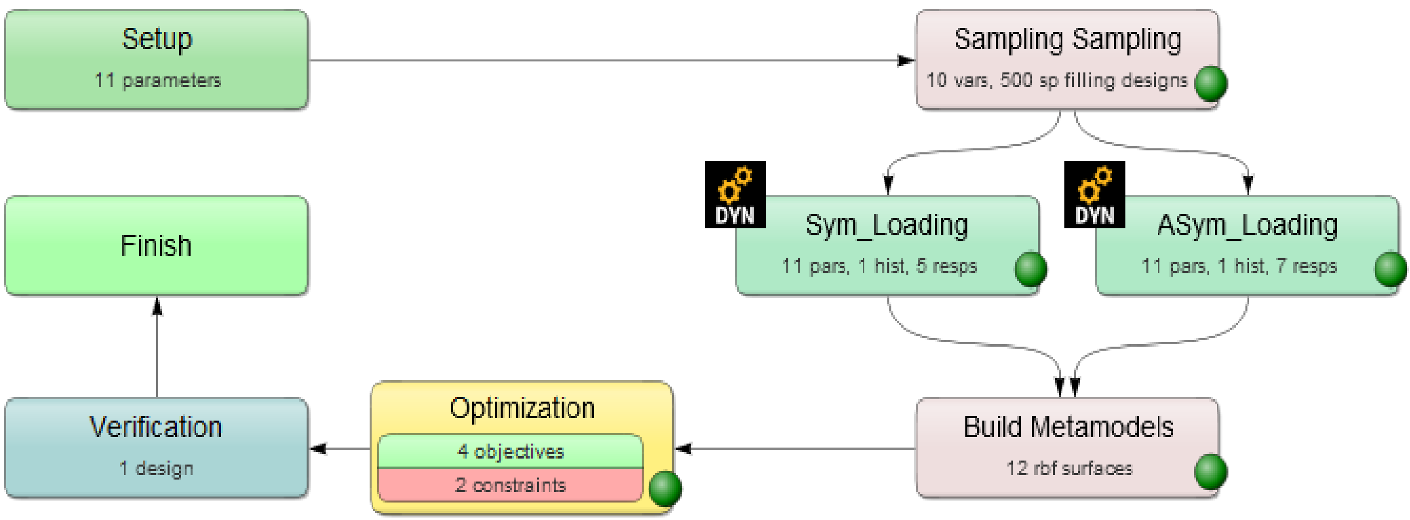

Fig. 9. Optimization procedure.

2.2.3. Optimization results – genetic algorithm

To make sure that the optimization results are consistent, authors decided to conduct simple sensitivity study. Firstly, optimization analysis was run with four variations of starting population size. This allowed to check the stability of the results (i.e. ability to find the same optimum) with respect to size of the first generation of decks. Convergence of function *f* for all four cases is shown in Table 4 and in Fig. 10. The results show that a population size equal to 200 is enough to make sure that analysis will find desired local optimum.

Table 4. Results of the analysis using genetic algorithms with different populations sizes.

First population size, GA	*m (kg)*	*d (mm)*	σ_{1max} *(MPa)*	σ_{2max} *(MPa)*	*f*
100	0.484	9.10	83.9	123.1	0.501
150	0.484	9.09	85.0	126.1	0.506
200	0.484	9.11	81.0	118.9	0.495
250	0.484	9.11	81.0	118.9	0.495

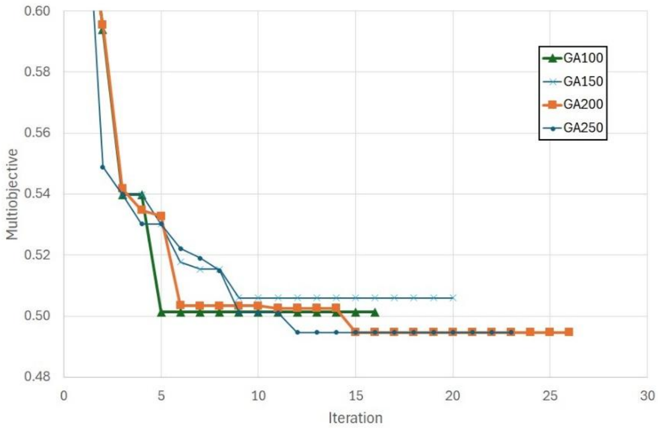

Fig. 10. Change of value of function f against number of iterations for different sizes of starting population.

In the next step authors verified if the assumed overall thickness may be seen as optimal starting value.

presents optimization results for thickness of the deck equal to 15 mm, 20 mm, 25 mm, and 30 mm respectively. It should be noted that the overall thickness of the deck was not included in the optimization analysis as a design variable. Decision about this parameter involved other aspects of the scooter design and can be seen as an "engineering decision" not to be driven by results of numerical analysis only.

Table 5. Results of the analysis using genetic algorithms with different initial deck thickness.

Thickness (mm)	*m (kg)*	*d (mm)*	σ_{1max} *(MPa)*	σ_{2max} *(MPa)*	*f*
15	0.997	9.10	51.9	62.4	0.642
20	0.484	9.11	81.0	118.9	0.495
25	0.382	9.08	109.6	156.5	0.527
30	0.554	9.22	48.3	97.5	0.490

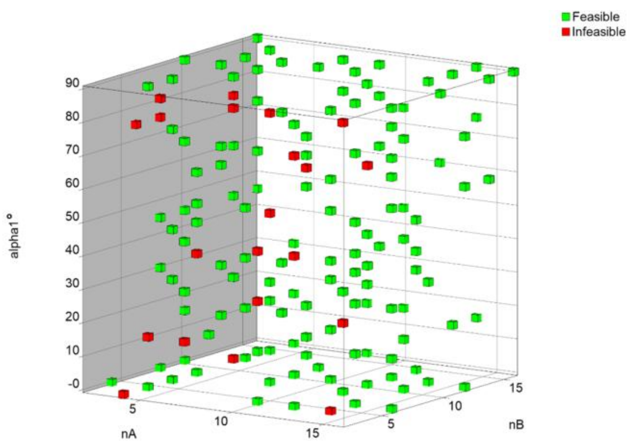

Fig. 11. Design points generated by optimization algorithm for 25 mm thickness case (in infeasible cases, the stresses are too high for the strength of the material).

It can be seen that the minimum value of the function *f* was obtained for the thickness 30 mm, while the minimum weight of the deck was achieved for 25 mm thickness. To visualize the number of data used in optimization process Fig. 11 shows sampling (design) points in the space: number of number of top layers (*nA*) – number of bottom layers (*nB*) – angle of the fibers in the first layer of the top skin (*alpha1*) obtained for the optimization process of 25 mm thickness deck.

2.2.4. Optimization results – RSM algorithm

Generally speaking, the idea behind RSM approach is to find a function describing response of the objective to the change of design variables. Once the function is found, it is assumed that extreme of this function within the decision space makes the solution of the optimization problem.

In the presented paper, once the decision space is determined, Space Filling algorithm is used to define sampling points that will be used to find response surface. The Space Filling algorithm used in the analysis randomly moves the design points so as to optimize the maximin distance criterion using so called simulated annealing [37]. The number of design points used to interpolate response surface was set to 500. The result of the optimization is presented in Table 6. In the first row the minimum solution derived from interpolated RSM is shown. The second row shows results representing one of the design points calculated during the annealing stage that lays outside the finally calculated response surface. It can be seen that this point can be interpreted as the local minimum that was omitted by the algorithm, i.e. it does not lay on the interpolated response surface. Fig. 12 shows interpolated response surface in a particular three-dimensional case in the space *nA*, *alpha1* and σ_{1max}. Fig. 13 shows displacement for different designs generated by RSM algorithm.

Table 6. Results of the optimization analysis using RSM.

Case	*m (kg)*	*d (mm)*	σ_{1max} *(MPa)*	σ_{2max} *(MPa)*	*f*
RSM 500	0.758	9.50	110.0	131.3	0.783
Local minimum	0.484	8.98	94.4	139.8	0.564

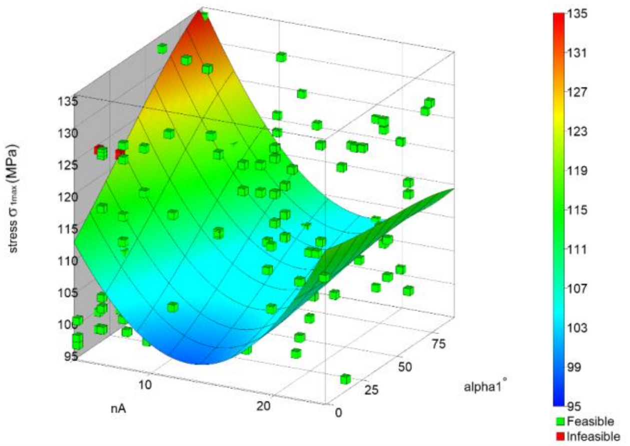

Fig. 12. Response surface developed by optimization algorithm.

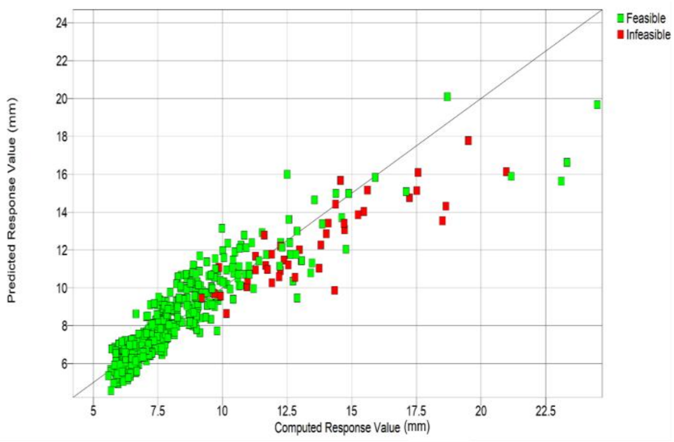

Fig. 13. Displacement of different deck lay-ups created by RSM algorithm.

3. Results, discussion and conclusions

The presented article, builds upon the findings of reference [13] by proposing an innovative approach to the design of an electric scooter deck, aimed at eliminating traditional suspension systems while ensuring ride comfort, stability, and reliability.

The main objective of the paper was to develop an effective multi-variant numerical-experimental method for optimizing the board, considering the actual course of operational loads acting on the structure, different load patterns and different types of materials. The practical aim of the work was to reduce the mass of the scooter, simplify the mechanical design for easier maintenance and improve overall durability.

The first part of the work was an experimental campaign using a scooter without suspensions, equipped with rectangular-shaped decks made of different materials and driven on a test track. Several parameters measured during the ride made it possible to assess the stability and comfort of the ride, in particular the forces discharged on the deck. It turned out that riding comfort is inversely proportional to deck stiffness, while the dependence of riding stability on deck stiffness is proportional. The overall result of the experimental campaign was that a deck made of bamboo provided the best compromise, considering the combination of comfort and stability.

The second stage of work was devoted to the development of an optimized platform tailored for the LEONARDO microvehicle. To replicate the favorable properties of bamboo while enhancing structural reliability and longevity, a fiber-reinforced composite (FRC) deck with a PVC core was designed. A multi-objective optimization approach was employed to determine the optimal layering and fiber orientation of the reinforcement. Two optimization methodologies—Response Surface Methodology (RSM) and Genetic Algorithm (GA)—were applied, with GA yielding superior results in achieving an optimal design. RSM method failed to find a really optimal solution. Even during the response surface search stage, algorithm was able to find design solution that improved the objective function by 28% compared to the solution finally chosen as optimal by the RSM algorithm (minimum point of the interpolated response surface).

In contrast, Genetic Algorithm-based optimization yielded a more efficient solution, with superior mass reduction and improved stress distribution. The final optimized deck retained similar stiffness to bamboo but with a significantly lower mass (0.4 kg vs. 0.6 kg), achieving a lightweight yet robust structure. The structural reliability of the solution was ensured by incorporating stress limits as design constraints.

The value of the response function f is the lowest for the deck of 30 mm thickness. On the other hand, the lowest mass was obtained for the 25 mm deck thickness. Value of multi-objective weighted function in this second case is higher due to higher stress values, which, however, does not cross defined constraints. Therefore, it was decided to favor the mass parameter and adopt the solution with a thickness of 25 mm. Running optimization cycles for different thicknesses actually expanded the range of possible optimal solutions, which allowed for greater flexibility and was a great help in choosing the final design solution.

The chosen optimal deck layout is shown in Fig. 14. The displacement of the deck for the symmetrical case is presented in Fig. 15. The deflection value of 8 mm translates into 32% of the deck thickness and therefore can be considered as acceptable. Stress component for symmetric and non-symmetric case can be seen in Fig. 16 and Fig. 17 respectively. The area of maximum stress for both cases is at the point of constriction of the deck, where there is a sharp reduction in its cross section. At the same time, this is the place where the greatest bending occurs. In other words, the maximum stresses appear in the area where they would be expected, which is another indicator that the obtained results are correct.

The stresses in the core material (PVC) are negligible, reaching no more than 8 MPa for the asymmetric case.

This also shows that from a mechanical standpoint, the composite deck successfully distributed loads, ensuring its durability under operational stresses. The maximum stress regions aligned with expected critical points, validating the numerical model. Importantly, the core material (PVC) played its intended role as a spacer, while the composite shells bore the primary bending loads, demonstrating a well-optimized load-bearing structure. Results indicate that the optimal deck withstands the applied loading. Given that the load value has been defined taking into account the dynamic overload, it can be concluded that the proposed optimal system will also withstand normal operating conditions.

The findings of this study confirm that removing traditional suspension elements does not compromise vehicle stability or comfort, provided that the deck is carefully designed and optimized. This low-maintenance architecture significantly reduces mechanical complexity, making servicing easier and more cost-effective over the vehicle's lifespan. Moreover, the optimized deck enhances reliability by minimizing stress concentrations and ensuring long-term durability under real-world dynamic conditions.

The present work is the first in the scientific literature to propose a comprehensive optimization framework for designing an electric scooter deck that replaces suspension systems while maintaining performance standards. The methodology integrates road testing, numerical simulation, and multi-objective optimization, offering a novel approach to micromobility design.

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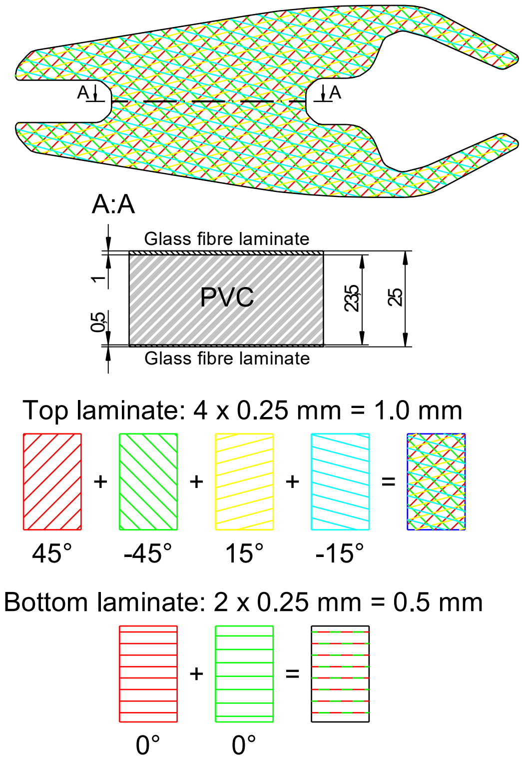

Fig. 14. Chosen optimal lay-up of the deck.

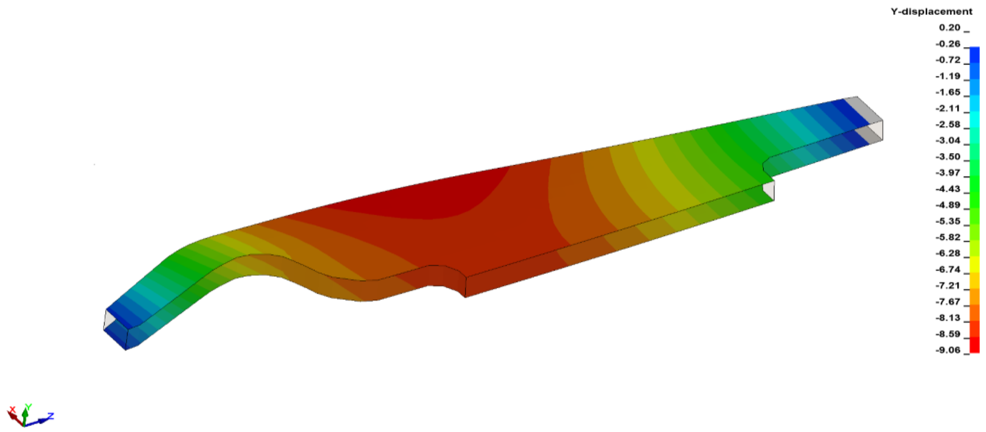

Fig. 15. Vertical displacement in mm of the deck with chosen optimal lay-up (symmetrical case).

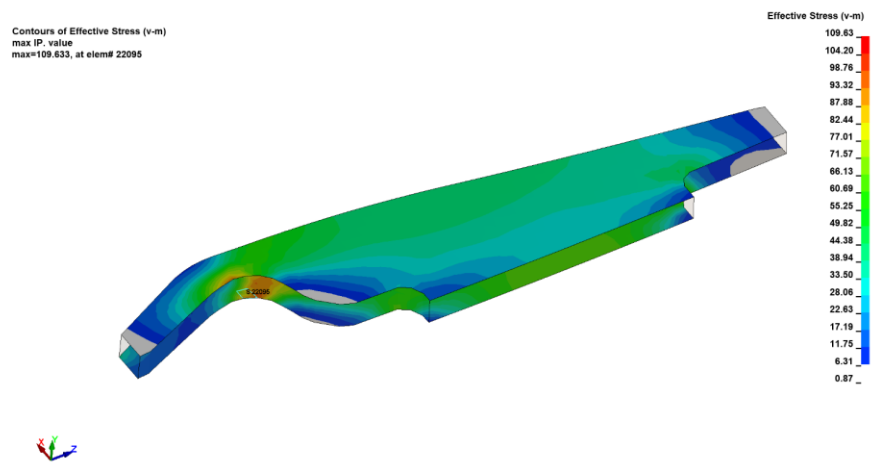

Fig. 16. Equivalent stress component in MPa of multi-objective function of the deck with chosen optimal lay-up – symmetric case.

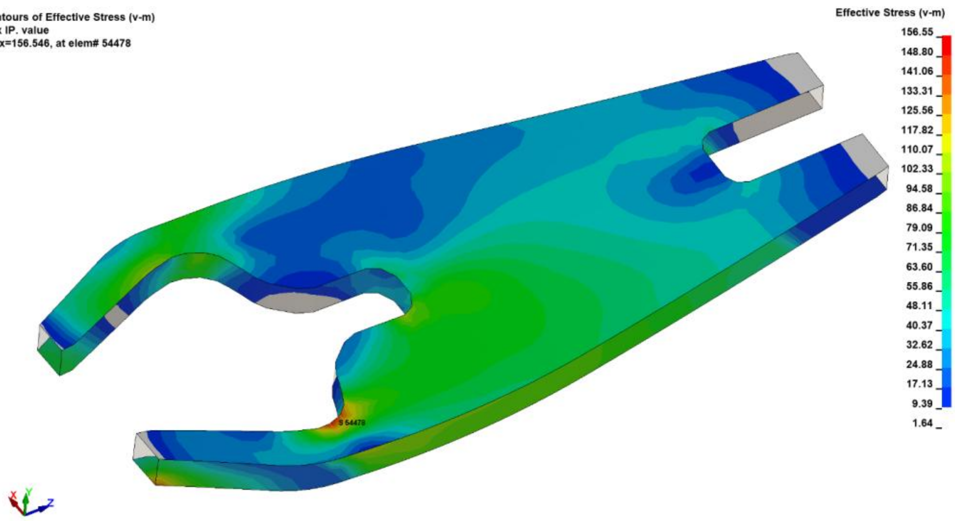

Fig. 17. Equivalent stress component in MPa of multi-objective function of the deck with chosen optimal lay-up – non-symmetric case.

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