Journal of Machine Engineering, Vol. 13, No. 1, 2013

carbon fibre reinforced plastics,
finite element analysis,
experimental modal analysis

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APPLICATION OF FIBRE COMPOSITES IN A SPINDLE RAM DESIGN

When compared to steel or cast iron, carbon fibre composites offer excellent tensile and bending stiffness together with significantly smaller density. Research at the Research centre of Manufacturing Technologies in Prague has been aimed at the application of composite materials in structural parts design. Case studies on spindle rams were performed focusing on the design of experimental composite spindle rams and their benchmarking with reference steel components. The cross-section of both parts was 350x350mm and the length was 1200mm. The first design was made as a thick-walled composite body with a minimal amount of steel. The goal was to achieve static stiffness comparable to a reference steel component of the same size. The second design was manufactured as a hybrid structure composed of fibre composites with cork layers and bonded steel reinforcements. The goal was to improve damping of the structural parts in comparison with the steel components. Results of stiffness and modal properties were obtained from experiments and also using FEA. Experimentally obtained damping ratios of composite and reference steel rams were compared with and without the effect of connection interfaces on damping.

1. INTRODUCTION

Structural parts of machine tools, or more specifically components of their motion axes, have been traditionally built from cast iron and in the last decades also from steel. These materials fulfil requirements of machine tool design, especially demands on components' stiffness, precise machinability of functional surfaces and environmental resistance in machining conditions (oils, emulsions, hot chips). The manufacture and assembly of components from these materials is also well known to machine tool producers. Nevertheless, the pressure on the improvement of machine tool fundamental properties (productivity, work-piece accuracy and surface quality) has caused that other materials have also been analysed for application in structural parts design. The main drive for the application of the new materials is to achieve an improvement of machine tools' dynamic behaviour. While the static stiffness of current solutions is usually sufficient, the dynamic behaviour suffers due to large density of cast iron and steel and due to a large amount

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of these materials, which is necessary to meet the demanded stiffness. The dynamic behaviour of components from common materials can be partially improved by efficient design (using topological, parametrical optimization), which shifts eigenfrequencies, but probably does not provide a major improvement in structural damping. The design of structural parts from the common materials can be also improved using sandwich based design combining the common materials with light-weight cores; Smolik [1] presented a case study of a moving column with sandwich side panels. Application of aluminium foam instead of metal ribs resulted in 20per cent mass reduction without significant changes to the column stiffness. An alternative way is to replace the traditional materials with new structures; in an ideal case the materials should have a lower density, increased damping, and increased stiffness and should be cheaper and easy to process as well. Unfortunately, no material is yet known to meet all these conditions.

However, there is potential in the application of fibre composites as they meet several of the aforementioned criteria. In comparison with steel they are significantly lighter; they can provide increased stiffness in a specified direction, and their structural damping is higher. On the other hand, the costs of fibre composites are significantly higher and the stiffness of orthotropic composites can be unacceptably low for several loading directions. In addition, manufacturing of composite components and designing of connection interfaces for assembling into a machine tool is more challenging in comparison with traditional materials.

2. COMPOSITE MATERIALS IN MACHINE TOOL DESIGN

The application of composite materials in the machine tool industry has been studied by several institutions during the last decades. The focus of the studies has been not only on structural parts, but also on other components of machine tools. Suh [2] researched a possible application of hybrid structures (carbon fibre composite bonded to steel) in a spindle cover design, stating that the loss factor of the hybrid cover was 3-5 times higher in comparison with a traditional cover. Neugebauer [3] presented a hybrid composite-steel ball screw, stating 10 times lower thermal expansion in comparison with a conventional metal ball screw. Other components with a composite or hybrid composite-metal design were analysed as well, such as spindle shafts (Brecher [4]; Bang [5]), high speed grinding wheels with increased damping [6]; cutting tool holders [7] or boring rods [8].

As for structural components, research of the application of hybrid composite-steel sandwich structures to an X-slide and a Y-slide of a high speed milling machine was carried out by Lee [9], resulting in approximately 30 per cent mass reduction and an increase in damping factors by 1,5-5,7 times. The Research Centre of Manufacturing Technology together with CompoTech Plus Ltd presented an experimental composite spindle ram in Uher [10].

Another case study of a composite spindle ram was presented at the EMO Hannover exhibition in 2011 by Roschiwal Partner [11]. Most structural composite components have been presented as case studies. Only a few industrial applications have been made so far. Composites in machine tools have been mostly applied to drive shafts.

2.1. PROPERTIES OF FIBRE COMPOSITES

As the application of fibre composites has been aimed at the stiffness application, carbon fibres have been selected as a reinforcement material. The most common type of carbon fibres are fibres derived from polyacrylonitrile (PAN). These fibres are available in high-strength (HS) or high-modulus variants (HM). Young's modulus of HS fibres in the fibres direction is approximately 230GPa. The second type of carbon fibres is based on PITCH precursors. The fibres based on PITCH precursors are usually made as high or ultra-high modulus fibres (UHM). Young's modulus of commercially offered ultra-high modulus fibres in the direction of fibres can be up to 900÷1000GPa [12],[13]. The most commonly used resins for these materials and application in machine tools are based on epoxy.

Nominal in-plane properties of tensile and shear modulus, coefficients of thermal expansion and conductivity are given in Table 1 for high-strength (HS) carbon/epoxy and ultra-high modulus carbon/epoxy composites of several lay-ups. UHM fibres with 640GPa modulus were selected. The main reason for selection of these fibres was in their processability. Properties in Table 1 were calculated from the fibre and matrix properties using the rule of mixture and laminate plate theory [14]. Coefficients of thermal conductivity were calculated using equations [15].

Table 1. Nominal properties of steel, cast iron and composites from high-strength (HS) and ultra-high modulus (UHM) carbon/epoxy composite (index 1 denotes a direction of fibres; index 2 denotes a direction perpendicular to fibres, values are given for composites with 60% fibre volume fraction)

	ρ	E_1	E_2	G_{12}	α_1	α_2	λ_1	λ_2	Cost of fibres
	$kg.m^{-3}$	GPa	GPa	GPa	K^{-1}	K^{-1}	$W.m^{-1}.K^{-1}$	$W.m^{-1}.K^{-1}$	Eu/kg
Steel	7850	210	210	80	13e-6	13e-6	50	50	3
Cast iron	7050	169	169	66	10e-6	10e-6	55	55	1,5
HS C/E: Unidirectional	1550	140	6	4	0,9e-6	27e-6	4,3	0,6	>20
HS C/E: [0/90]s	1550	73	73	3,8	2,5e-6	2,5e-6	2,5	2,5	>20
UHM C/E: Unidirectional	1750	380	5	3	-1,2e-6	31,4e-6	83	0,6	>60
UHM C/E: [0/90]s	1750	192	192	3	1,4e-6	1,4e-6	42	42	>60
UHM C/E: [45/-45]s	1750	13	13	97	1,4e-6	1,4e-6	59	59	>60

It can be seen that especially composites from UHM fibres can have significantly higher tensile stiffness (unidirectional layers) or slightly better torsional stiffness (composites with + and – 45 degree orientated fibres) when compared to isotropic steel or cast iron. However, if the stiffness for both the modes is needed, then a composite component of the same volume as the component from steel or cast iron cannot have equivalent stiffness for both the loading cases. Also, unfortunately for the application of composite materials to a spindle ram, for the case of bending it is necessary to include transverse shear stiffness, which is significantly lower for composite materials than for isotropic metals. For a unidirectional layer, the transverse shear modulus G_{23} is approximately at the level of the in-plane shear modulus G_{12}; i.e. while Young's modulus of a UD layer from ultra-high modulus fibres is 380GPa, the transverse shear modulus is only 3GPa. A similar situation would occur if the UHM fibres with higher Young's modulus were used.

A new design with composite materials has to overcome these difficulties. One option is to design a component with a part of the material oriented to obtain the maximal bending stiffness and a part of the material oriented to obtain the maximal torsional and transverse shear stiffness. Another option is to create a hybrid design that combines isotropic metal and orthotropic composites. In this case, torsional and transverse shear stiffness can be for example achieved by metals, while the composite reinforcements with lay-up composed of 0 degree oriented fibres can improve the bending stiffness.

The hybrid design is more cost-efficient as it does not need a large amount of expensive fibres. However, problems can occur due to different thermo-mechanical properties of carbon/epoxy composite and steel or cast iron. The machine tool industry has high demands on the precision of connection interfaces; these demands are difficult to fulfil for functional surfaces from composite materials due to their machinability and hardness. Therefore, it is necessary to use traditional materials for connection interfaces, so the functional surfaces can be prepared with acceptable tolerances.

3. SPINDLE RAMS' DESIGN CONCEPTIONS

Two design conceptions were prepared at the Research Centre of Manufacturing Technology together with the specimens' manufacturer. Both experimental spindle rams were designed with external dimensions (mm) 350x350x1200. The design goals were the following:

- To perform experimental modal analysis and compare damping of composite or hybrid spindle rams with steel reference coupons.
- To evaluate static stiffness of composite specimens.
- To verify finite element models of composite spindle rams with experimental results.

3.1. COMPOSITE SPINDLE RAM

The first design (composite spindle ram) was made as a composite spindle ram with a minimal amount of steel components, see Fig. 1. The composite body was composed of a central tube with a lay-up for bending, torsional and transverse shear stiffness; corner tubes for connection interfaces; and the rest was filled by unidirectional layers of UHM fibres wrapped into cell structures. Connection interfaces were made using steel profiles that were bonded to the composite body and bolted to steel rods which were placed into the corner tubes. This specimen has been designed to have a maximal amount of bending stiffness. The specimen was manufactured using a filament winding technology and fibre placement methods. More details were given in [10].

Fig. 1. Experimental composite spindle ram (Composite body – left; spindle ram with connection interfaces-right)

3.2. HYBRID SPINDLE RAM

The second specimen (hybrid spindle ram), see Fig. 2, was created as a hybrid design combining carbon/epoxy composites with cork layers and steel reinforcements. The basic 10mm thick square profile was made from HS and UHM carbon/epoxy layers, mainly with 0 and ± 45 degree orientation, using a filament winding technology. Cork layers were integrated into the lay-up to increase the damping. On the other hand, the application of flexible cork layers reduced the stiffness of the basic profile. Overall, the profile's stiffness was not comparable to the other specimens. In the case of the mounted specimen, the first mode shapes would be torsional, while for the other specimens, the first mode shapes would be in bending.

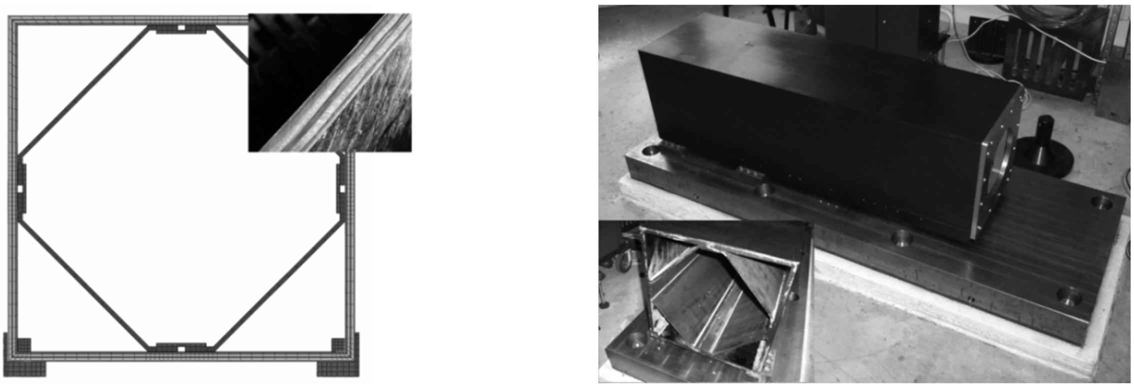


Fig. 2. Experimental hybrid composite-steel spindle ram; composite square profile with integrated cork layers (detail of the lay-up on the right side); steel: inner reinforcements, outer skin and connection interfaces

Stiffness reinforcements were provided by 4mm thick steel profiles, which were bonded into the basic profile, and by 2mm thick steel skins, which were bonded to the outer surfaces of the composite profile. The reinforcements helped to make the specimen's behaviour comparable with the other coupons; however, the design was not focused on achieving stiffness equivalent to reference steel coupons, but on evaluation of damping of the hybrid metal-composite-cork structure. The second goal was to verify finite element models for prediction of similar structures. Connection interfaces were again realized by steel profiles, which were bonded to specimens and bolted to inner profiles. For bonding of all components, two-component epoxy adhesive Spabond Sp345 was used.

3.3. COMPARISON WITH REFERENCE SPINDLE RAMS

As a reference specimen, a spindle ram from welded steel was used. the basic specimen (steel spindle ram i) was originally used as the stiffness benchmark when designing the composite spindle ram. the specimen was made from 10mm thick steel sheets without any reinforcements by ribs. for comparison of modal properties, the second steel specimen (steel spindle ram ii) with improved stiffness was made with a skin of thickness from 10mm to 15mm and also with 10mm thick transverse ribs, see Fig. 3.

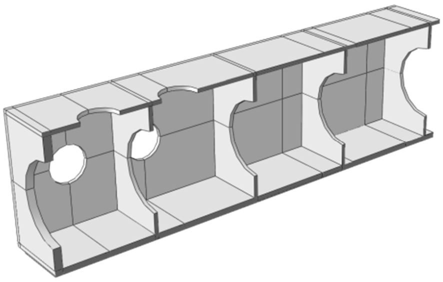


Fig. 3. Section of reference steel spindle ram II

Steel specimen II was used as the reference specimen for comparison of modal properties as it was closer to the real spindle rams than specimen I. All steel and composite specimens were manufactured with the equal outer dimensions 350x350x1200 and with the same connection interfaces for mounting of the spindle rams. The composite spindle ram (total weight 130kg, composite part – 110kg) and hybrid spindle ram (total weight 98kg, composite and cork – 20kg) were significantly lighter than steel spindle ram II (weight 220kg); their weight was closer to the original reference specimen – steel spindle ram I (150kg).

The cost of the components is an important parameter in the comparison. The cost of composite structures depends significantly on the amount of high-strength and ultra-high-modulus fibres (see costs in Table 1), amount of metal and costs of manufacturing technology. For the spindle rams, a price range of 150-200 Euro for 1kg of the composite structure can be expected, depending on the spindle ram structure. For the hybrid composite spindle ram with a square profile made by filament winding, the cost was in the lower level of the specified cost range. For the composite spindle ram from several sub-components which were produced by filament winding and fibre placement technology and then were pressed together, the cost was in the higher level of the range. In comparison with the steel components, both experimental specimens were multiple times more expensive.

4. STIFFNESS OF SPINDLE RAMS

Static stiffness was experimentally investigated for bending loading; the configuration is shown in Fig. 4. Specimens were loaded by dynamometer using a special fixture; deflection along the Z axis was captured using the TESA GT22 and GT44 electronic probes. The basic measurement, both for bending in the direction of the X and Y axis, was performed on an experimental stand, with the aim of comparing the static stiffness of the composite spindle ram with reference spindle ram I. Configuration of the experiment and deformation along the Z axis for the same force is shown in Fig. 5. Deflection was measured on the bottom edge of the composite specimen and also on the steel clamps used for mounting.

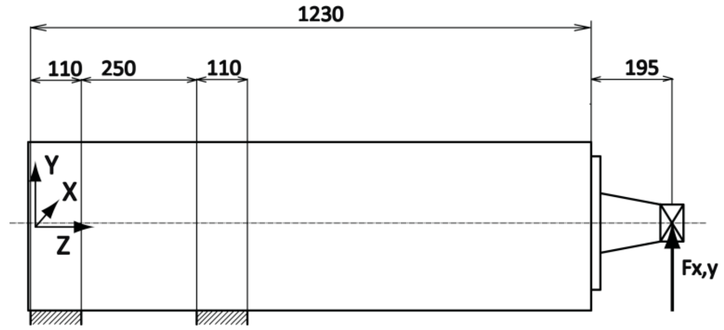


Fig. 4. Configuration of static stiffness measurement

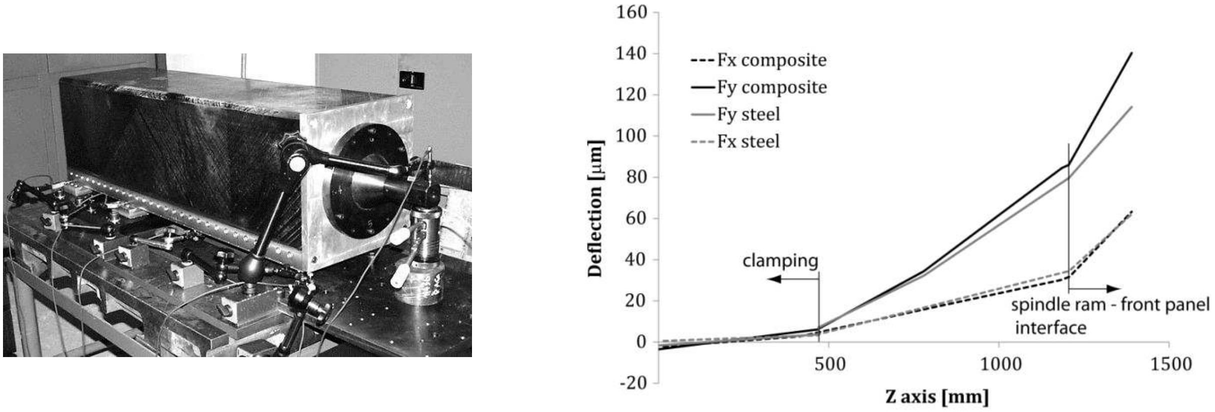


Fig. 5. Measurement of static stiffness – comparison of the composite spindle ram with steel specimen I; bending in horizontal (X) and vertical (Y) direction

Deflection for bending in horizontal direction (X axis) at the end of the spindle ram (z=1230mm) was slightly better for the composite specimen (32μm/kN) than for steel specimen I (34μm/kN). For bending in vertical direction (Y axis), deflection at the end of the spindle ram was slightly better for steel specimen I (80μm/kN) than for the composite specimen (86μm/kN).

In comparison with reference steel specimen I, the stiffness of the composite specimen was higher by 6 per cent for loading in the X axis and lower by 7 per cent for loading in the Y axis. The stiffness of the composite component was reduced in the clamping area; another major reduction was caused by compliance of the joint between the spindle ram and front panel with the loading fixture (z=1230mm). When the deformation taken from the steel clamps were subtracted from the deformation curve (slope of the curve in 0-440mm range of Z axis), the final deformation for loading in the X axis was 17μm/kN for the composite specimen and 24μm/kN for steel specimen I. For loading in the Y axis, the final deformation of the composite specimen was 62μm/kN, the deformation of steel specimen I was 66μm/kN. After the subtraction of the mounting compliance, the stiffness of the composite specimen was higher by 42per cent in horizontal direction and by 6 per cent in vertical direction.

The second comparison of static stiffness was performed with the improved boundary conditions, using a concrete plate built into the ground as a base for mounting of the specimens. Behaviour of the composite and the hybrid specimen during bending loading in vertical direction was experimentally compared; the setting was the same as shown in Fig. 4. The experiment and the results are shown in Fig. 6. Deformations of the specimens' ending for bending in vertical direction were: composite specimen - 34μm/kN; hybrid specimen - 61μm/kN. In comparison with the composite specimen, the static stiffness of the hybrid specimen was lower by 44per cent. The stiffness of the hybrid specimen was reduced by deformations in the clamping area, which negatively influenced the slope of the deformation curve. Improvement of the reinforcement to redistribute the force from the mounting to the body would be beneficial to the hybrid design. For comparison, steel specimen II deflection evaluated from finite element simulations is also shown in Fig. 6. The calculated deflection was 22μm/kN; this value was obtained from the finite element model that predicted 1st vertical bending mode shape frequency in 4per cent variation with the experimental value, using the identical mounting for the modal analysis as was used for the stiffness measurement (FEA 118Hz [16]; experiment 122Hz - Table 3).

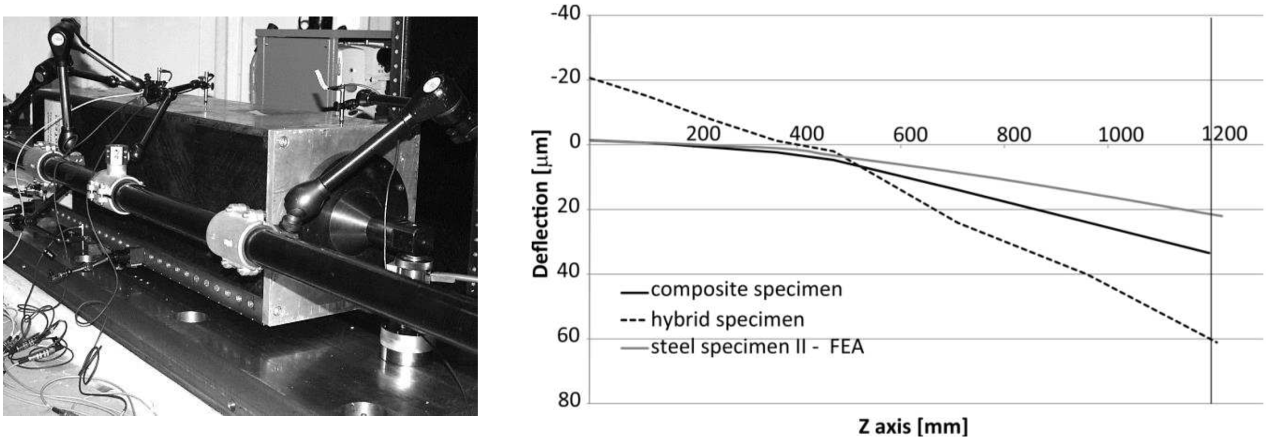


Fig. 6. Measurement of static stiffness – comparison of composite and hybrid spindle ram with steel specimen II (FEA) – vertical bending

5. EXPERIMENTAL MODAL ANALYSIS OF SPINDLE RAMS

Two configurations of experimental modal analysis were used to map the possible benefits of composite materials application to the spindle rams:

- Damping analysis of spindle rams with the minimal effect of connection interfaces.
- Damping analysis of spindle rams with additional effect of connection interfaces – bolted clamps on damping.

In the first configuration, the specimens were hung using flexible ropes mounted to the front panel. This configuration was used to evaluate eigenfrequencies of free vibrations and corresponding damping values. In the second configuration, specimens were mounted to the basic frame, using bolted joints and steel clamps, i.e. in the same configuration as the stiffness measurement. The configurations were used to prevent a misleading interpretation of identified damping from spindle rams without joints. Weck [17] stated that the influence of component damping on the final damping is 10 to 100 times lower than the influence of connection interfaces. Padmanbhan [18] published that 90per cent of the overall damping is caused by damping in connection interfaces. Therefore, at least temporary steel clamps for bolted joints were designed to evaluate the change in damping from free vibrations to clamped specimen. Unfortunately, at the time of the experiment all except the first composite specimen were not machined for assembling of linear guide-ways.

The experimental modal analysis of all specimens was performed using the Brüel & Kjær 3560C analyser, the Brüel & Kjær 8206-003 modal hammer and the Brüel & Kjær 4506 triaxial accelerometer. Modal parameters were evaluated using the complex mode indicator function (CMIF) [19]. For evaluation of damping of structural components, a damping ratio ζ was used.

5.1. EXPERIMENTAL MODAL ANALYSIS - FREE VIBRATIONS

The experimental modal analysis was performed on reference steel spindle ram I and II as well as on the composite spindle ram. For the hybrid specimen, only the basic square composite profile with integrated cork layers was tested. The configuration of the measurements is shown in Fig. 7. Vibrations were excited by the modal hammer in the bottom corner of the specimens; response was taken in 24 points (corners, centres of faces, centres of edges), see Fig. 7-d.

Values of frequencies and evaluated damping are given in Table 2, including the average damping ratio, which was determined from the first 9 mode-shapes. Due to differences in the internal structure of the specimen, it was difficult to compare the frequencies of each specimen on the same mode shapes; the first 5 mode shapes of the composite spindle ram were mostly torsional.

A difference in the damping ratio of the steel spindle rams was small, $\zeta_{steel\text{-}I}$ =0,05% to $\zeta_{steel\text{-}II}$=0,10%. The average damping ratio of the composite spindle ram was 4 to 8 times higher than the damping ratio of the reference steel specimens. Also, the natural frequencies

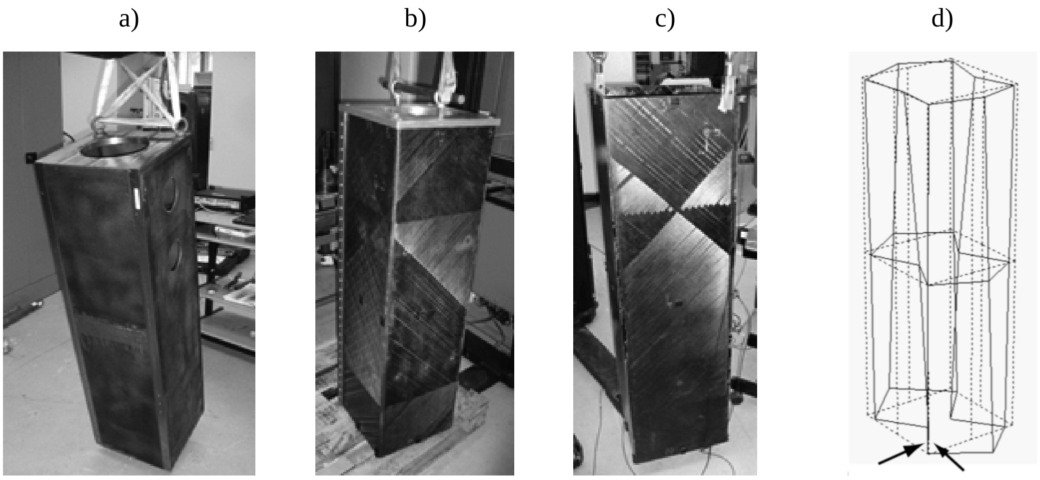


Fig. 7. Experimental modal analysis of spindle rams: a) steel spindle ram II, b) – composite spindle ram, c) – basic composite profile for hybrid spindle ram, d) – points of excitation and response measurement

were similar to the frequency of steel spindle ram II, i.e. spindle ram with higher stiffness and with a structure reinforced by transversal ribs. The composite-cork basic profile could not be compared in terms of stiffness, due to missing reinforcements. The geometry of the basic profile was similar to the reference specimen I (with the exception of the missing front panel); the frequencies were significantly lower. However, the average damping ratio of the composite-cork structure was 50 to 100 times higher than of the steel structures.

Table 2. Comparison of frequencies and damping ratios determined for unclamped spindle rams

Mode	Reference steel specimen I		Reference steel specimen II		Composite spindle ram		Composite-cork square profile	
[-]	f [Hz]	ζ [%]	f [Hz]	ζ [%]	f [Hz]	ζ [%]	f [Hz]	ζ [%]
1	127,4	0,04	582,2	0,17	533,2	0,52	27,0	9,85
2	222,2	0,02	618,9	0,20	553,3	0,30	62,7	4,26
3	256,1	0,02	646,5	0,09	721,5	0,37	75,6	6,58
4	326,7	0,02	678,7	0,07	785,4	0,32	180,0	4,90
5	383,2	0,07	693,4	0,09	1017,0	0,27	202,0	5,18
6	430,4	0,03	760,9	0,07	1197,0	0,43	205,0	5,21
7	432,6	0,05	813,7	0,09	1267,0	0,58	235,0	4,37
8	506,9	0,14	840,0	0,07	1309,0	0,36	235,0	3,20
9	524,3	0,06	933,8	0,06	1429,0	0,56	237,0	2,10
ζ_{1-9} [%]	**0,05**		**0,10**		**0,41**		**5,07**	

5.2. EXPERIMENTAL MODAL ANALYSIS – CLAMPED SPECIMENS

The experimental modal analysis of clamped specimens was performed on steel spindle ram II, composite spindle ram and hybrid composite-cork-steel spindle ram. The configuration of the experiments is in Fig. 8. The measurement of hybrid composite-cork-steel spindle ram was performed before and also after bonding of the outer steel skins.

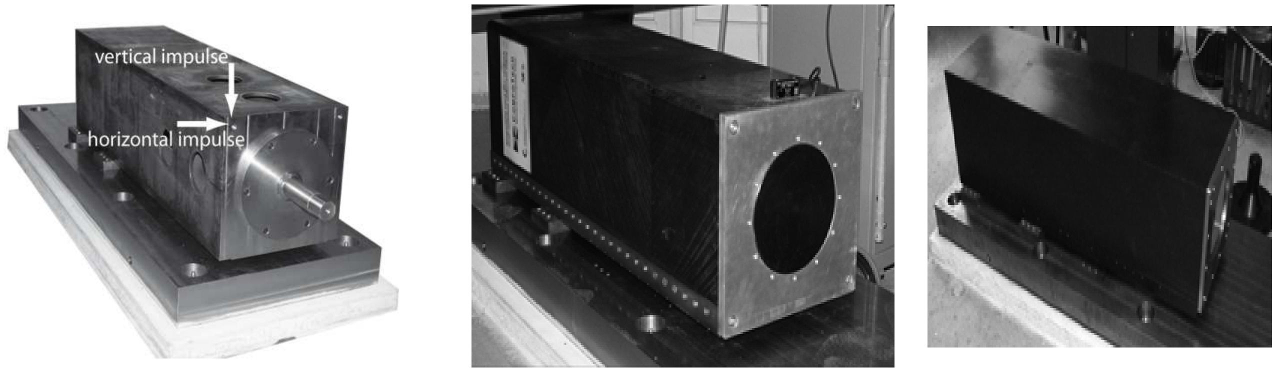


Fig. 8. Experimental modal analysis of clamped experimental spindle rams (left – steel spindle ram II with denoted points of excitation; centre - composite spindle ram, right – hybrid spindle ram)

Excitation was performed in the front corner of the specimens; the response was taken from the accelerometers on the top skin of the steel specimen or the top and side skins of the composite specimens, as shown in Fig. 9. The excitation in the corner of the spindle rams was selected to provide the possibility of comparing the dynamic compliance of all specimens without the effect of the spindle ram – front panel joint compliance. Spindle rams were designed with slightly different connection interfaces of the front panel (steel – welding, composite – bonding, bolts); also different masses were connected to the specimens during the measurement. It is expected that this fact influenced the comparison of frequencies, but did not have a significant effect on the values of damping.

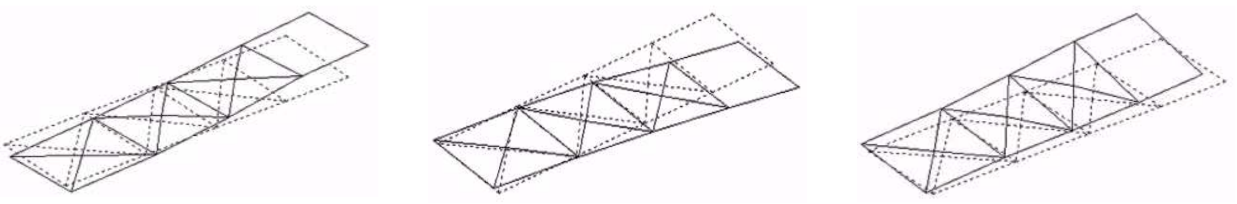
Values of frequencies and damping ratio for the performed measurements are given in Table 3. The first two frequencies corresponded to bending modes (the first in vertical direction, the second in horizontal direction). For the hybrid specimen, the first modes of the hybrid specimen were also in bending, however, in the clamping area a shear deformation occurred. The other modes were not directly comparable between the specimens (e.g. 3rd mode – see Fig. 9: steel – torsion, hybrid –bending and torsion).

Table 3. Comparison of frequencies and damping ratios determined for clamped spindle rams (first bending mode in horizontal and vertical direction highlighted)

Mode	Reference steel specimen II		Composite spindle ram		Hybrid spindle ram without steel skins		Hybrid spindle ram with steel skins	
[-]	f [Hz]	ζ [%]	f [Hz]	ζ [%]	f [Hz]	ζ [%]	f [Hz]	ζ [%]
1	122,3	3,42	122,4	5,61	99,5	2,93	110,6	4,06
2	155,3	6,46	159,5	6,78	107,3	4,50	121,2	5,86
3	346,9	1,43	266,4	6,04	167,6	1,44	178,2	1,61
4	458,6	4,55	435,6	5,96	345,0	1,38	387,4	1,67
5	584,8	0,13	521,0	1,59	413,6	1,85	419,8	1,85
6	619,0	0,14	786,5	1,07	452,9	1,61	438,4	3,90
7	649,0	0,18	882,8	1,35	621,0	1,96	626,5	1,82
	$\zeta_{1\text{-}7}$ [%]	**2,33**	**$\zeta_{1\text{-}7}$ [%]**	**4,06**	**$\zeta_{1\text{-}7}$ [%]**	**2,24**	**$\zeta_{1\text{-}7}$ [%]**	**2,97**

As expected, a change in the boundary conditions due to mounting (using the steel clamps and bolted joints) significantly influenced the damping. Overall, the structural damping of the assembly with clamped specimens was several times higher than of the unclamped specimens (with the exception of the basic composite profile for the hybrid specimen). The change in the boundary conditions also caused significant reduction in the frequencies, causing the first mode shapes of the specimens to be in bending and, therefore, to be directly comparable between the specimens.

steel II – 1st mode steel II – 2nd mode steel II – 3rd mode



hybrid – 1st mode hybrid – 2nd mode hybrid – 3rd mode

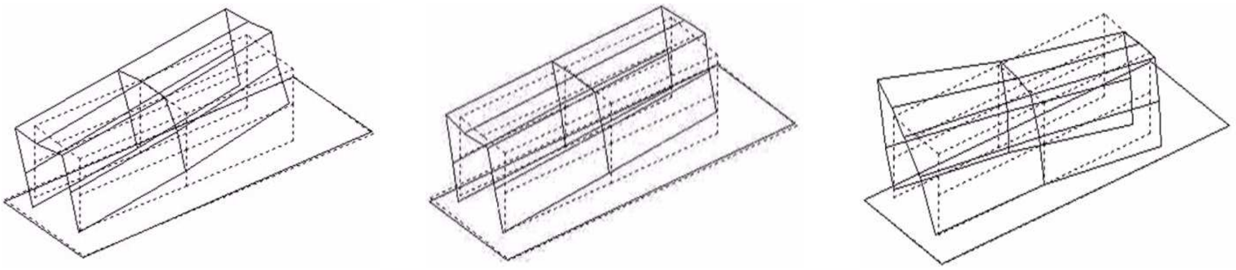


Fig. 9. First three mode shapes of steel specimen II and hybrid specimen

Although the average damping ratio of the unclamped composite spindle ram was 4 times higher than the average damping ratio of steel spindle ram II, the difference for the clamped specimens was significantly lower. For the first bending modes the values of the detected damping were comparable almost for all specimens, slightly higher values were detected for the composite specimen. For other structural and non-structural modes (skins vibrations), damping decreased more significantly for the steel specimen.

The average damping, evaluated from 7 mode shapes, was for the composite specimen $\zeta_{\text{composite}}$ =4,1%. and for the steel specimen $\zeta_{\text{steel-II}}$ =2,3%. When replacing steel by carbon/epoxy composite, the average damping of the clamped specimen increased by more than 70 per cent. Even with the effect of the connection interfaces on damping, application of composite materials led to the improvement in structural damping.

The high damping of the basic composite profile with cork layers was reduced in the hybrid structure and was also influenced by friction in connection interfaces. The average damping ratio of the hybrid specimen was slightly higher than the damping of the steel specimen. Bonding of the thin steel sheets to the outer surfaces of the profile increased the average damping ratio and also increased the stiffness of the specimen.

5.3. DYNAMIC BEHAVIOUR OF CLAMPED SPINDLE RAMS

In the case of the equivalent stiffness, the improved damping would result in an improvement in the dynamic behaviour of the spindle ram and correspondingly of the machine tool. In the case study, however, the stiffness of both the composite and hybrid spindle ram was lower than that of steel spindle ram II. The comparison of compliance from the experimental measurement (composite specimen - 34µm/kN, hybrid specimen - 61µm/kN) and numerical simulation (steel specimen II - 22µm/kN) showed that the compliance of the composite specimen was higher by 55per cent than the compliance of steel specimen II; for the hybrid specimen the compliance was higher by 170per cent. The question was how the increased damping would reflect in the comparison of dynamic stiffness/compliance of the composite, hybrid and steel specimen.

From the described modal analysis of the clamped specimens, dynamic compliance from frequency response functions was evaluated. The configuration of measurement was the same as shown in Fig. 8, both excitation and response were taken from the corner of the specimens. The frequency response function for the excitation in vertical direction is in Fig. 10, for excitation in horizontal direction in Fig. 11.

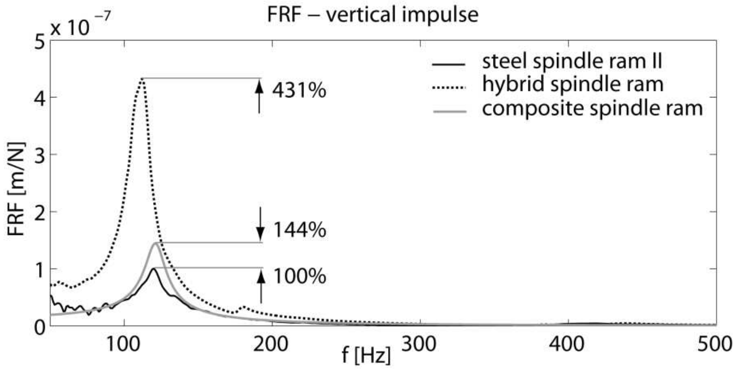


Fig. 10. Dynamic compliance – absolute value of frequency response function for steel, composite and hybrid spindle rams with excitation in vertical direction

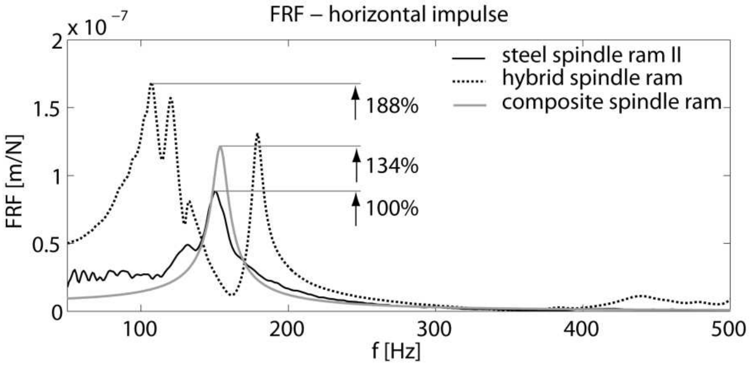


Fig. 11. Dynamic compliance – absolute value of frequency response function for steel, composite and hybrid spindle rams with excitation in horizontal direction

For the composite specimen, the major peak of dynamic compliance was higher by 44 per cent for excitation in vertical direction and by 34per cent for excitation in horizontal direction, both in comparison with steel specimen II. The higher damping of the composite decreased the difference in composite-to-steel-specimen dynamic compliance in comparison with compliance from static measurements and simulations. In the evaluation of the component, the specimens’ weight must be taken into account as well. While the weight of steel specimen I was 220kg, weight of the composite specimen was 130kg. In the presented case study, an improvement of dynamic behaviour that would result in the increase in machining productivity was not reached when comparing the composite and steel specimen II. The weight was reduced by 41per cent, replacing steel with composite, and average damping of assembly was higher by 70per cent, however, the compliance of the composite specimen was higher by 44per cent or 34per cent, depending on the direction of excitation. Improvement of transverse shear stiffness of the composite specimen (increase of ±45 degree layers in the central tube) would decrease the variation in compliance and make the composite design more suitable.

For the hybrid spindle ram, the major peak of dynamic compliance for the excitation in vertical direction was 4.3 times higher than for steel spindle ram II. In horizontal direction, the dynamic compliance of the hybrid specimen was higher by 88per cent. The major difference in compliance in vertical and horizontal direction was caused mainly by low transverse shear stiffness and torsion stiffness of the hybrid specimen. The increased damping did not reflect in the improvement of dynamic behaviour of the hybrid specimen, but that was not expected due to the design of the specimen for damping, not stiffness.

The presented results demonstrated the capability of increasing damping and even of increasing the eigenfrequencies using carbon/epoxy reinforcements. Furthermore, these results demonstrated the ability to manufacture large-scale composite specimens that can fulfil the requirements of the machine tool industry. The behaviour of the composite and hybrid specimen was reduced by low transverse shear stiffness of the component which neglected great bending stiffness of ultra-high modulus carbon fibres. This effect was significant especially for loading in the direction perpendicular to connection interfaces (linear guide-ways).

For industrial application, an improvement of transverse shear stiffness is necessary. One of the options is to use a more robust hybrid design, where transverse shear stiffness would be reached using isotropic metals, and a composite material would reinforce the bending stiffness and increase the damping.

6. FINITE ELEMENT SIMULATIONS OF COMPOSITE/HYBRID SPINDLE RAMS

Successful prediction of static stiffness and modal properties is important for efficient design of the structural components of current machine tools. For structural parts with composite materials, modelling is usually more complicated than for structural parts from common materials. It is caused by the necessity to specify the orientation of the material, by inaccuracy of orthotropic material inputs, by inaccuracies of manufacturing technology, etc. A complicated structure usually also leads to the necessity of using solid elements, or solid-shell elements, and the FE models are much larger than FE models of isotropic components.

The work on an FE model of the presented composite spindle ram was originally published in [20]. Although the geometry was modelled with a large amount of details, acceptable agreement with the experimental results was not reached. A difference between the first predicted and measured frequency was approximately 30 per cent. Complicated assembly of 8 corner tubes, 1 central tube, 3D fibre cells with unidirectional fibres and outer winding had so many unknown parameters that it was not possible to improve the disagreement between FEA and experiment.

The hybrid composite-cork-steel spindle ram was modelled in Abaqus CAE 6.12 using continuum shell elements (i.e. solid elements with shell-like behaviour). The finite element model is shown in Fig. 12. Young’s modulus of the modelled cork layers was 50MPa, its value was higher than the value given by the manufacturer of the material (38MPa), the increase was caused by absorption of resin into the cork during manufacturing. The modulus was determined from sensitivity analysis of the basic profile; FE results of the profile were compared with the experimentally determined frequencies. As the stiffness of cork layers was more than 1 magnitude smaller than the stiffness of the composite layers, the wall of the hybrid specimen had to be modelled by several elements per its thickness. The properties of composite layers were determined from fibre and matrix properties; a fibre volume fraction of each layer was estimated from the technology. Comparison of experimental and numerical results is shown in Table 4, both for the model with and without bonded steel skins on the outer surfaces of the composite body. The verification was aimed at comparison of predicted and measured frequencies of the clamped specimen. The difference between the predicted and measured frequencies was in range: -10per cent to 13per cent which was acceptable. The verification of structures combining steel and composite reinforcement with integrated cork layers enabled further development of the new hybrid material structures in the machine tool components.

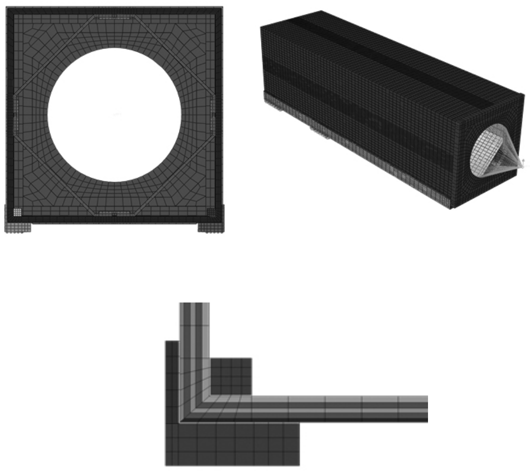


Fig. 12. FE model of hybrid composite spindle ram with integrated cork layers. (right - detail of the corner)

Table 4. Comparison of clamped hybrid spindle ram frequencies – experimental modal analysis and FEA

Mode	Hybrid spindle ram without covers			Hybrid spindle ram with covers		
[-]	f_{EXP} [Hz]	f_{FEA} [Hz]	Δf [%]	f_{EXP} [Hz]	f_{FEA} [Hz]	Δf [%]
1	99,5	110,3	+10,9	110,6	122,7	10,9
2	107,3	97, 5	-9,1	121,2	105,2	-13,2
3	167,6	168,0	0,2	178,2	180,7	1,4
4	345,0	352,1	2,1	387,4	367,7	-5,1
5	413,6	390,9	-5,5	434,8	415,2	-4,5

7. CONCLUSIONS

Application of composite materials in the design of machine tool structural components – spindle rams was researched at RCMT at CTU in Prague. The experimental part of the research focused on the dynamic behaviour of composite structures or hybrid structures which combine common materials (steel, cast iron) and composites. Two experimental spindle rams were designed, successfully manufactured and tested. The damping ratio evaluated from the free vibrations was several times higher than the damping ratio of the steel specimens. In the case of the assembly with connection interfaces, the evaluated damping ratio was increased by 70 per cent in comparison with the reference steel spindle ram. Although the stiffness of the designed component was not sufficient, the presented results have been promising enough for further development of composite spindle rams.

Together with experimental testing, verification of finite element models of the composite spindle rams was performed. FE modelling was aimed at prediction of static stiffness and modal properties (frequencies, mode-shapes). For the hybrid components (metal and composite, or metal and composite/cork reinforcement), an agreement of up to 15 per cent between the simulated and experimentally determined mode shapes and frequencies was reached. Work is currently focused on the development of hybrid metal-composite structures with improved stiffness.

ACKNOWLEDGEMENTS

The results have been obtained as part of the TE01020075 Competence Center – Manufacturing Technology project supported by the Technology Agency of the Czech Republic. Authors would also like to acknowledge the support of the company CompoTech Plus, s.r.o in manufacturing of the specimens.

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