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TESTING GLASS FIBRE REINFORCED POLYMER BEAMS FOR THEIR DYNAMIC PROPERTIES

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Abstract. *Glass Fiber Reinforced Polymer (GFRP) is a modern construction material characterized by high strength, corrosion resistance, and significantly lower self-weight compared to steel. These properties make it an attractive alternative to traditional structural solutions, particularly in applications where reducing the weight of the structure is advantageous. At the same time, lightweight elements may exhibit increased susceptibility to vibration, which makes the analysis of their dynamic behavior essential for evaluating the practical applicability of such materials. The aim of this study was to determine the dynamic properties of GFRP beams and to verify the parameters adopted in the numerical model by comparing the results of modal analysis with experimental data. Numerical simulations were performed in RFEM 6 and ABAQUS, while experimental studies were carried out using a non-destructive impulse excitation test with a modal hammer. The obtained results enabled the identification of natural frequencies, mode shapes, and the assessment of the level of agreement between the numerical model and the actual behavior of the tested beams. The presented findings form the first stage of a broader research project. The next step will involve casting a concrete slab using high-performance lightweight concrete (HPLWC), connecting it with the GFRP beam, and re-evaluating the dynamic properties of the composite system.*

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1 INTRODUCTION

Glass fibre reinforced polymer (GFRP), recognised in the construction industry as an innovative material, deserves this description because, beyond the solutions already implemented in actual structures, it still holds considerable potential for further applications [1].

In addition to matching typical construction materials in terms of strength (high strength-to-weight ratio) and stiffness, GFRP stands out for its low weight, corrosion resistance, low electrical and thermal conductivity, electromagnetic neutrality, lower maintenance costs and durability [1-5].

These characteristics have resulted in the material being used in a variety of applications in the construction industry, including as prefabricated profiles, structural components, concrete reinforcement, external cladding, swimming pool equipment and footbridges [1-3, 5, 6] or even recycled GFRP as a component of concrete [7].

However, it is also important to mention the weaker aspects of GFRP, such as its low fire resistance, high coefficient of thermal expansion across the fibres, lower Young's modulus than steel, lack of plastic reserve, and low resistance to UV radiation [5]. Nevertheless, despite these characteristics, and thanks to its advantages, this material is and will continue to be widely used in the construction industry [1][2].

The aim of this study is to determine the dynamic properties of glass-fibre-reinforced polymer (GFRP) I-beams, so that in subsequent studies the beam can be combined with a reinforced concrete slab to form a lightweight composite slab element. Further investigation of the dynamic behaviour of such a structure would contribute to the development of dynamic behaviour prediction for lightweight composite floors, and consequently to the conscious design and wider application of GFRP in the construction industry. Lightweight floor slabs are frequently used in multi-storey buildings, where weight reduction is often desirable; however, a change in self-weight affects the natural frequencies of the structure which may be more sensitive to vibrations [3, 8]. This is especially important in the case of floor slabs, as their vibrations must not significantly disturb the users' comfort (serviceability limit state) [8, 9]. Similar challenges are also encountered with lightweight timber floors [10].

2 MATERIALS, METHODS AND EXPERIMENHTAL SETUP

The tested profiles were produced from glass-fibre-reinforced polymer using the pultrusion process. It is characteristic that such GFRP profiles have different material properties in the direction along and across the pultrusion direction. Table 1 below presents the basic material properties of the I 200×100×10 and I 160×80×8 I-section profiles, taken from [6]; these values apply to dry conditions and temperatures between -20°C and 60°C. The symbols 0° and 90° denote values in the longitudinal and transverse directions, respectively.

Parameter	Value 0°	Value 90°
Young's modulus E	28000 MPa	8500 MPa
Poisson's ratio ν (0°,90°)	0.23	-
Poisson's ratio ν (90°,0°)	-	0.09
Shear modulus G	3000 MPa	3000 MPa
Shear strength	25 MPa	
Compressive strength (0°)	240 MPa	70 MPa
Flexural strength (0°)	240 MPa	100 MPa
Tensile strength (0°)	240 MPa	50 MPa

Table 1: Material properties for GFRP I 200×100×10 and I 160×80×8 profiles

For the numerical analysis, RFEM 6 and ABAQUS were selected, whilst the non-destructive dynamic tests were carried out using a modal hammer (model: 086D05, PCB Piezotronics, Depew, NY, USA) and triaxial accelerometers (model: 356A01, PCB Piezotronics, Depew, NY, USA). Measurements were carried out on two GFRP I-sections I 200×100×10 and I 160×80×8, each 3 m long. On each of the profiles, on the top and bottom flanges, measurement points were marked at the centre of their width in the following locations: 10 cm from both ends, and then every 35 cm, up to the centre of the span. Nine sensors (accelerometers) were then attached to the top flange using a special wax.

Vibrations were induced by a hammer impulse in three directions as described:

- A vertical force applied with a modal hammer at the centre of the top flange, 5 cm away from the edge of the beam – vertical flexural vibration excitation (Figure 1),
- A horizontal impact with a modal hammer on the front of the beam, at the centre of symmetry of the cross-section – horizontal axial vibration excitation (Figure 2),
- A horizontal impact with a modal hammer on the side of the top flange, 5 cm away from the edge of the beam – torsional and horizontal flexural vibration excitation (Figure 3).

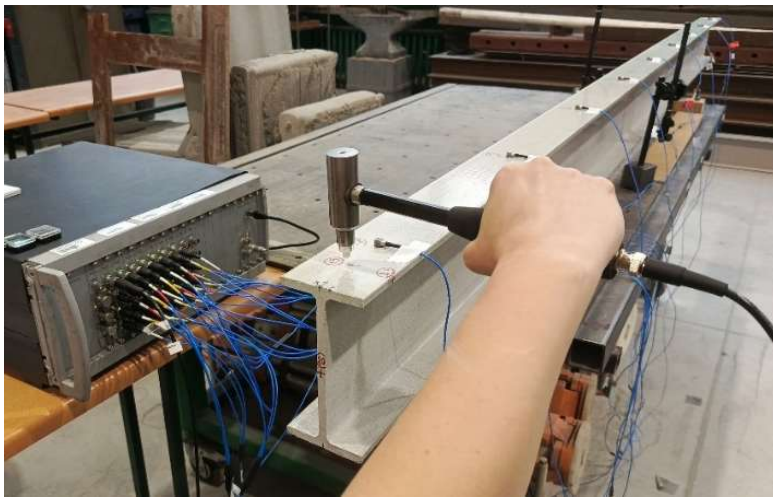


Figure 1: View of the measuring stand and vibration excitation points – vertical flexural vibration excitation



Figure 2: View of the measuring stand and vibration excitation points – horizontal axial vibration excitation



Figure 3: View of the measuring stand and vibration excitation points – torsional and horizontal flexural vibration excitation

The sensors were then transferred to the lower shelf and the test was repeated in the same manner. The signal was recorded using an LMS SKADAS III analyser.

The paper will present the results of experimental and numerical studies in RFEM 6 obtained for the I 200×100×10 profile.

In order to test 3-metre-long GFRP I-beams with cross-sections of I 200×100×10 and I 160×80×8 a test stand was constructed which consisted of a table and wooden pads rigidly secured with bolts, on which flexible supports were placed. The support spacing along the length, equal to 165 cm, was selected so that the support points of the web fell as close as possible to the zero points of the first vertical mode of vibration. In this way, two point supports were placed 67.5 cm from both ends of the beam, spaced 7 cm apart across the width. The beam was placed freely on the supports so that they were symmetrical about its centre.

The measuring equipment, a modal hammer and a computer with the appropriate software were set up. The accelerometers were connected to the equipment and attached to the beam using special wax.

3 NUMERICAL MODEL AND RESULTS

In RFEM 6, a surface model of a I 200×100×10 I-beam was created, consisting of three surfaces each with a specified uniform thickness of 10 mm, and an orthotropic material with the parameters given in Table 1 was assigned to them. The stiffness matrix was filled in manually to take into account the actual Poisson's ratio in two directions, rather than the value calculated automatically by the software.

The weight was calculated by dividing the actual mass of the element (20.39 kg) by its volume, which gave 1747.21 kg/m^3.

Spring support was introduced at the actual support points. A square mesh with a side length of 2.5 cm was used.

Figure 4 and Figure 5 show the shape of the first flexural vertical mode of vibration.

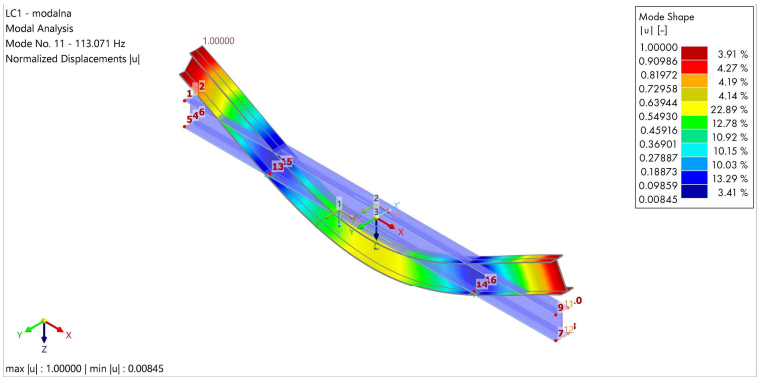


Figure 4: The first flexural vertical vibration mode obtained in RFEM 6

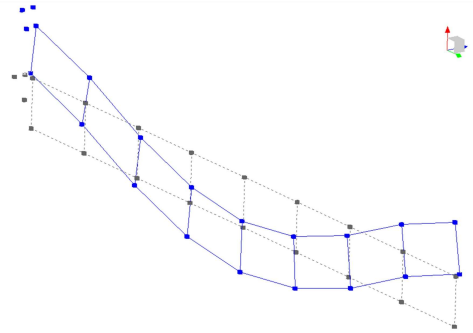


Figure 5: The first flexural vertical vibration mode as determined in experimental tests

Table 2 below summarises the experimental test results and the results from the RFEM 6 model for the I 200×100×10 beam, including the vibration mode name.. The final column compares the absolute value of the difference in natural frequencies with the actual results. The relative error Δ was calculated using equation (1) and expressed as a percentage, where: $f_{e,i}$ – the vibration frequency determined in the experimental study for the *i-th* mode [Hz], $f_{n,i}$ – the vibration frequency determined in the numerical model for the *i-th* mode [Hz].

$$\Delta = \frac{|f_{n,i} - f_{e,i}|}{f_{e,i}} \cdot 100\% \quad (1)$$

Mode shape	**Experimental study result [Hz]**	**RFEM 6 result [Hz]**	**Relative error Δ [%]**
1st axial	708.5	668.6	6
1st flexural (vertical)	124.7	113.1	9
2nd flexural (vertical)	299.0	263.1	12
3rd flexural (vertical)	501.1	428.0	15
4th flexural (vertical)	702.8	587.5	16
5th flexural (vertical)	897.5	735.8	18
6th flexural (vertical)	1080.4	869.3	20
1st flexural (horizontal)	35.3	33.1	6
2nd flexural (horizontal)	95.4	88.4	7
3rd flexural (horizontal)	178.2	158.3	11
1st torsional	23.1	22.0	5
2nd torsional	59.9	53.7	10
3rd torsional	128.9	121.9	5

Table 2: Natural frequencies' results and mode shapes identification

4 CONCLUSIONS AND FURTHER RESEARCH PLANS

- Due to measurement inaccuracies ranging from approximately 5% to 20%, it was decided that, in addition to the shell model, a more accurate and detailed solid model needed to be created in ABAQUS. It is assumed that this will enable the development of a more accurate analytical model, which will more closely reflect the actual behaviour of the GFRP element under dynamic impulse loading. Furthermore, obtaining an FEM model approximating the real beam model will allow further analysis and model development in the numerical workspace. A properly functioning initial computational model provides broad opportunities for testing solutions before actual laboratory tests on the final solution.
- The measurement error may be due to the inability to input all parameters into the RFEM programme in such a way that they fully correspond to the real parameters of the anisotropic GFRP material, from the omission of the exact cross-sectional shape in the numerical surface model, and, during experimental tests, from human error – e.g. applying a load to a still vibrating beam, although in a manner imperceptible to the human eye.
- For the purpose of analysing the dynamic properties of components made from composite materials, more sophisticated software such as ABAQUS is more suitable. The FREM software is primarily designed for issues relating to the design of structures made from conventional building materials (e.g. reinforced concrete, steel, timber).
- The analysis of the dynamic properties of GFRP profiles is useful for the further analyses and tests planned by the research team, i.e. for determining the dynamic properties of the entire composite beam consisting of a GFRP profile and a concrete slab. This approach could potentially be applied to lightweight composite floors, e.g. in multi-storey buildings, where attention is paid to reducing the self-weight. With the significant reduction in the element's mass, it is appropriate to investigate its dynamic characteristics.

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