Damping of Prismatic Hybrid Structures

Ing. Pavel Vrba

Supervisor: Ing. Jan Smolík, Ph.D.

Abstract

In the development of machine tools, emphasis is placed on continuous improvement of machine properties, such as permanent accuracy in machining, static and dynamic properties, weight, etc. All of these parameters can be influenced to a certain extent, but mostly their improvement is a result of appropriate trade-offs. One option is to add composite materials to the existing structure. The paper deals with the way how to increase the value of the natural frequencies and damping on these frequencies using the added composite materials. The analysis is supported by dynamic calculations using the finite element method and experimental modal analysis.

Keywords

Unconventional materials, finite element method, experimental modal analysis.

1. Introduction

In the large field of production machines, emphasis of customers is placed on continuous improvement of machine parameters. The main monitored parameters are primarily: permanent precision of machining, improved workpiece surface quality, increased productivity, and a reduction in the price of the workpiece. These parameters can be positively influenced by improving the properties of the machines, which are primarily: the rigidity of the machine, static and dynamic properties (eigenfrequencies, eigenmodes and damping on the same mode shapes), weight, thermo-mechanical stability, etc. All of these properties can be influenced to a certain extent, but mostly their improvement is due an appropriate compromise between the ideas of the designers, technology options, drives requirements and production costs. A part of the process of improving the properties of the machines is also making more sophisticated models and compensations that describe real behaviour of structures as well as reducing computational requirements.

1.1 The potential applications of unconventional materials

The application of non-conventional materials in the construction of load-bearing structures of machine tools it is important to specify the appropriate uses, when we have as an objective:

1) maintaining or enhancing static stiffness of the load-bearing structure of the machine
2) weight reduction of moving masses
3) the increase in the values of eigenfrequencies on eigenmodes
4) the increase in the damping of these eigenmodes
5) the increase of thermo-mechanical stability

In practice, however, the solutions are often conflicting and it is therefore necessary to assess the benefits of the applicability of the unconventional material and the rate of increase of the production costs. The area of production machines where it is common to use unconventional materials is the design of beds and columns. Here, the conventional structural materials (steel, cast iron) have been replaced by unconventional materials of generally higher damping

(hydro-concrete, polymer-concrete, and granite). These materials are, with respect to the improper ratio E/ρ, unsuitable for moving parts.
In order to improve the damping of these structures, it is possible to choose from several approaches. The first of them is the replacement of the existing structure by a composite structure (see Fig. 1). The advantage of this solution is the possibility of designing the configuration of composite structures so that its properties are significantly better than the properties of traditional materials (steel, cast iron). Even with lower weight, higher stiffness (especially bending) can be achieved. It may be problematic to achieve this increase in rigidity in the case of combined stress (bending and torsion) of composite structures. Some of the conclusions related to this issue are listed in [1, 2 and 3].
The second approach is to replace the current design by a hybrid structure (see Fig. 2). These structures combine traditional materials with composite materials. An appropriately designed hybrid structure can have benefits not only in the area of the maintenance of the rigidity, but may also lead to:

1) improvement of dynamic properties – an appropriate combination of different materials
2) optimizing the ratio of stiffness and weight of components – the increase in bending stiffness of composite components
3) simplification of component production
4) effective use of composite material

The disadvantages of hybrid structures can be different thermo-mechanical properties of the materials used and the strength problems at the interface between metal and composite. Information on designing hybrid structures is listed in [1].

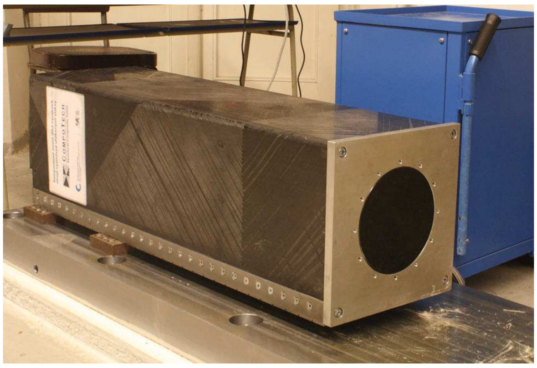

Fig. 1. *Composite ram*

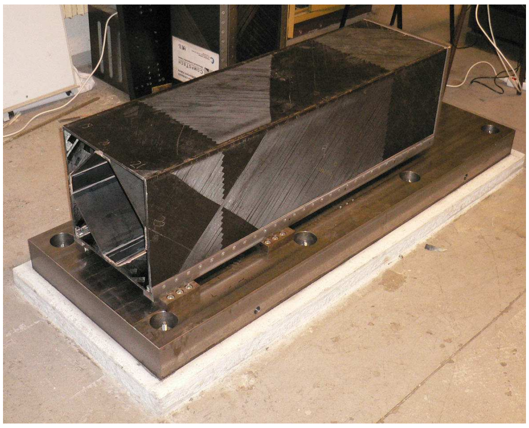

Fig. 2. *Hybrid ram with a composite base and steel reinforcements*

The third approach is largely from the standard structure; however, the design of part is changed. Composite is added to the existing structure by bonding or direct wrapping (bonding is created directly by the matrix of composite). This approach is based on the hypothesis that adding another layer of adhesive material can positively affect the properties of the structure (especially damping). According to [4], the joints between the individual elements have a dominant influence on the final damping of the machine tool. The inner damping of the material is, in comparison with the effect of joints, 10 to 100 times smaller. Another advantage may be that adding a suitably designed composite can, in addition to damping, also favourably affect the static rigidity of the machine.
An analysis of the influence of adding a composite material is the subject of this work and is described in the following sections.

2. Proposal samples

In order to assess the influence of the added unconventional materials on the damping of load-bearing components, the following procedure was elected:

Damping of basic samples → Damping of samples of structures → Damping of real structures

2.1 Basic composite samples

The aim was to design a sufficient number of basic samples with different combinations of fibre material, composition used, and number of layers in the composite sample. The samples were designed with dimensions of 700 x 70 mm. Materials of fibres used for the production were:

- high-modular carbon fibres (HMC)
- high-strength carbon fibres (HSC)
- glass fibres (G/E)

Basic properties of unidirectional prepregs used in the production of the samples are defined in Table 1.

Table 1. *– The definition of the basic properties of unidirectional prepregs*

Fibre material	**Thickness of 1 layer [mm]**	**Density [kg.m-3]**	**Modulus of elasticity E1 [GPa]**	**Modulus of elasticity E2 [GPa]**	**Weight [g/m2]**	**Volume fraction of fibre [-]**	**Volume fraction of matrix [-]**
HMC	0.285	1521	210	3.6	465	0.53	0.47
HSC	0.43	1540	130	5.1	693	0.56	0.44
G/E	0.25	1900	38.4	5.4	400	0.50	0.50

The number of layers in the composite sample:

- 8 layers
- 16 layers

Composition used for the composite sample:

- 0°
- 90°
- $[0°, +45°, -45°, 90°]_s$

The direction of 0 ° is considered parallel to the long edge of the sample (700 mm) and the direction of 90 ° is considered parallel to the shorter side of the sample (70 mm). The orientation of the fibres in the samples is shown in Fig. 3.

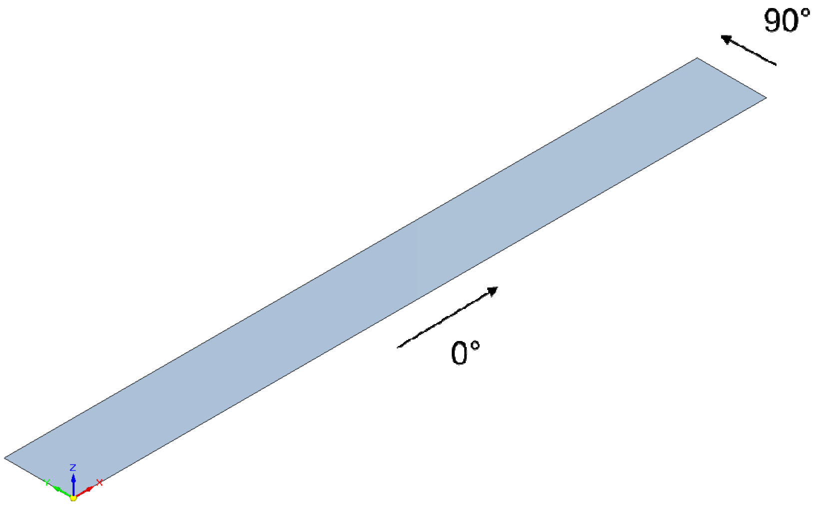

Fig. 3. *The orientation of the fibres in the composite sample*

A total of 6 basic samples were suggested. The list can be seen in Table 2. For a comparison of properties the steel sample is presented as well.

Table 2. *– Definition of the basic composite samples*

Label	**Composition**	**Material**	**Modulus of elasticity of the sample E_1 [GPa]**	**Modulus of elasticity of the sample E_2 [GPa]**	**Shear modulus of the sample G_{12} [GPa]**	**Poisson's ratio ν_{12} [-]**	**Sample thickness [mm]**	**Sample weight [g]**
Carbon_01	2x(0,45,-45,90)s	HMC C/E	73.86	73.86	28	0.32	4.6	343.5
Carbon _02	(0,45,-45,90)s	HSC C/E	47.9	47.9	18.28	0.31	3.6	262.5
Carbon _03	8x(0)	HMC C/E	210	3.66	3.15	0.37	2.24	168.7
Carbon _04	8x(90)	HMC C/E	3.66	210	3.15	0.007	2.24	166.8
Carbon _05	(0,45,-45,90)s	HMC C/E	73.86	73.86	28	0.32	2.24	166.5
Carbon _01	(0,45,-45,90)s	G/E	17.1	17.1	6.64	0.29	1.6	130
Steel		11 500	210	210	81	0.3	5	1923

2.2 Samples of structures – shell samples

Basic composite samples were used for the design of samples of shell structures. For these samples of structures, the effect of the following parameters on the increase in damping was observed:

- Steel plate thickness applied
  - 3 mm
  - 5 mm
  - 8 mm
- Type of adhesive joint
  - Solid adhesive joint – Spabond 345 – 2 component epoxy adhesive [E = 3000 MPa; ρ = 1116 $kg.m^{-3}$]
  - Flexible adhesive joint – Sikabond T2 – 1 component polyurethane adhesive [E = 2.5 MPa; ρ = 1200 $kg.m^{-3}$]
- Influence of the symmetry of the sample
  - One-sided bonded composite coating
  - Double-sided bonded composite coating

A total of 10 shell samples were designed, see Table 3. Produced samples are shown in Fig. 4.

Table 3. *– Definition of the shell samples*

Label	Composition of composite	Composition of sample	Sample thickness [mm]	Sample weight [g]
Carbon _01_α	2x(0,45,-45,90)s	HMC C/E + Spabond 345 + 5 mm Fe	10.3	2286
Carbon _02_α	(0,45,-45,90)s	HSC C/E + Spabond 345 + 5 mm Fe	9.5	2201
Carbon _03_α	8x(0)	HMC C/E + Spabond 345 + 5 mm Fe	7.9	2097
Carbon _04_α	8x(90)	HMC C/E + Spabond 345 + 5 mm Fe	8.0	2092
Carbon _05_α	(0,45,-45,90)s	HMC C/E + Spabond 345 + 5 mm Fe	8.0	2115
Carbon _05_β	(0,45,-45,90)s	HMC C/E + Spabond 345 + 8 mm Fe	11.4	3285
Carbon _05_γ	(0,45,-45,90)s	HMC C/E + Spabond 345 + 3 mm Fe	6.0	1336
Carbon _05_δ	(0,45,-45,90)s	HMC C/E + Spabond 345 + 5 mm Fe + + Spabond 345 + HMC C/E	10.7	2293
Carbon _05_ε	(0,45,-45,90)s	HMC C/E + Sikabond T2 + 5 mm Fe	8.0	2095
Glass_01 _α	(0,45,-45,90)s	G/E + Spabond 345 + 5 mm Fe	7.2	2058

Fig. 4. *Shell samples*

3. Analysis of sample damping

For a comparison of the different structures, a viscous damping model was chosen, as described by the damping ratio ζ. This is defined by the ratio of the magnitude of the fading away of the constants to undamped natural frequency.

3.1 Damping of basic composite samples

Operational modal analysis was performed on basic composite samples. During measurement, the samples were hung using a strap to minimize the effect of the fastening on the resulting frequency and damping. The scheme of measurement is shown in Fig. 5.

Fig. 5. *Scheme of measurement of basic composite samples*

The evaluated average damping ratio from the first 9 eigenmodes of basic samples and the reference sheet steel is shown in Table 4.

Table 4. *– Evaluation of average damping ratio for basic samples*

Label	**Composition**	**Material**	**Average damping ratio $\xi_{AVERAGE}$ [%]**
Carbon_01	2x(0,45,-45,90)s	HMC C/E	0.15
Carbon _02	(0,45,-45,90)s	HSC C/E	0.15
Carbon _03	8x(0)	HMC C/E	0.33
Carbon _04	8x(90)	HMC C/E	0.56
Carbon _05	(0,45,-45,90)s	HMC C/E	0.21
Glass_01	(0,45,-45,90)s	G/E	0.54
Steel		11 500	0,01

The best damping ratio of the researched composite laminates are demonstrated by laminates reinforced with fiberglass. From laminates reinforced by carbon fibres, laminates reinforced by high-modular fibres (HMC) are to be preferred. A composition of composite has a significant effect on the damping. The sample with the orientation of the fibres in the direction of 90° has the greatest average damping ratio. However, for these more subdued samples, it is at the expense of their stiffness. The result of the sample with the 0° orientation is interesting. It has the third-largest inhibition, and at the same time should have the best bending stiffness. In comparison, the average damping ratio of the basic composite samples was 15 to 56 times better than the damping ratio of the steel sample.

3.2 Damping of shell samples

Experimental modal analysis was carried out on the shell samples. The measurement was carried out under the same conditions as the measurement of basic samples. The scheme of measurement is shown in Fig. 6.

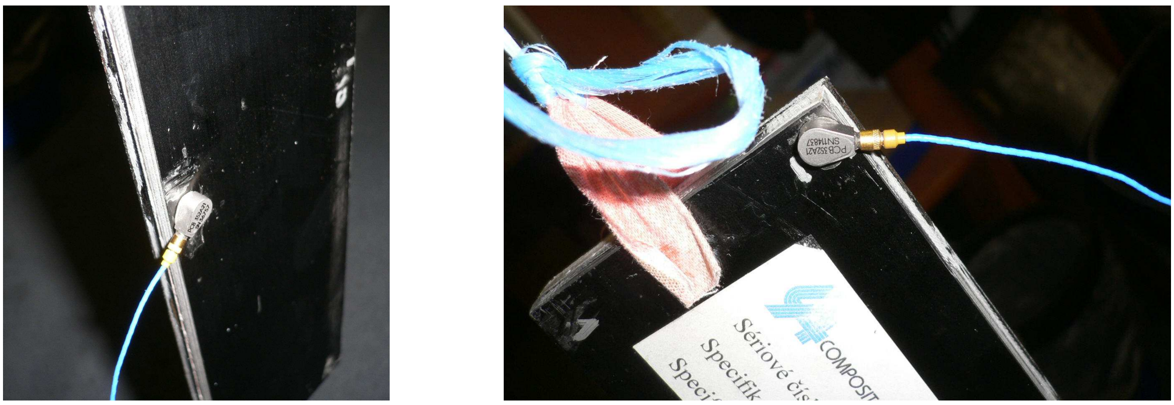

Fig. 6. *Scheme of measurement of the shell samples*

The evaluated average damping ratio from the first 7 eigenmodes of shell samples and the reference sheet steel is shown in Table 5.

Table 5. *– Evaluation of average damping ratio for shell composite samples*

Label	**Composition of composite**	**Composition of sample**	**Average damping ratio $\xi_{AVERAGE}$ [%]**
Carbon_01_α	2x(0,45,-45,90)s	HMC C/E + Spabond 345 + 5 mm Fe	0.20
Carbon _02_α	(0,45,-45,90)s	HSC C/E + Spabond 345 + 5 mm Fe	0.20
Carbon _03_α	8x(0)	HMC C/E + Spabond 345 + 5 mm Fe	0.17
Carbon _04_α	8x(90)	HMC C/E + Spabond 345 + 5 mm Fe	0.24
Carbon _05_α	(0,45,-45,90)s	HMC C/E + Spabond 345 + 5 mm Fe	0.25
Carbon _05_β	(0,45,-45,90)s	HMC C/E + Spabond 345 + 8 mm Fe	0.26
Carbon _05_γ	(0,45,-45,90)s	HMC C/E + Spabond 345 + 3 mm Fe	0.27
Carbon _05_δ	(0,45,-45,90)s	HMC C/E + Spabond 345 + 5 mm Fe + + Spabond 345 + HMC C/E	0.21
Carbon _05_ε	(0,45,-45,90)s	HMC C/E + Sikabond T2 + 5 mm Fe	0.86
Glass_01 _α	(0,45,-45,90)s	G/E + Spabond 345 + 5 mm Fe	0.23
Steel			0.01

The influence of different types of fibre seems very small in the case of shell samples. The benefits of fiberglass disappear here. A significant increase in the average damping ratio of the different composite composition, compared to basic samples, has not been proven. The average damping ratio for samples with the same composition and solid adhesive is in the range of 0.20 to 0.27%. In comparison, the average damping ratio of the shell composite samples was 17 to 86 times better than the damping ratio of the steel sample.
Of the researched hybrid structures, the sample with unidirectional orientation (0°) has the worst damping ratio. The greatest average damping ratio is shown by a sample with a flexible adhesive joint. However, increased damping of this sample is degraded by a significant reduction in stiffness. It would be beneficial to apply this approach to the load-bearing structure, where the composite would not ensure structural rigidity. In the flexible bonding joint, dissipation of energy would occur and this would lead to the enhancement of the overall damping of the structure.

4. Computational models of researched structures

Computational models have been created in the program Ansys. For simulation of experiments the modal analysis was calculated on all models. The main objectives of the computational work were:

- creation of finite elements models for all investigated structures
- comparison of measured and calculated values of eigenfrequencies
- prediction of stiffness
- prediction of tension
- prediction of eigenfrequencies and eigenmodes
- verification of the correctness of input material constants

4.1 Modal analysis of basic composite samples

Computational models of basic composite samples were created as orthotropic material models, with the need to assign material orientation. The model was created using conventional shells (an element on a reference surface) with one element for thickness. Basic materials used and the composite structure were defined for each sample separately (see Fig. 7).

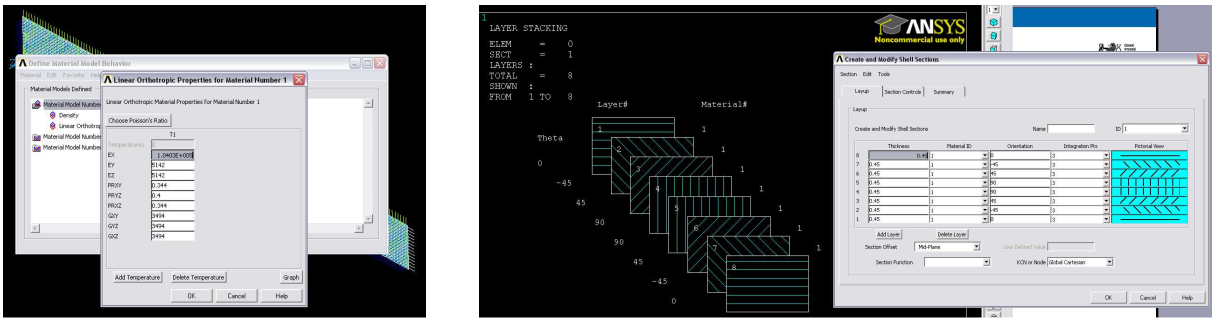

Fig. 7. *An example of a material definition and composition of the basic composite sample*

An example of the results and comparison with the experiment for one of the basic samples is shown in Table 6.

Table 6. *– The results of the modal analysis of one of the basic composite samples*

Mode	Type of shape	Ansys calculation [Hz]	Experiment [Hz]	Percentage difference [%]	Damping [%]
1	bending	50.1	47.1	6.21	0.12
2	bending	138.2	131.5	5.09	0.16
3	torsion	198.9	198.0	0.44	0.24
4	bending	271.4	257.2	5.52	0.11
5	torsion	403.8	407.7	-0.94	0.23
6	bending	449.2	428.6	4.80	0.03
7	bending	620.4	638.3	-2.80	0.15
Sample weight [g]		266	262.5	1.33	

Preview of the first three eigenmodes is shown in Fig. 8.

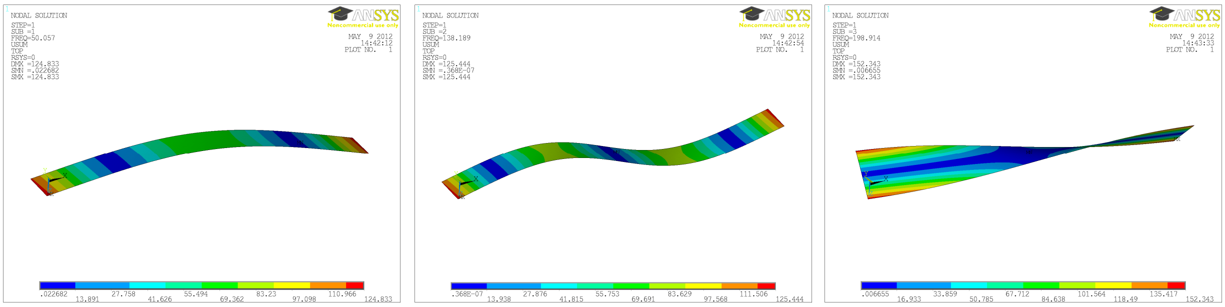

Fig. 8. The first tree eigenmodes of the basic composite sample

Good agreement was found when comparing the results of calculations with experimental data. A difference of up to 10 % was identified for all of the proposed basic composite samples on their first 7 eigenmodes.

4.2 Modal analysis of shell samples

Two approaches were compared in order to create calculation models of shell structures:

1) A layered shell model using conventional shells (an element on a reference surface, one element for thickness)
    - necessary to define the material orientation and thickness of each layer separately
    - necessary to assign the material orientation
    - SHELL281 element used for modelling
2) A layered shell model using continuum shells (volume geometry, the possibility of increasing the number of elements for thickness)
    - laminate, adhesive and steel are defined as a separate layer of continuum shells
    - individual layers in the laminate are defined by equivalent constants
    - SOLSH190 element [5] used for modelling

An example of a model created by continuum shells is displayed in Fig. 9.

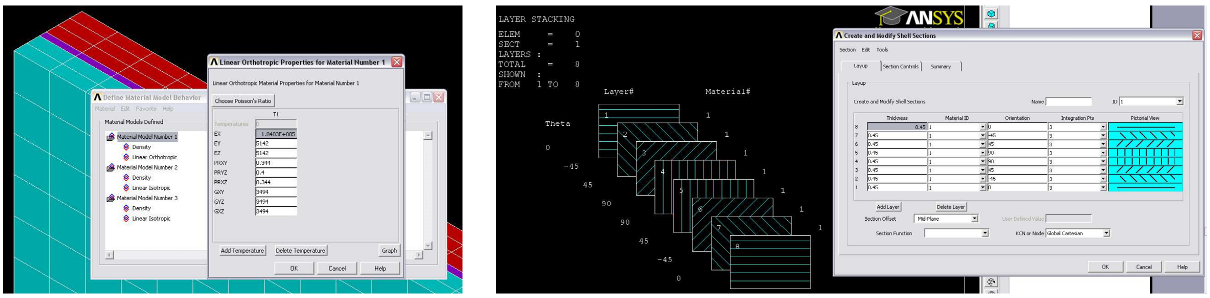

Fig. 9. An example of a material definition and composition of the shell composite sample

An example of the results using various approaches and comparison with the experiment for one of the shell samples is shown in Table 7.

Table 7. *– The results of the modal analysis of one of the shell composite samples*

Mode	Type of shape	Experiment [Hz]	Ansys SHELL_281 [Hz]	Ansys SOLSH_190 [Hz]
1	bending	**84.6**	82.1	81.5
2	bending	**229.5**	225.6	224.1
3	bending	**444.1**	440.4	437.7
4	torsion	**458.6**	442.8	450.8
5	bending	**728.9**	723.7	719.9

Preview of the first three eigenmodes is shown in Fig. 10

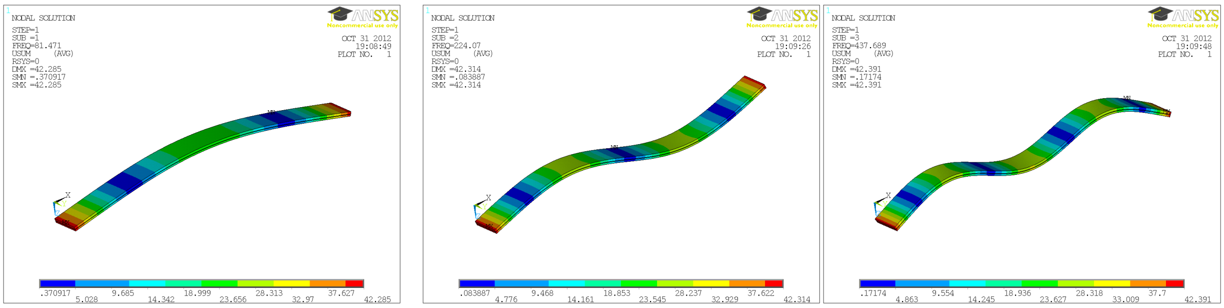

Fig. 10. *The first tree eigenmodes of the shell composite sample*

In the calculation of the sample with a flexible adhesive, the appropriateness of the use of the continuum shells was demonstrated. Their use allows a more accurate solution of contact tasks and the influence of the transverse shear as opposed to conventional elements. When using the element SHELL_281, the difference with the experiment was approx. 70 %. For the element SOLSH_190 it was only 7 %. The continuum shells will be used during further development of computational models. Similarly to basic samples, good agreement of the model and the experiment was detected for shell samples. The difference was 7 % for the first 5 eigenmodes.

5. Conclusion

The aim of the work was to assess the possibility of increasing the damping of existing steel structures using bonding composite layers. 6 basic composite samples together with different fibre materials, composition and number of layers were proposed. Furthermore, 10 shell samples were designed to assess the influence of the thickness of the steel sheet, the type of adhesive and the sample symmetry. Modal analysis, as well as a comparison of the damping ratio, was performed on all of these samples.

In the case of basic samples a significant influence on the damping ratio was detected for fibreglass. The influence was not so pronounced in the case of carbon fibre (HMC and HSC). The composition of a composite had a significant effect on the damping ratio. The sample with the orientation of the fibres in the direction of 90° had the greatest average damping ratio. It was, however, at the expense of the stiffness of the sample. **The average damping ratio of basic samples was in the range of 0.15 – 0.56% (steel 0.01%).**

The influence of the different types of fibre seems very small for hybrid samples. A significant increase in the average damping ratio of the different composite composition, compared to basic samples, has not been proven. **For samples with the same composition and solid adhesive the average damping ratio is in the range of 0.20 to 0.27 %**

(steel 0.01 %). An exception was the hybrid sample with a flexible adhesive joint. It showed the greatest average damping ratio of 0.86 %. However, the increased damping of this sample is degraded by a significant reduction in stiffness. It would be beneficial to apply this approach to the load-bearing structure, where the composite would not ensure structural rigidity. In the flexible bonding joint, dissipation of energy would occur and this would lead to the enhancement of the overall damping of the structure. This hypothesis will be validated in the future work.

List of symbols

E	modulus of elasticity in tension/pressure	[MPa]
ρ	density	$[kg \cdot m^{-3}]$
E_1	modulus of elasticity in fibres direction	[MPa]
E_2	modulus of elasticity perpendicular to the fibres direction	[MPa]
ν_{12}	Poisson's ratio	[1]
G_{12}	shear modulus of elasticity	[MPa]
ζ	damping ratio	[%]

References

[1] Kulíšek, V., Dvořák, M., Horejš, O., Janota., M.: *Závěrečná zpráva projektu 1.2.2.A.* [Výzkumná zpráva V-11-065], 2011.

[2] Kulíšek, V., Jiran, L., Mareš, T., Růžička., M.: *Verifikované výpočetní modely pro predikci tuhosti a modálních vlastností komponent z nekonvenčních materiálů.* [Výzkumná zpráva V-12-060], 2012.

[3] Smolík, J., Kulíšek, V., Janota, M.: *Moving Column Hybrid Structure Design.* Innovation in Machining 2012. Guipúzcoa: Centro Tecnológico Tekniker, 2012, p. 237-244. ISBN 978-84-932064-6-8.

[4] Weck, M., Brecher, Ch.: *Werkzeugmaschinen Konstruktion und Berechnung*, Band 1, VDI-Verlag, Dusseldorf, 1981.

[5] Ansys v13.0 Help

[6] Dai Gil Lee, Jung Do Suh, Hak Sung Kim, Jong Min Kim, *Design and manufacture of composite high speed machine tool structures*, Composites Science and Technology, Volume 64, Issues 10-11, August 2004, Pages 1523-1530, ISSN 0266-3538

[7] Baumeister, E. Klaeger, S. Kaldos, A. *Lightweight, hollow-sphere-composite (HSC) materials for mechanical engineering applications*, Journal of Materials Processing Technology, Volumes 155-156, Proceedings of the International Conference on Advances in Materials and Processing Technologies: Part 2, 30 November 2004, Pages 1839-1846, ISSN 0924-0136

[8] Jung Do Suh, Seung Hwan Chang, Dai Gil Lee, Jin Kyung Choi, Bo Seon Park, Damping characteristics of composite hybrid spindle covers for high speed machine tools, *Journal of Materials Processing Technology*, Volume 113, Issues 1-3, 15 June 2001, Pages 178-183, ISSN 0924-0136

[9] Smolík, J.: *Nosné díly obráběcích strojů z nekonvenčních materiálů : Disertační práce*, Fakulta strojní ČVUT v Praze, Praha, 2007. 158 s.

[10] Vrba, P.: *Stojan horizontálního centra s odlehčenou strukturou : Diplomová práce,* Fakulta strojní ČVUT v Praze, Praha, 2009. 94 s.

[11] Kulíšek, V., Smolík, J., Dvořák, M., Vrba, P., Ondráček, M., Sedláček, P. *Závěrečná zpráva projektu 1.2.2 za rok 2008 – část 2* [Výzkumná zpráva V-08-075], 2008

[12] Kulíšek, V., Dvořák, M., Vrba, P., Šindler, J., Smolík, J., Janota., M.: *Závěrečná zpráva projektu 1.2.2.A. za rok 2010* [Výzkumná zpráva V-10-078], 2010.