THE INVESTIGATION OF MECHANICAL BEHAVIOUR OF CYLINDRICAL STRUCTURES COMPRISING SANDWICH FIBRE REINFORCED PLASTIC COMPOSITES

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Abstract
A methodology for the investigation of stiffness and strength of cylindrical structures made of sandwich composite with facesheets made from glass fibre and polyvinylester resin and a core made from recycled paper hexagonal honeycomb impregnated with polyvinylester resin was deduced. Using this methodology, the finite element method and an experimentally validated model of an annular section of a hollow cylinder the optimal geometrical arrangement of stiffness elements which ensures the stiffness and strength properties with the largest efficiency of fibre reinforced plastic volume usage was determined.

1. Introduction

Sandwich fibre reinforced plastic (FRP) composites are a frequently used material in various applications. Besides the fact that they are widely used in the aviation, transport, marine and other similar industries due to the extremely high flexural stiffness to weight ratios and flexural strength to weight ratios [1,2,3], they have become more prevalent in civil engineering applications where the low weight and high structural performance are also needed [4,5,6].

A great deal of work has been published on the behaviour of sandwich composites with a honeycomb core. The authors of this study recently investigated the impact and quasi-static behaviour of woven glass FRP sandwich composites containing a hexagonal polypropylene honeycomb core [7,8,9].

The determination of the optimal geometrical parameters which ensure the stiffness and strength of various structures with the largest efficiency of material volume usage is a very real problem not only due to the high cost of materials but also due to the requirement of developing environmentally friendly technologies.

Stiffness elements are often used for cylindrical steel constructions with the intention of increasing the stiffness and strength of structures without increasing of wall thickness of cylinder. The arrangement of such stiffness elements is clear because it is defined by standards (ISO 16528, EN 13445, EN 14015). Recently, non-metallic cylindrical structures, made from various composites are often used. The use of stiffness elements in such structures could also help to reduce the volume of composite materials but the arrangement of stiffness elements for these structures is not defined by standards.

The object of the investigation was cylindrical structures made of sandwich composite with facesheets made from filament wound glass fibre and polyvinylester resin (FRP) and a core made from recycled paper hexagonal honeycomb impregnated with polyvinylester resin.
The aims of the study were: to find out a methodology for the investigation of the stiffness and strength of hollow cylindrical structures; to determine the optimal geometrical arrangement of stiffness elements which ensures the stiffness and strength properties with the largest efficiency of FRP volume usage.

2. Materials and tests

The sandwich structure presented in Figure 1 was used for experimental investigation.

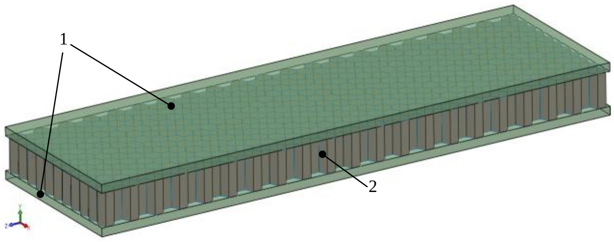

Figure 1. Sandwich structure used: 1 –glass fibre and polyvinylester resin composite facesheets; 2 – recycled paper hexagonal honeycomb impregnated with polyvinylester resin core

The facesheets were fabricated from glass fibre and polyvinylester resin. In order to determine the mechanical properties of separate sandwich components the sheet of glass FRP comprising of one ply glass filament and polyvinylester resin was cured. The average thickness of sheet was 1.0 mm. The glass FRP was also tested in compression. For this, the sheet of thickness of 10 mm comprising 10 plies of glass filament was cured. Testing was performed according to applicable standards.
A recycled paper hexagonal honeycomb impregnated with polyvinylester resin was used for the sandwich core. The height of honeycomb was equal to 10 mm. The shear and compression tests of honeycomb were performed according to applicable standards.
All used tests were run at room temperature and a rate of loading 2 mm/min using the universal testing machines with load cell of 10 – 100 kN and the measuring system HBM (Hottinger Baldwin Messtechnik GmbH) which consisted of displacement and force transducers, a four channel measuring amplifier SPIDER-8 and a computer with CatmanExpress software.

3. Verification of numerical models

Using the obtained data for materials properties, a numerical FE model which defined a hollow cylinder of internal diameter D_c = 600 mm and width b_c = 196 mm, was designed. The wall of cylinder was defined as sandwich FRP composite with a honeycomb core. The facesheets had three layers; the laminate code was [90 / ±65]. The layers of angle of ply equal to 90 ° and ±65 ° had thickness of 0.9 mm and 1.5 mm, respectively. The total thickness of the facesheet was equal to 3.9 mm. According to the Laminate theory [10] the materials properties of laminate in axial and hoop directions were calculated. It was found that E_{fx} = 27.7 MPa, E_{fy} = 8.76 MPa, G_{fxy} = 9.83 MPa, ν_{fxy} = 0.47. The thickness of core was equal to 10 mm.

To verify the model, an experimental test according to ISO 9969 standard was performed. Six rings of the same dimensions and materials as in the model were made and tested using the universal testing machine and the measuring system HBM. In both the numerical and experimental investigations the same compression loading conditions were used. The constant deflection δ equal to 18 mm was applied. This value of the deflection satisfies the requirement to use a deflection equal to 3 % of ring diameter. The force F_{exp} was measured and compared to F_{FE} calculated by FE modelling. The model was verified to 10 % accuracy. The results of testing are presented in Table 1. Accordingly, this model was used for further numerical investigations of the influence of the arrangement of stiffness elements on the annular section stiffness and strength, with effective usage of the facesheet material volume.

Test	**δ, mm**	**F_{exp}, N**	**F_{FE}, N**	**Difference, %**
1	18	4.4	4.7	7.3
2	18	4.2	4.7	12.4
3	18	4.1	4.7	15.1
4	18	4.5	4.7	4.9
5	18	4.2	4.7	12.4
6	18	4.3	4.7	9.8
Average				**10.3**

Table 1. Testing and finite element modelling results

4. Methodology for investigation of stiffness and strength of cylindrical structures

This methodology allows investigation of the stiffness and strength of cylindrical structures and determination of the optimal geometrical arrangement of stiffness elements which ensures the stiffness and strength properties with the largest efficiency of FRP volume usage. The methodology is based on the calculation of particular coefficients. These coefficients can be defined as followed

$$k_V = \frac{\text{FRP volume of cylinder with stiffness elements}}{\text{FRP volume of cylinder of the same thickness as stiffness element}}, \quad (1)$$

$$k_\delta = \frac{\text{deflection of cylinder with stiffness elements}}{\text{deflection of cylinder without stiffness elements}}, \quad (2)$$

$$k_\sigma = \frac{\text{stress of cylinder with stiffness elements}}{\text{stress of cylinder without stiffness elements}}, \quad (3)$$

were k_V, k_δ and k_σ are the FRP volume, deflection and stress coefficients, respectively.
The verified FE model of the annular section of cylinder was used. The diameter of cylinder D_c was constant and was equal to 2500 mm. The facesheets thickness and core thickness were also constant. The length of section L, which is equal to the length between adjacent stiffness elements L_{SE}, were changeable and varied in a range $L = 500 \div 4500$ mm. Two types of cylinder models were used: one with stiffness elements in the ends of section and the other without. The width of the stiffness element was equal to 100 mm.

5. Results

Figure 2 shows the dependences of FRP volume, deflection and stress coefficients upon section length. The volume coefficient decreases as the length of cylinder increases. From eq. (1) and the defined geometry of the cylinder it seems that if the cylinder has the length of 200 mm the volume coefficient is equal to one. As the length of cylinder is 500 mm the volume of FRP decreases in half. As the length of cylinder increases up to 1500 mm the influence upon the FRP volume decreasing is not significant. The stresses and deflections of the cylinder increase as the length increases. For the length of 1500 mm calculated stress was 60 % less than for a cylinder without stiffness elements. The same result was found in the case of stiffness; the deflection was 30 % less. As the curve of the deflection coefficient dependence is below the curve of the stress coefficient, an effective arrangement of stiffness elements can be defined according to volume and stress coefficients. The point at which the stress and volume coefficients curves cross shows the value of the length L_{SE} between two adjacent stiffness elements. This length ensures the optimal value of the three parameters: the high stiffness and strength and the minimal FRP volume. This point is obtained when the L_{SE} = 1134 mm. It is about 70 % of the FRP volume is saved, the stress is 70 % and deflection is 90 % less than in the case of a cylinder without stiffness elements.

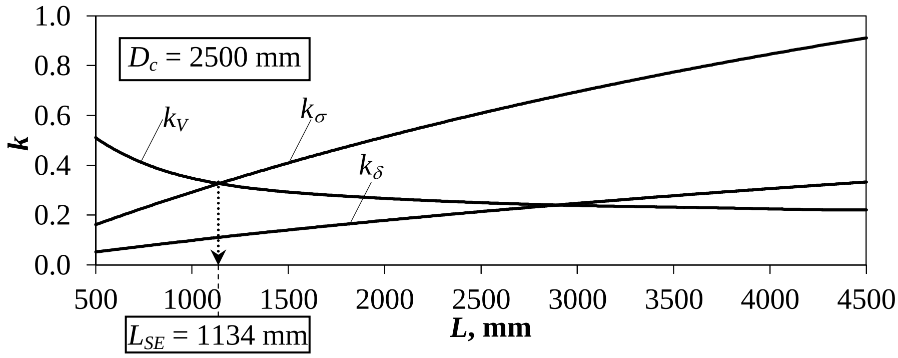

Figure 2. The dependences of FRP volume, deflection and stress coefficients k_V, k_δ and k_σ upon section length and the determination of the optimal geometrical arrangement of stiffness elements

6. Conclusions

An analysis of the strength and stiffness of hollow cylindrical structures comprising sandwich fibre reinforced plastic composites was carried out.

The materials of the separate components of sandwich structures were tested and the mechanical properties of them were determined. Using experimentally obtained data of materials properties, the numerical FE model of a sandwich structure comprising facesheets from wound glass fibre and polyvinylester resin and a core from recycled paper hexagonal honeycomb impregnated with polyvinylester resin was designed. The numerical FE model of an annular section of cylinder was designed and verified by the standard test of annular section measuring applied force. Accuracy of 10 % was also reached for the annular cylinder model.

On the basis of the verified hollow cylinder model, a methodology for investigating strength and stiffness was created. This methodology allows determination of the optimal geometrical arrangement of stiffness elements which ensures the stiffness and strength properties with the largest efficiency of FRP volume usage.

The presented methodology can be used also for other purposes such as for other loading conditions and structures.

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