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RESEARCH ARTICLE

FEA analysis and optical measurement of city bus composite floor structure

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Abstract: Polymer composites have various application in a automotive industry. Achieving vehicle efficiency in public transportation, among other goals, is often done by lightweight materials like fibre reinforced plastics as structural elements of the vehicle. A concept solution for a V shaped structural floor element of a city bus is proposed in this paper. CAD model of floor structural element has been designed from which, in later phases, construction of complete composite floor will be optimized and designed. Test sample made of hybrid (carbon and glass) fibre composite was produced and tested under the flexural load for comparison with a FEA model. Test sample displacement was measured using a GOM Tritop optical measurement system. Comparison showed that difference between real measurement and FEA for maximal displacement is only 11.7%.

Keywords: carbon fibre, flexural displacement, FEM, glass fibre, hybrid composites, optical measurement

1. Introduction

Weight reduction and improvement in efficiency in public transport vehicles can be achieved with the application of composite materials. Composite materials are widely used for parts of the interior such as passenger seats[1] or side walls [2] but also they can be used for structural elements of the vehicle body such as side panels and superstructure profiles [3,4]. Potential to reduce weight in the chassis has been recognized by several leading bus manufactures in the last few decades [5,6].

Penetration of electric drive systems, driven by environmental concerns, results in additional weight of the vehicles due to battery systems having relatively low specific energy capacities. Possible solution to that challenge is a complete composite monocoque chassis in addition to other composite parts[7,8]. Additionally, application of lightweight composite materials in electric vehicles could improve performance in terms of vehicle range and battery size containment [9]

Such an approach has been used in the development of a modular electric low floor city bus. In this paper, concept of lightweight composite structure as a part of vehicle superstructure is considered in which conventional steel frame floor structure was replaced with the hybrid composite material (Figure 1). As a part of the design process application of modern measuring techniques like optical measuring was used for verification of CAD design and FEM calculation results.

2. Methods

2.1. V-shaped structural element model

Proposed lightweight composite vehicle floor, as a part of the supporting structure, consists of an upper and a lower plate which are joined by V-shaped structural elements that form a honeycomb-shaped reinforcement as shown in Figure 2.

Design of structural element in V-shape was chosen because it enables different ways of forming the entire structure and allowing various profile combinations to be considered in the following design stages. For such profile, first, a CAD model was made, which was also used for FEM calculations (Figure 3). FEM analysis was made in *Autodesk Inventor Professional 2022*. For analysis, following boundary conditions in the supports were used: only rotation in the x-axis direction is allowed, while other are constrained. Regarding translations, one support was set as fixed, and another allows translation in the z-axis. Material was set as isotropic and five different load cases (from 200 to 1000 N) were analysed.

In this early phase of design, the properties of only that

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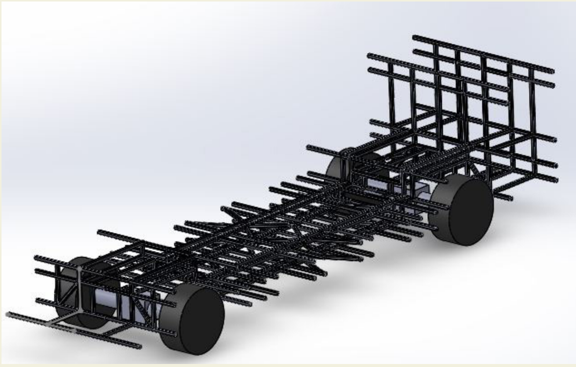

a)

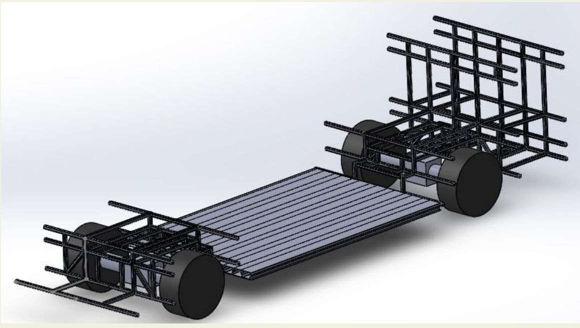

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Figure 1. Conventional steel frame (a) and composite passenger carrying module (b)

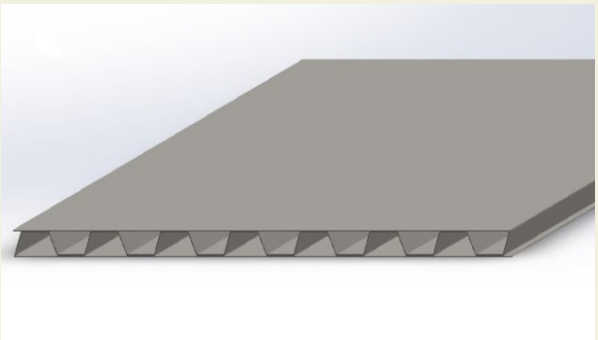

Figure 2. Floor panel with V shaped structural floor element

one element will be analyzed, and in the later phases, the design of that element and the entire composite floor will be optimized to obtain the appropriate strength and rigidity with the lowest mass possible. In addition to the design, in the process of optimization, as influencing factors type of composite, stacking and thickness of the composite will be considered.

2.2. Profile production

Glass fibre composites, due to the relatively low cost, are commonly used for production of vehicle body parts, while the carbon fibre composites are used for the parts requiring high strength-to-weight ratio and rigidity. Hybrid composite made of glass and carbon fibre can be an optimal solution due to appropriate mechanical properties and acceptable costs.

Such hybrid approach was also applied for production of V shaped structural element (profile), where polyester resin reinforced with 5 layers of biaxial carbon fibre and three-axial glass fibre woven fabric and a glass mat were used. Hand lay up lamination has been chosen as a production method for economical and practical reasons. Lay-up of a hybrid laminate is shown in Figure 4. The outer layers of the laminate are carbon fabric, and the middle is glass fabric, while two layers between the outer fabric and the middle layer are made of glass mat.

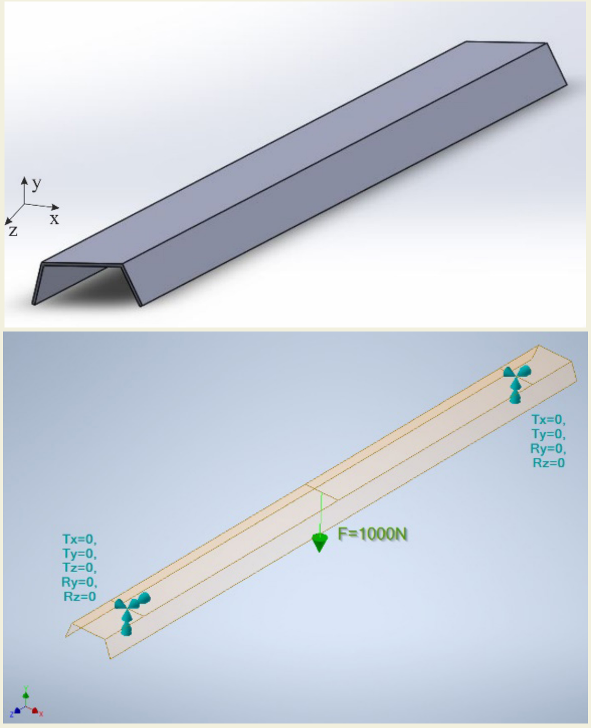

Figure 3. V shaped structural floor element CAD (left) and FEM model (right)

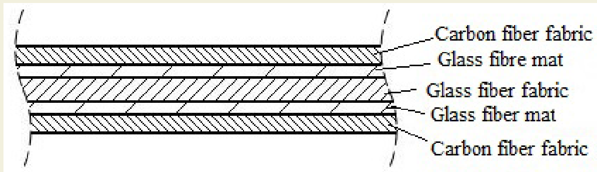

Figure 4. Structure of the profile laminate

Metal mould was used for the production of specific V shape. Thickness of the laminate structure was around 3 mm. Due to technological reasons and resin wet lay up time (45 min), production length of the profile was 2000 mm, width 150 mm and height 50 mm. From the end part of the profile, in length of 250 mm, samples for flexural tests were machined. Final length of the profile was 1750 mm. Production process and finished profile are shown in Figure 5.

2.3. Measurement method

Optical measurement methods are used for deformation and displacement measurements on a large scale objects made from composite materials [11,12]. As they offer non-destructive, practical, and precise measurements they

a)

b)

Figure 5. Production process (a) and finished profile (b) [10]

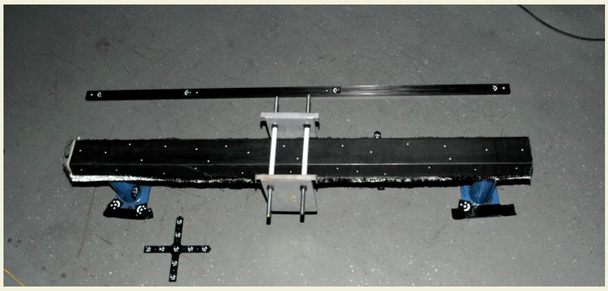

Figure 6. Measurement test set up (load of 200 N)

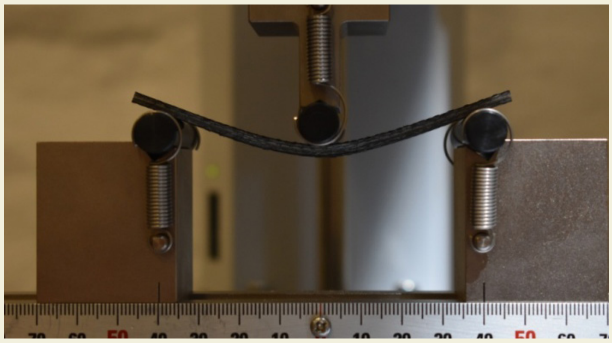

Figure 7. Flexural testing of the hybrid composite test specimen

are applicable for evaluation of parts behaviour as well as quality control.

Optical measurement method was used to determine the behaviour of the profile under the load. Steel weights were used to simulate the load generated by passenger standing in the centre of the profile, while the profile was supported at the ends by two supports. The test set up was constructed to be similar to the mechanical model of a beam with two supports to enable the verification of the obtained results by the analytical method. GOM Tritop optical measurement system was used for measurements. Test procedure was carried out with the progressive load in 5 stages (200, 400, 600, 800 and 1000 N) while the unloaded state was used as reference.

GOM Tritop system uses triangulation principle to determine the coordinates of the measurement points glued on the object (black and white round stickers shown in Figure 6). The position and size of the object is defined with reference points (coded points) on scale bars and reference crosses. Using a photogrammetric camera GOM software creates a cloud point for each load stage and can compare the displacement of the points. Camera focal length is constant for each stage while the effect of the environment temperature (22 °C) is taken in account in pre-measurement set up and calibration process before each stage.

2.4. Determination of flexural properties

Flexural properties required for analytical and numerical evaluation have been determined by the three point flexural test on a *Shimadzu AGS-X* universal testing machine in accordance with the standard HRN EN ISO 14125:2005 [13]

Testing procedure, shown in Figure 7, was carried out at 23 °C and 49 % humidity. Testing speed was 2 mm/min, support rollers radius was R_2= 5+/-0,2 mm and pressure roller radius R_1= 5+/-0,2 mm. Distance between support rollers was L = 80 mm. In total 4 test specimens were machined from the profile and tested to determine flexural modulus needed in analytical and numerical calculations. Dimension of the test specimen was from standard 100 x 15 x 4 mm.

3. Results and Discussion

After all measurements with different loads were done, measurement data was analysed by *GOM TRITOP Professional V7.5 SR2* software. From analysed, dependence of the vertical displacement in the middle of the profile on the applied force was obtained. Vertical displacement distribution on the profile under series of loads are analysed after the measurement and shown in Figures 8-12.

For every load case measured with optical measurement system, FEM calculation with the same boundary conditions was made. Simplified mechanical model with a concentrated vertical force was used to describe load behaviour of a passenger standing in the middle of the profile. Since vehicle structure is still in early design phase additional loads could not be taken in account, but all assumptions made are overestimation of sort and re-evaluation of the concept is expected to have better results in terms of mechanical response of the floor structure as a whole. Although real measurements are taken with

Figure 8. Displacement distribution under the 200 N load measured with *GOM Tritop*

Figure 9. Displacement distribution under the 400 N load measured with *GOM Tritop*

Figure 10. Displacement distribution under the 600 N load measured with GOM Tritop

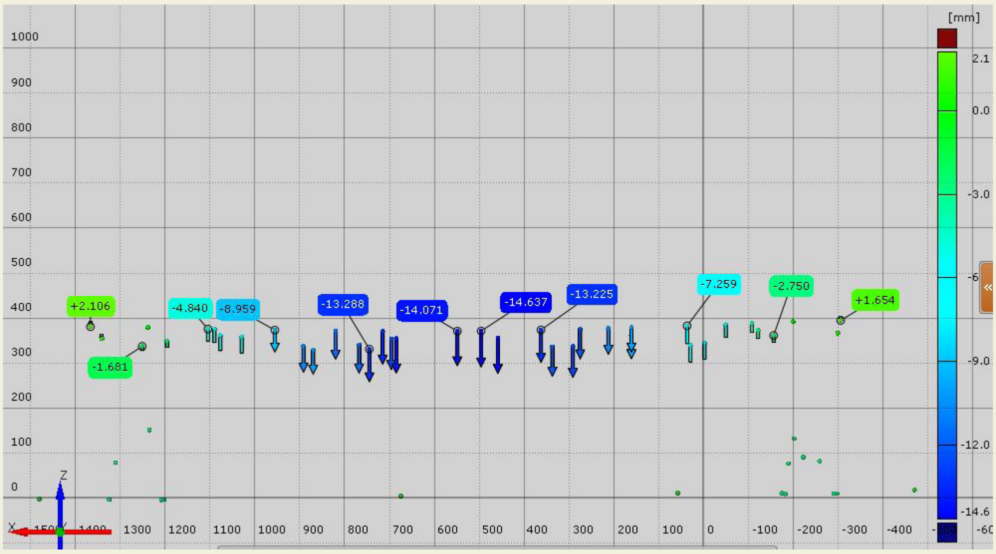

Figure 11. Displacement distribution under the 800 N load measured with GOM Tritop

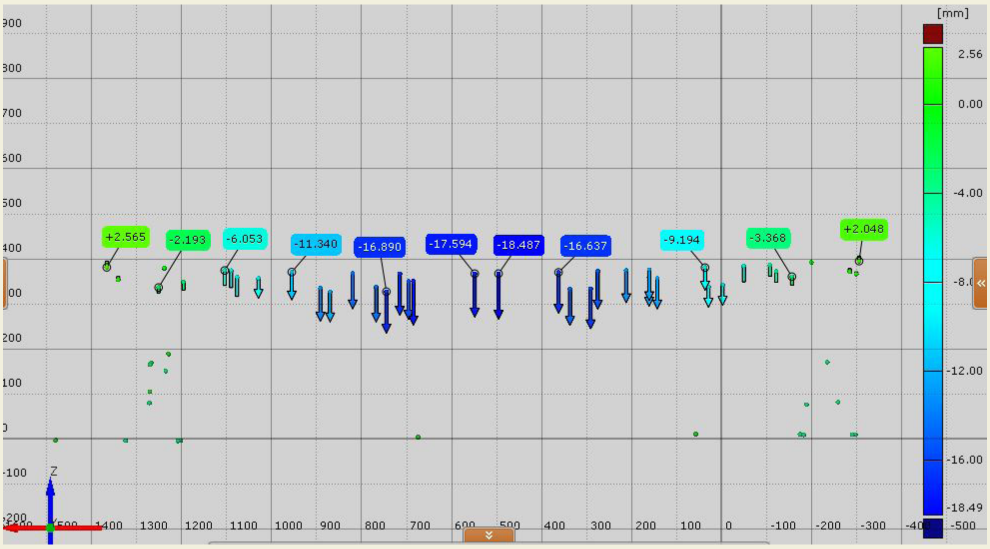

Figure 12. Displacement distribution under the 1000 N load measured with GOM Tritop

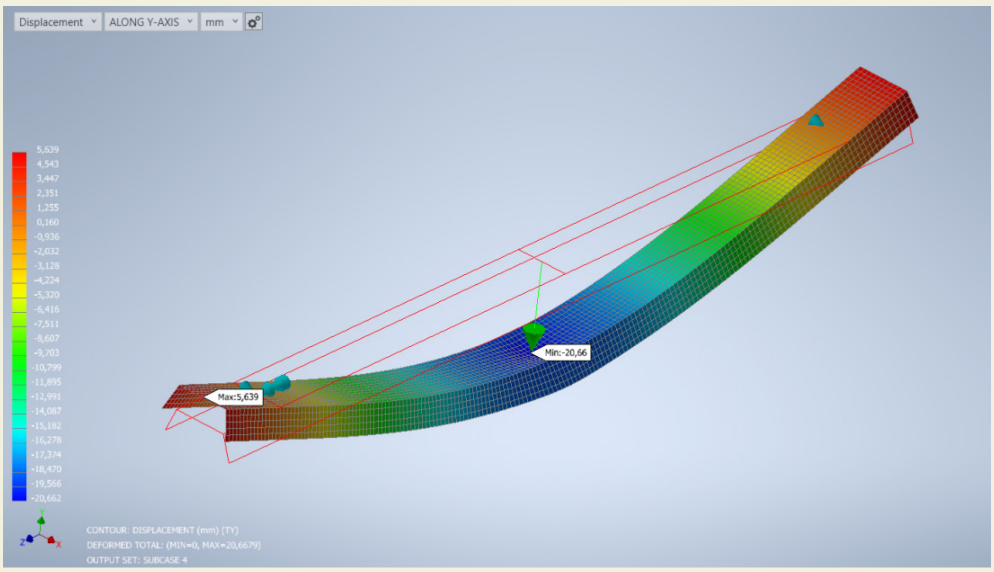

Figure 13. Displacement distribution in FEM under the 1000 N load

weights with two struts for practical reasons there is a neglible difference between the case in reality and one concentrated force used for FEM model. Vertical displacement distribution on the profile under the load of 1000 N calculated with the FEM is shown in Figure 13. From the figures, it can be concluded that both forms of distribution show the shape of a conventional distribution of displacement in a beam with two supports which was expected. In both cases, the results of the vertical displacement along the profile between the support match relatively well. Only deviation in the vertical displacement occurs at overhangs at the ends of the profile, which may occur due to the support difference in the real profile and the FEM model.

As a final part of result analysis, both, measurement, and FEM method were compared with the analytical values calculated by conventional engineering methods using equation:

$$w = \frac{F \cdot L^3}{48\, E_f\, I} \tag{1}$$

Where: F – force load, N

L – profile length, mm

E_f – flexural modulus, N/mm^2

I – moment of inertia, mm^4

Length of profile beam between supports was 1500 mm. Moment of inertia of 168,867 mm^4, determined from the CAD model and flexural modulus of 23,119.7 N/mm^2, as a mean of measured values, were used for calculations. The results of the flexural modulus of all four test specimens with mean value and standard deviation are shown in Table 1.

Table 1. Flexural modulus results

No.	Flexural modulus, N/mm^2
1	23,798.6
2	22,766.1
3	23,179.9
4	22,734.0
	23,119.7
S	496.1

Table 2. Vertical displacement values results

Load F [N]	Vertical displacement w, mm			Deviation to measurement, %	
	Measurement	FEM	Analytical	FEM	Analytical
0	0.00	0.00	0.00	0.00	0.00
200	4.43	4.13	3.60	-6.77	-18.74
400	7.83	8.27	7.20	5.62	-8.05
600	11.55	12.4	10.81	7.36	-6.41
800	14.50	16.5	14.41	13.79	-0.62
1000	18.49	20.66	18.01	11.74	-2.60

Vertical displacement results as a function of force, measured with *GOM Tritop* optical system, calculated with FEM and analytical method are given in Table 2 and shown in Figure 14.

Comparing the results of FEM analysis and measurement it can be concluded that the FEM model is on the safety side, since the calculated displacements are higher than measured (except for the 200 N load). In that sense, real composite beam is stiffer than the calculated with the FEM.

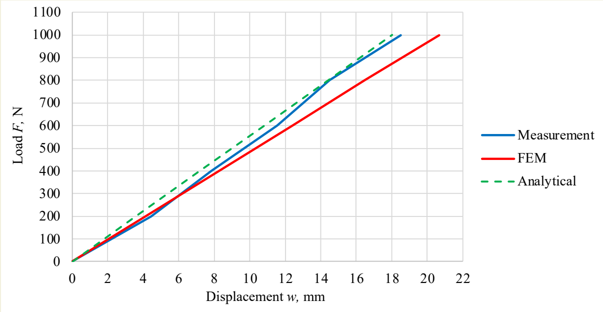

Figure 14. Load-displacement diagram

4. Conclusion

Optical measurement has shown to be reliable method to evaluate mechanical behaviour of structures which is a great advantage at an early stage of the product development. This analysis also showed that lightweight composite materials can be used as structural elements in vehicle design. Real displacement values range between analytical and numerical values which confirms that FEM calculations as well as optical measurement methods are reliable.

Displacement values, measured by optical measurement method, differ slightly from the values calculated with FEM and analytical methods. Comparison showed that the difference in results between real measurement and FEM calculation in vertical displacement under the maximal load is only 11.7%. Precision of methods and calculations as well as assumptions regarding the isotropy of the materials made for FEM can be potential cause of these differences.

5. Acknowledgements

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