NUMERICAL AND EXPERIMENTAL MODAL ANALYSIS OF A CARBON FIBRE MONOCOQUE

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This paper deals with the comparison of experimental measurements and numerical simulation of the natural frequency and natural shape of a carbon fibre monocoque. This comparison is used to validate the numerical analysis with a real monocoque. Usually, monocoques consist of orthotropic materials like carbon fibre sandwich with a honeycomb core. The monocoque is manufactured by hand from several layers of different materials, which are connected by glued joints. This does not guarantee the material properties or the same mass the idealized numerical simulation.

KEYWORDS

Modal analysis, Carbon fibre, Monocoque, Experimental measurement.

1 INTRODUCTION

The estimation of modal characteristics (natural frequencies and vibration modes) is commonly employed to avoid resonance vibrations in constructions. It requires reliable data about the mechanical properties of the material. Determining such characteristics for polymer composites is more difficult than for isotropic materials because of the greater number of elasticity characteristics and their dependency on a wide range of structural and technological factors. Also, most of the literature and available sources contain controversial data about the material properties of composites, and for crucial construction calculations it would be better to perform additional experimental identification of these properties [Nikhamkin 2018]. Modal analysis is a modern study of dynamics which allows us to determine the modal properties of the assessed part. The modal analysis is used to obtain the dynamic characteristics of the designed system. In practice, most of the problems associated with excessive noise or mechanical vibration are caused by the characteristics of the mechanical system [Cizikova 2016]. Most of the technical problems which can cause a system to resonate at a natural frequency can be solved by modal analysis. In comparison with experimental measurements, the system can then be retuned outside the resonant frequency band. [Silva 2007] An FEM model can be validated for the following FEM static load analysis by verifying the natural frequency of the model. The FEM model of the carbon fibre monocoque includes 9 material constants for the carbon fabric and 3 material constants for the honeycomb core. This means errors are possible in the input material properties. If the model is validated using natural frequencies, then we eliminate possible errors in the static calculation.

2 CARBON FIBRE MONOCOQUE

The carbon fibre monocoque of the formula student racing car which we assessed was made of carbon fabric twill CC200 with Toray T300 3K fibre with a weight of 200 g.m^{-2} and an aluminium honeycomb core PAMG-XR1-4.5-1/8-10-P-5056 with density 72 kg.m^{-3}. The basic dimensions of the monocoque (Fig. 1) are length 1677 mm, width 640 mm and height 618 mm. The total final weight of the monocoque was 22.45 kg. The monocoque was made using a negative mould in two cycles with curing in an autoclave at an overpressure of 3 and 6 bars and a temperature of 120 °C. The individual layers were manually placed in a negative mould. An adhesive film was used to join the skins and the core.

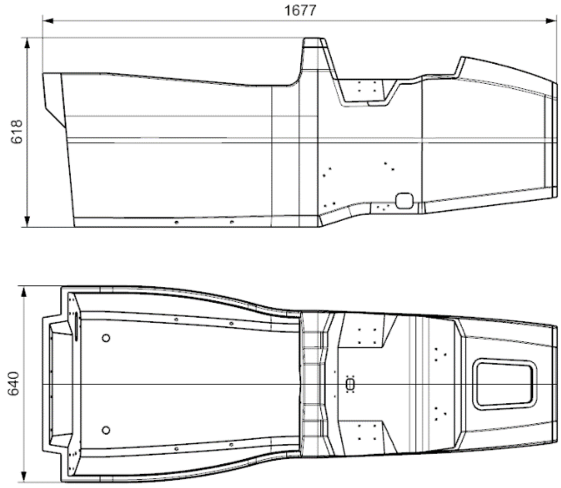


Figure 1. Side and top view of carbon fibre monocoque

The monocoque consists of three different laminate lay-ups which are illustrated in Figure 2. The values in bracket below indicate the caron fiber angle orientation of the individual laminate layer.

a) Base layup (Fig. 2 – green area):
$[0/45/0/0/-45/0/]_T$ [C-20-3.2-72] $[0/45/0/0/-45/0]_T$

b) Front bulkhead (Fig. 2 – yellow area):
$[0/45/0/0/-45/0/0/-45/0/0/45/0]_T$ [C-20-3.2-72] $[0/45/0/0/-45/0]_T$

c) Upper part of side impact + front floor (Fig. 2 – blue area):
$[0/45/0/0/-45/0]_T$ [C-10-3.2-72] $[0/45/0/0/-45/0]_T$

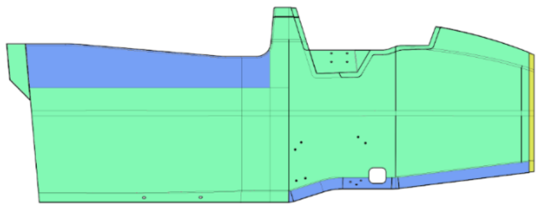


Figure 2. Different layup zone of fibres in the monocoque

The monocoque was reinforced in the front hoop with a laminated aluminium profile 30x30x3 mm from alloy EN AW 6082 (Fig.3 in orange). The honeycomb core was replaced at the attachment points by inserts made of TECAPEEK CF30 (Fig.3 in green).

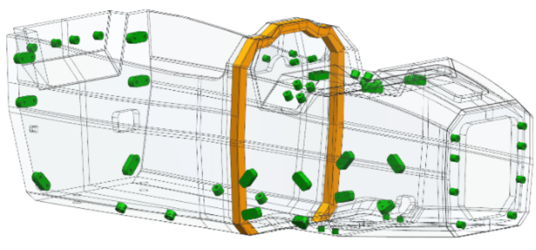


Figure 3. Inserts and front hoop profile which was laminated into the monocoque

3 EXPERIMENTAL AND NUMERICAL MODAL ANALYSIS

The natural frequencies and natural shapes were measured experimentally to validate the overall stiffness of the FEM model. The value of the natural frequency of a simple system without damping is given by equation (1). Assuming an equal mass *m* for the experimental measurements and the FEM model, the only unknown value is the total stiffness, which will then be validated.

$$\Omega = \frac{1}{2\pi}\sqrt{k/m} \qquad (1)$$

where Ω is natural frequency (Hz), k is the stiffness in a specific direction, m is mass (kg). [Fu 2001]

The experimental measurement was performed as follows. The monocoque was hung on rubber hangers to minimize effects on the structure. Repeated excitation was performed at the reference point (Fig. 4) by striking the modal hammer (weight 100 g with a rubber tip) in a vertical direction. Responses to this excitation were measured in three directions (X, Y, Z) with a triaxial accelerometer (Bruel& Kjaer 4529B, with a range of 50 g) consecutively at each point.

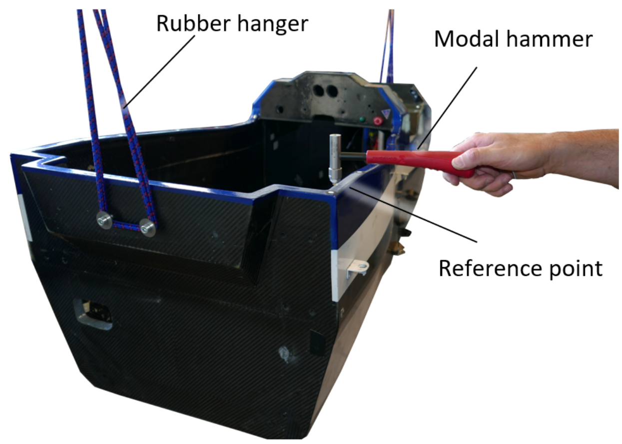


Figure 4. Position of reference point and modal hammer

The measuring points were selected by dividing the monocoque into a grid of 18 measuring points on each side (Fig. 5**Chyba! Nenalezen zdroj odkazů.**).

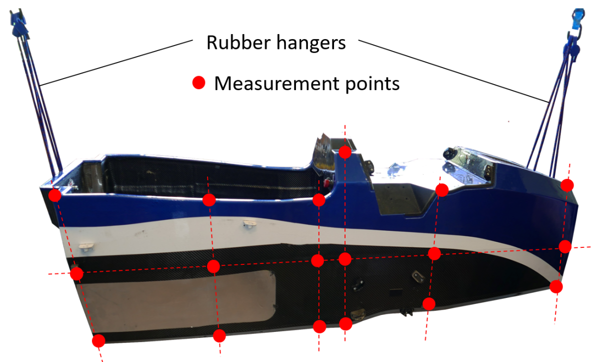
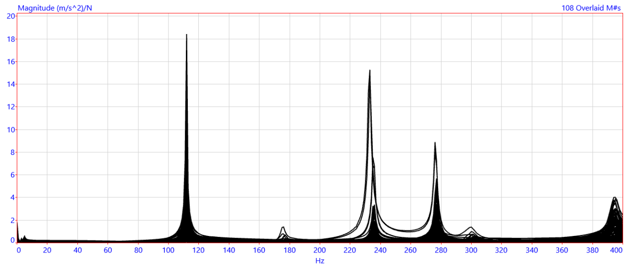


Figure 5. One side with grid of measurement points

The output of the analysis is the frequency response function (FRF- H1). The FRF is the ratio of the output response of a structure due to an applied force. We measure both the applied force and the response of the structure simultaneously. (The response can be measured as a displacement, a velocity or an acceleration.) [Avitabile 2017] FRFs are complex, they contain both amplitude and phase, which means we can quickly visualise the natural oscillation shapes for the individual natural frequencies (resonant peaks). The measured FRFs are shown in Graph 1, where the peaks represent the natural frequencies of the body. The first six natural frequencies were defined from this graph and shown in Table 1. The first natural frequency was set to 112Hz, the second to 117Hz, the third to 235 Hz, the fourth to 277 Hz, the fifth to 301 Hz and the sixth to 395 Hz.



Graph 1. Measured frequency response functions (FRF)

The natural shape of the oscillations was visualized on a simple wireframe model of the body.

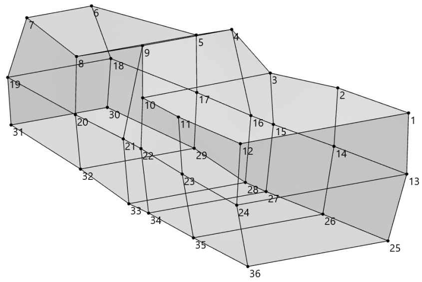


Figure 6. Simplified wireframe 3D model of measured points

The natural shape for the natural frequency of 112 Hz is shown in Figures 7. It was determined that the first natural frequency is the natural shape and torsion of the whole monocoque. The following 5 natural shapes were determined in the same way and are described in Table 1.

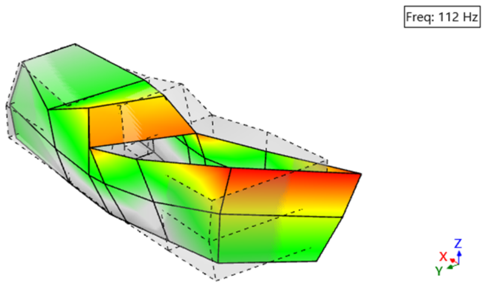


Figure 7. Isometric view of natural shape for natural frequency 112 Hz

No.	Natural frequency (Hz)	Natural shape
1.	112	1st Torsion of whole monocoque
2.	177	Cockpit walls bend in opposite phase
3.	235	Cockpit walls bend in phase
4.	277	2nd Torsion of whole monocoque
5.	301	Cockpit walls bend in opposite phase
6.	395	Whole monocoque bends

Table 1. Results of experimental measurement of natural frequency

The numerical simulation was done in Nastran NX 12 software with module SOL 103 - Real Eigenvalues using the method for extracting natural frequencies Lanczos. [Goncharov 2014] The FEM mesh of the model was created by second order quadrilateral shell elements (CQUAD8 type) with a relative size 10 mm, see Figure 8. The composite layup was defined by using special module NX Laminate Composite including the inclusion of material orientation and honeycomb cores. This ensures the transfer of the physical properties of the material directly to the individual elements according First-order shear deformation theory for laminates. Connection between composite monoque and reinforced in the front hoop in the form aluminium profile 30x30x3 mm from aluminium alloy was created with using surface to surface gluing connection (without considering the flexibility of the bonded layer).

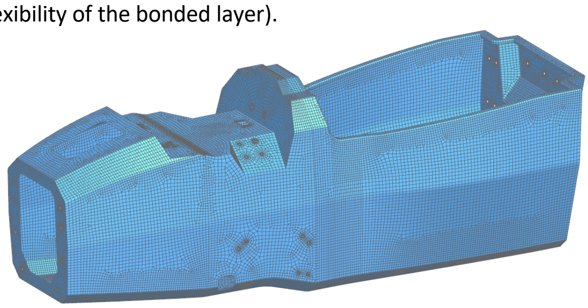


Figure 8. 2D Mesh model in NX 12 with 10 mm elements

Composite orthotropic materials such as carbon fabric laminates are characterized by 9 material constants to determine the mechanical properties in all three directions. [Campbell 2010] We used the material properties of the CC200 carbon fabric twill with Toray T300 3K fibres (Table 2) in the FEM model, which were previously determined by experimental measurement to have a density of 1690 kg.m^{-3}. The following material properties were taken from the manufacturers' material sheets. Honeycomb core: density 72 kg.m^{-3}, Young's modulus in compression 1.27 GPa, shear modulus in L direction 0.55 GPa, and shear modulus in W direction 0.23 GPa; TECAPEEK CF30 inserts: density 1380 kg.m^{-3}, and Young's modulus in tensile 6.8 GPa; front hoop alloy EN AW 6085: density 2700 kg.m^{-3} and Young's modulus in tensile 70 GPa.

Material properties		Value
Young's modulus	E_1	52.3 (GPa)
	E_2	48.7 (GPa)
	E_3	5 (GPa)
Shear modulus	G_{12}	2.32(GPa)
	G_{13}	2 (GPa)
	G_{23}	2 (GPa)
Poisson's ratio	μ_{12}	0.11 (-)
	μ_{13}	0.35 (-)
	μ_{23}	0.35 (-)

Table 2. Material properties of Twill CC200 – Toray T300 3K

The adhesive layers between the skin and the core were not considered in the numerical model because, they do not affect the stiffness of the structure. These adhesive layers were included in the weight of the structure. The adhesive layers in the skin were included by experimental measurement of the Young's modulus of the laminate. The real thickness of the skins was entered into the numerical model. The calculated weight of individual monocoque components is given in Table 3. Weight is an important factor that affects the resulting natural frequency according to equation 1. Therefore, the resulting mass was verified on a real monocoque. The actual weight of the monocoque was 22.46 kg. The difference of 0.77 kg in the calculated weight compared to the actual weight was compensated in the numerical simulation by changing the density of the skin layer from 1690 kg.m^{-3} to 1785 kg.m^{-3}. The weight of the skin layer was increased to 14.35 kg. The Young's modulus was measured experimentally therefore there could be a change in the density of the laminate, which can be different depending on the manufacturing process.

Item	Volume/Area	Density	Weight (kg)
Inserts	0.00083 m^3	1380 kg.m^{-3}	1.15
Skin	0.00804 m^3	1690 kg.m^{-3}	13.58
Core	0.05701m^3	72 kg.m^{-3}	4.10
Adhesive	5.95335 m^2	0.25 kg.m^{-2}	1.49
Front hoop	0.00050 m^3	2700 kg.m^{-3}	1.37
Total weight			21.69

Table 3. Result of natural frequency experimental measurement

Numerical simulation was performed in the frequency range 0 – 400 Hz according to the experimental measurements. The constraints of the monocoque in the numerical analysis was it unconstrained (so called free modal analysis). The six natural frequencies with natural shapes as close as possible to the experimental measurement were found. The comparison of the experimental measurements with the numerical simulation is shown in Table 4. The differences between the numerical simulations and experimental measurement ware up to 3.6 % for the first natural frequency with a torsional shape of the oscillation. This natural shape represents the torsional stiffness of the monocoque.

The torsional stiffness of the monocoque is the most important factor in the design of the car. Therefore, this validation of the FEM model with the real experiment for the first natural frequency of the torsional shape is helpful in determining the final torsional stiffness. The conformity of up to 3.6 % in the 1st, 4th and 6th natural frequencies, which represents the total stiffness of the monocoque, is sufficient when considering the possible manufacturing inaccuracy of laying the carbon fabric and the complex technological processes involved.

No.	Natural frequency experimental measurement (Hz)	Natural frequency numerical simulation (Hz)	Deviation (%)
1.	112	116	3.6
2.	177	162	-8.5
3.	235	224	-4.7
4.	277	284	2.5
5.	301	320	6.3
6.	395	387	-2.0

Table 4. Result of natural frequency experimental measurement

A double wave in the opposite phase shape in the cockpit area was determined from the 5th natural shapes of the numerical simulation, shown in Table 5. This shape was not observed in the experimental measurements. It was detected in only one wave. This was caused by an insufficient number of measuring points in the cockpit area. It is advisable to first perform a preliminary numerical simulation to predict the natural shape. Based on this prediction, the positions of the measuring points can be chosen to confirm the points with the largest amplitude.

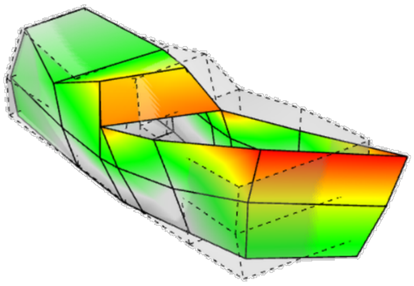
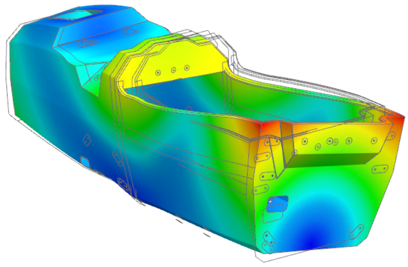
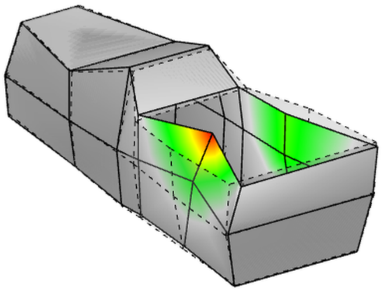
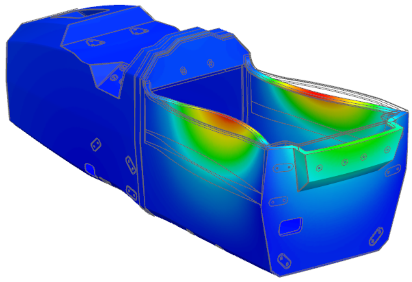
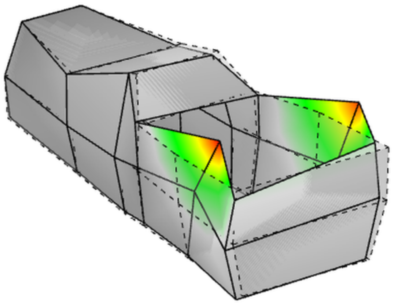
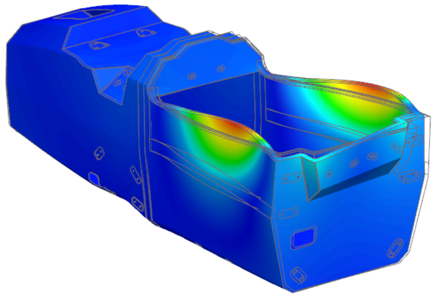
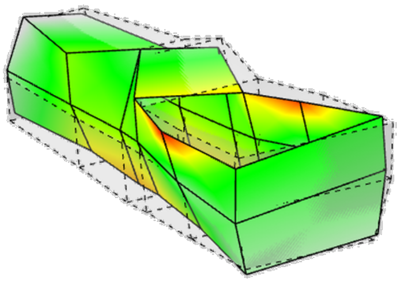
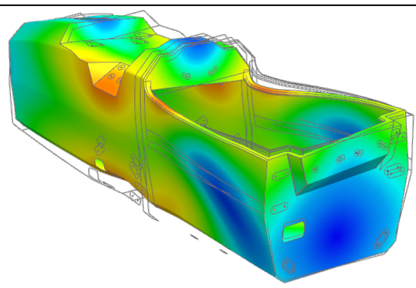
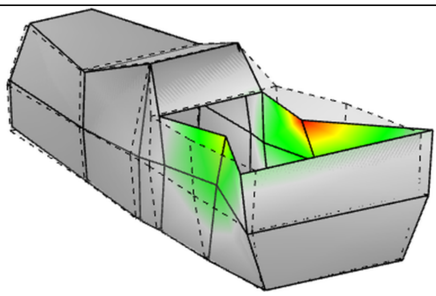
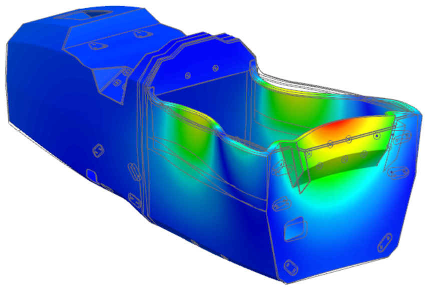
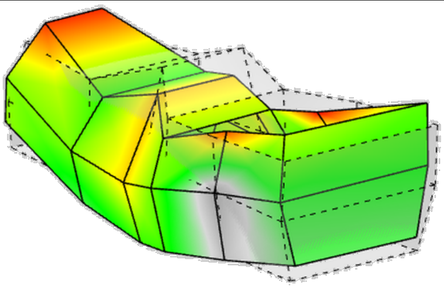
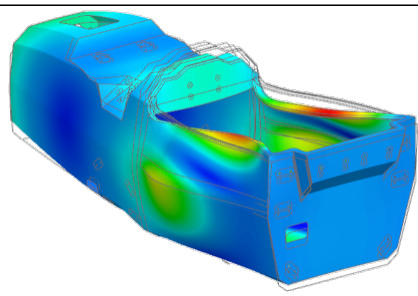
Deviation	Natural shape – Experimental measurement	Natural shape – Numerical simulation
1st Deviation 3.6 %		
2nd Deviation -8.5 %		
3rd Deviation -4.7 %		
4th Deviation 2.5 %		
5th Deviation 6.3 %		
6th Deviation -2 %		

Table 5. Result of natural frequency experimental measurement

4 CONCLUSION

The paper deals with the comparison of the experimental measurements and the numerical simulation of the natural frequency and shape of the carbon fibre monocoque of a racing car. The area of composite materials is a rapidly developing field. Modal analysis is a suitable means for the validation of a complex FEM model because of the complexity of the material properties of the orthotropic materials used to produce a carbon monocoque. For the experimental measurements, the monocoque was divided into a grid of 36 measuring points. The natural shape of the oscillations was visualized on a simple wireframe model of the body. The differences between the numerical simulations and the experimental measurement were up to 3.6 % for the 1^{st}, $4^{th}$and 6^{th} natural frequencies which represent the total stiffness of the monocoque (1^{st} – Torsion, 4^{th} – Torsion, 6^{th} – Bend). This conformity is sufficient considering the possible manufacturing inaccuracy of laying the carbon fabric and the complex technological processes. Several factors can cause deviations between the experimental measurements and the numerical simulation. Firstly, the difference between the real mass of the measured structure with the calculated mass in the FEM model, which fundamentally affects the resulting values of the natural frequency. Secondly, the material properties of the composite panel, which are determined by 9 material constants for the skin and 3 material constants for the core. These properties need to be determined experimentally so they have a minimum influence on the numerical simulation. The greatest influence on the natural frequency measurement can be the different composition of the laminate layup compared to the idealized FEM module layup skin. The monocoque consists of more than 250 cuts of fabric, which were hand-laid at different angles. This causes a possible error rate in the production process and subsequently influences the measurement caused by the different stiffness of the skin.

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