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Structural investigation of steel-reinforced epoxy granite machine tool column by finite element analysis

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Abstract

Higher damping with higher static stiffness is essential for improving the static and dynamic characteristics of machine tool structures. The structural vibration in conventional machine tools, which are generally made up of cast iron and cast steel, may lead to poor surface finish and the dimensional inaccuracy in the machined products. It leads to the investigation of alternative machine tool structural materials such as concrete, polymer concrete, and epoxy granite. Although epoxy granite has a better damping capacity, its structural stiffness (Young's modulus) is one-third as compared to cast iron. Therefore, the present work represents optimization of the structural design of the vertical machining center column by introducing various designs of steel reinforcement in the epoxy granite structure to improve its static and dynamic characteristics using experimental and numerical approaches. A finite element model of the existing cast iron vertical machining center column has been developed and validated against the experimental data obtained using modal analysis. Furthermore, finite element models for various epoxy granite column designs have been developed and compared with the static and dynamic characteristics of cast iron column. A total of nine design configurations for epoxy granite column with steel reinforcement are evolved and numerical investigations are carried out by finite element analysis. The proposed final configuration with standard steel sections has been modeled using finite element analysis for an equivalent static stiffness and natural frequencies of about 12–20% higher than cast iron structure. Therefore, the proposed finite element model of epoxy-granite-made vertical machining center column can be used as a viable alternative for the existing column in order to achieve higher structural damping, equivalent or higher static stiffness and, easy and environmental-friendly manufacturing process.

Keywords
Epoxy granite, machine tool vibration, structural damping, finite element analysis

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Introduction

With the advancement of modern methods of manufacturing, conventional machining processes have been pressured to deliver better quality products quicker like never before. The performance of a machine tool depends upon static and dynamic stiffness, fatigue strength, damping characteristics, thermal property, light weight construction, and long-term stability.[1] The above characteristics are influenced by physical properties of the materials used for machine tool structures. The materials currently in use are largely cast iron and steel. Cast iron possesses a higher damping ratio due to the presence of lamellar graphite[2] and is widely used for casting large components in high volume. However, precision is greatly dependent on the weight of moving components in the machine tool as the inertial forces developed here affect the integrity of the machine. Machine tool structures made of cast iron and steel deform over a period of time due to continuous twisting and bending loads causing it to misalign.

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This leads to poor dimensional accuracy in machined parts. Such disadvantages and the inherent nature of iron to corrode have pushed the industry to look for alternative materials.

Ferro-cement is used as an alternative material in lathe bed, which provides significantly higher natural frequency, damping, and also nearly a 40% deeper cut before chatter when compared to cast iron.[3] Polymer concrete with viscoelastic matrix (basalt and quartzite with 10% epoxy resin) was observed to provide noteworthy increase in damping (up to 160 Hz) when compared to cast iron material.[4] Selvakumar et al.[5] investigated on polymer concrete (PC) lathe bed and it was found that PC lathe bed have 2.2 times higher damping and 38.64% reduction in weight when compared to the cast iron lathe bed. Mahendrakumar et al.[6] developed a micro-lathe bed using Himalayan nettle polyester composite as an alternative material to investigate its static and dynamic characteristics. It was found that the newly developed lathe bed provides better static and dynamic characteristics with 20% reduction in mass without sacrificing the static bending and torsional stiffness.

An optimum mixture of polymer concrete comprising basalt, sand, and fly ash with epoxy resin (filler 87% and resin 13%) was found to have good adhesion strength, fast curing property, and lower cost compared to other mixtures and compositions.[7] The usage of low-density cellular concrete impregnated with methyl methacrylate (MMA) was found to provide higher damping when it was used for linear guideways instead of steel dampers, but it is applicable only for lower frequency range.[8] Fiber-reinforced composites are better substitutes for conventional cast iron, as they also have better dynamic performance and satisfactory static performance.[9] Fiber-reinforced composites provide up to 30% decrease in weight, when proper topological design was adopted. The authors have investigated the use of carbon fiber plastics for maximum weight reduction but it involves complicated design along with the higher cost of fabrication.[10] Even though composites have lower static strength they can be used for making moving parts of machine tools. It can be achieved through strategic placing of active dampers.[11] Usage of hybrid composite–metal columns, where in glass fiber-reinforced epoxy composite plates are adhesively bonded to cast iron column provides up to 35% increase in damping ratio without any deterioration in the static performance of the machine tool.[12] Carbon fiber epoxy composite sandwiched with welded steel machine tool structures using adhesive and bolts improves damping to a maximum of 5.7 times, reduced weight up to 34% without any compromise in the stiffness.[13] Furthermore, carbon fiber fabricated by co-cure bonding method can be used as a replacement for spindle cover in high-speed machine

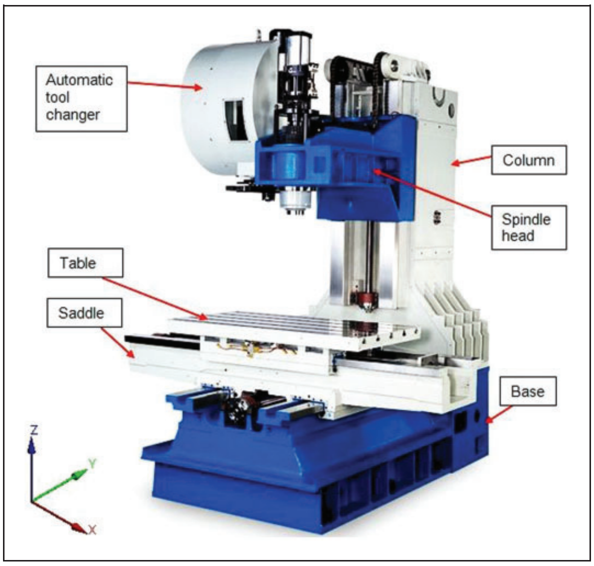

Figure 1. Vertical machining center.

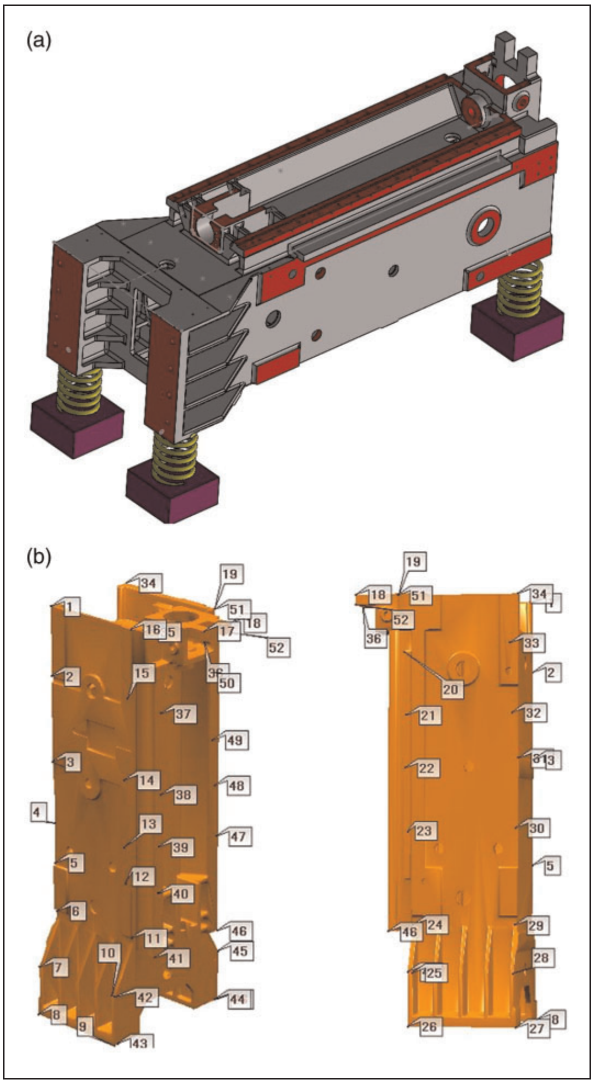

Figure 2. (a) Experimental modal analysis – free–free condition; (b) measurement points located on existing column.

tools, which improves the loss factor by a maximum of five times compared to conventional steel spindle covers.[14] The carbon fiber can be used for the manufacturing of spindle bearing system,[15] high-speed boring bar, and also for table top machine tool.[16,17] It provides higher natural frequency, damping ratio, and increased depth of cut before chatter and thus improves the productivity. It reduces the weight by 48.5% when compared to original structures but the complexity involved in fabrication of these structures makes it difficult to use.[18] Functionally graded aluminum matrix composite (AMC) can also be used for manufacturing machine tool components to achieve superior machinability.[19]

Apart from this, biomimicry is one of the latest design methods, which involves nature-inspired design that provides the alternative for improved light weight construction of machine tool structures. Use of stiffening ribs designed based on giant lily leaves in gantry machining center cross beam improved the specific stiffness.[20] Furthermore the designs based on bone structure and plant stem (bamboo) leads to weight reduction of 6.15% with considerable decrease in static deflection and increase in the lower natural frequency.[21] Leaf vein has effective structure with branching pattern, which provides good geometrical and mechanical characteristics and when the same is adopted for stiffener pattern in machine tool column, it provides good structural stiffness.[22] Epoxy granite (EG) provides a performance equal to that of carbon fiber-reinforced composite with 10 times higher damping than cast iron, high structural stability but only one-third of cast iron's stiffness, which leads to the use of thicker walls.[23] Nevertheless, with optimum topological design[24] and holistic integrated dynamic design and modeling method, the stiffness distribution based on available work space can be improved.[25,26]

The literature review reveals that not much work has been carried out towards improving the static stiffness of machine tool structures made of EG. Hence, in the present study, an attempt has been made to design and develop a vertical machining center column by using EP with reinforcement as the alternative material so as to improve the static and dynamic characteristics compared to that of the existing cast iron column. In order to gain insight into the design configuration of the milling machine, modal analysis is done by finite element method (FEM) and it is validated with experimental modal analysis. Finite element investigations were performed to assess the static and dynamic characteristics of the vertical machining center column made up of cast iron and epoxy granite composite. With this, different design configurations with steel reinforcements were made and examined.

Table 1. Results of modal analysis.

Mode number	Natural frequency (Hz)			Damping ratio
	By expt.	By FEA	% deviation	
1	411	397	3.4	0.0016
2	439	410	6.6	0.0010
3	447	418	6.5	0.0009
4	491	477	2.9	0.0011
5	504	482	4.4	0.0010
6	532	517	2.8	0.0015

FEA: finite element analysis.

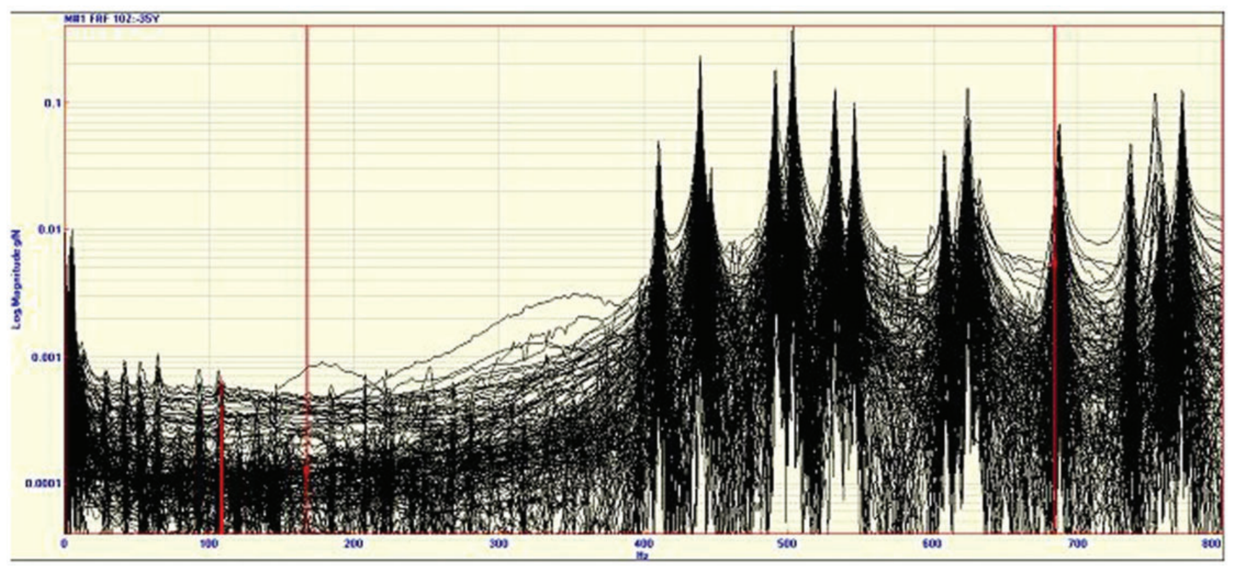

Figure 3. Cumulative frequency response functions for all the measurement points.

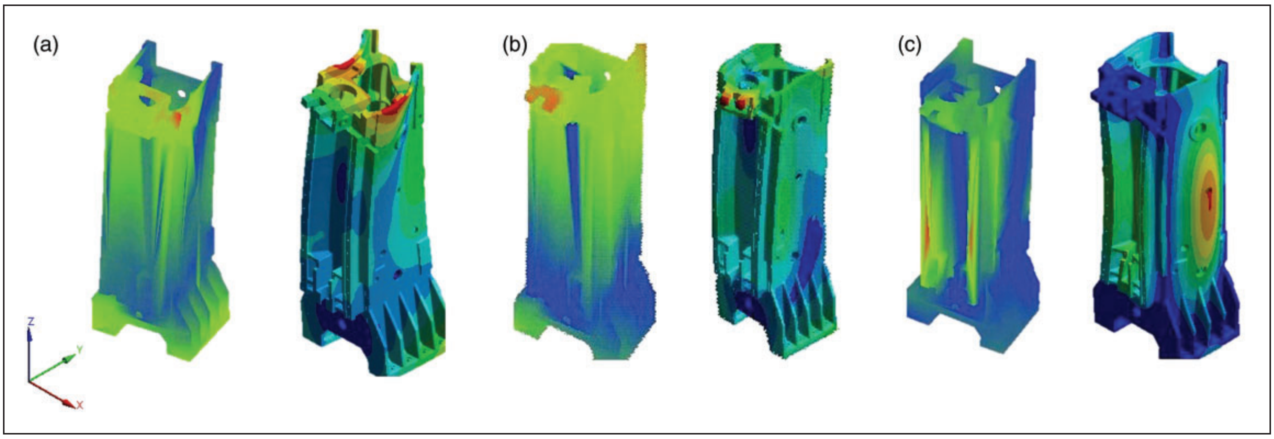

Figure 4. (a) Mode shape 1 – first bending mode; (b) mode shape 2 – first torsion mode; (c) mode shape 3 – bulging of side wall.

Dynamic analysis of existing VMC cast iron column

Description of vertical machining center

Milling is one of the most important machining processes in the shop floor today. The column of vertical machining center rests on a sturdy base as shown in Figure 1. The base prevents any unwanted movement of the column and further, dampens machine tool structural vibrations. The stability of column greatly influences the dimensional control of part features and hence it is precisely machined. The column is fitted with components like milling head, feed drive motor, counter balance, electrical systems, and automatic tool changer (ATC). The ATC is an essential add-on component for modern day machining where time is of the essence. The ATC holds a collection of tools that are to be used in the process and a power draw bar that quickly swaps the used tool from the spindle with the next tool on cue from the tool rack. The ram helps to move the milling head forward and backward while the knee holds the work table in place and at the same time allows for lateral movement of the table. Guideways are fixed on the work table with great care and a carriage moves over it. The carriage is given linear motion through a ball screw and nut powered by a motor mounted on the work table itself. The motor is always vertically mounted to avoid unnecessary transmission of components.

Experimental modal analysis on the existing VMC column

Experimental modal analysis (EMA) is a technique to describe a structure by means of its natural characteristics such as natural frequencies, relative damping ratios, and mode shapes, which has been a major concern for structural dynamicists. The modal analysis of the VMC column made of cast iron was carried out experimentally. The column has been placed over four springs of equal stiffness to simulate free–free boundary condition as shown in Figure 2(a). The stiffness of the springs was selected in such a way that the rigid body mode does not interfere with the fundamental mode of the column. Roving accelerometer method has been adopted for which 51 measurement points were selected throughout the column at various locations including the driving point, since it contains the information that allows the residue to be related to the mode shapes[27] as shown in Figure 2(b). Identical three-axis Meggitt accelerometer (Model: 45A19-1032) with a sensitivity of 1000 mV/g was used. The accelerometer is capable of measuring vibration up to ±5 g, with a bandwidth of 0.5 Hz to 6000 Hz and a resonant frequency of 28 kHz. The point of excitation was selected in such a way that the impulse excites both bending and twisting modes of the column. The excitation was given to the column in the "Y" direction with the help of modally tuned impact hammer of make Meggitt (Model: 9726A20000) with a sensitivity of 0.2 mV/N and a resonant frequency of 27 kHz. A hard tip is selected for impact hammer since it produces a narrow impact impulse.[28] The modal parameters of the column were obtained using ME'ScopeVES

Table 2. Cutting forces for worst-case conditions.

Sl. no.	Machining operation	F_x (N)	F_y (N)	F_z (N)
1	Milling feed along *X*-axis	1700	4700	2600
2	Milling feed along *Y*-axis	4700	1700	2600
3	Drilling along *Z*-axis	0	0	5000

Table 3. Comparison of FEA result.

Machining operation	Deformation at spindle head nose (μm)	Maximum principal stress (MPa)
Milling – along *X*-axis	55.5	6.2
Milling – along *Y*-axis	85.8	7.6
Drilling – along *Z*-axis	41	4.6

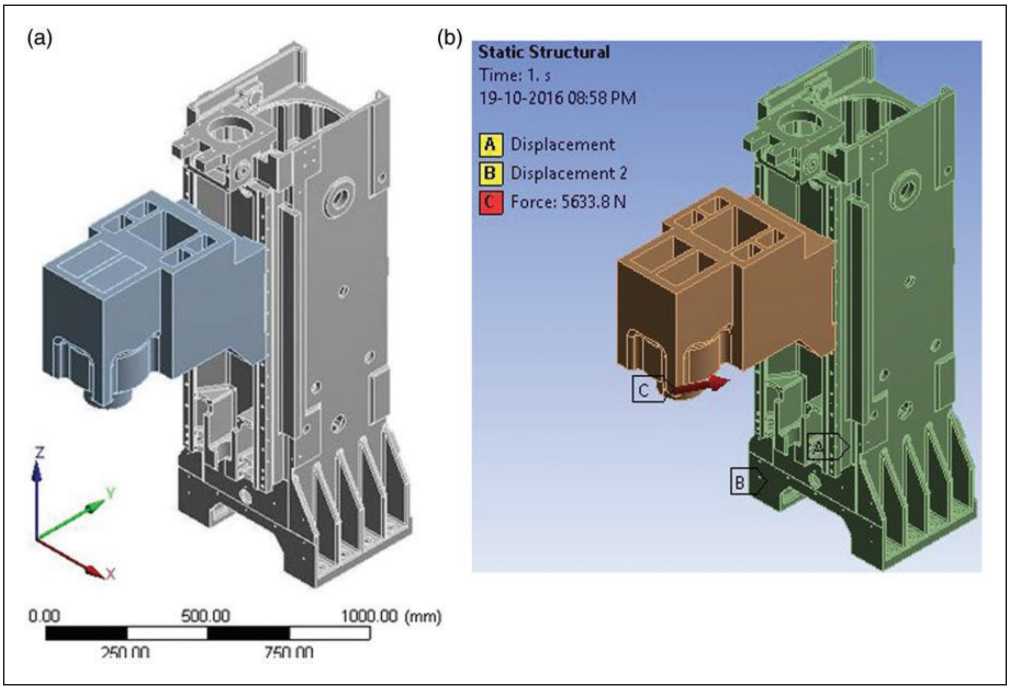

Figure 5. (a) Column with spindle head; (b) loading and boundary conditions.

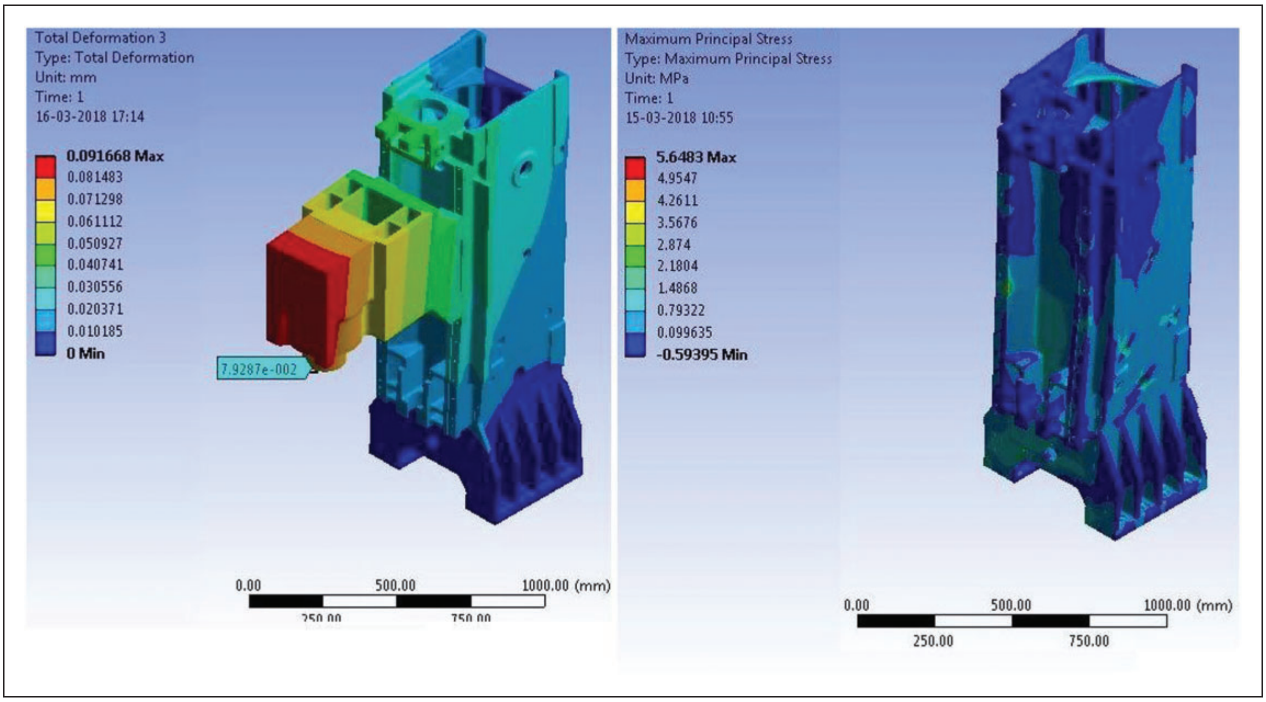

Figure 6. Deformation at spindle head nose and stress plot for milling feed along Y-axis.

software (Version 6.0.2013.0618). The force and exponential windows are used to acquire frequency response function during impact hammer excitation.[29] The first six natural frequencies of the column were observed to be 411 Hz, 439 Hz, 447 Hz, 491 Hz, 504 Hz, and 532 Hz (Figure 3). The first bending mode was observed at 411 Hz, twisting and torsion modes at 439 Hz and 491 Hz, respectively, while the Z-axis rails out-of-phase movement was observed at 447 Hz. The average damping ratio for the existing cast iron structure was found to be in the order of 0.001 in all the six modes.

Modal analysis by finite element method

Finite element analysis (FEA) has been performed to determine the dynamic characteristics of the existing cast iron VMC column using ANSYS

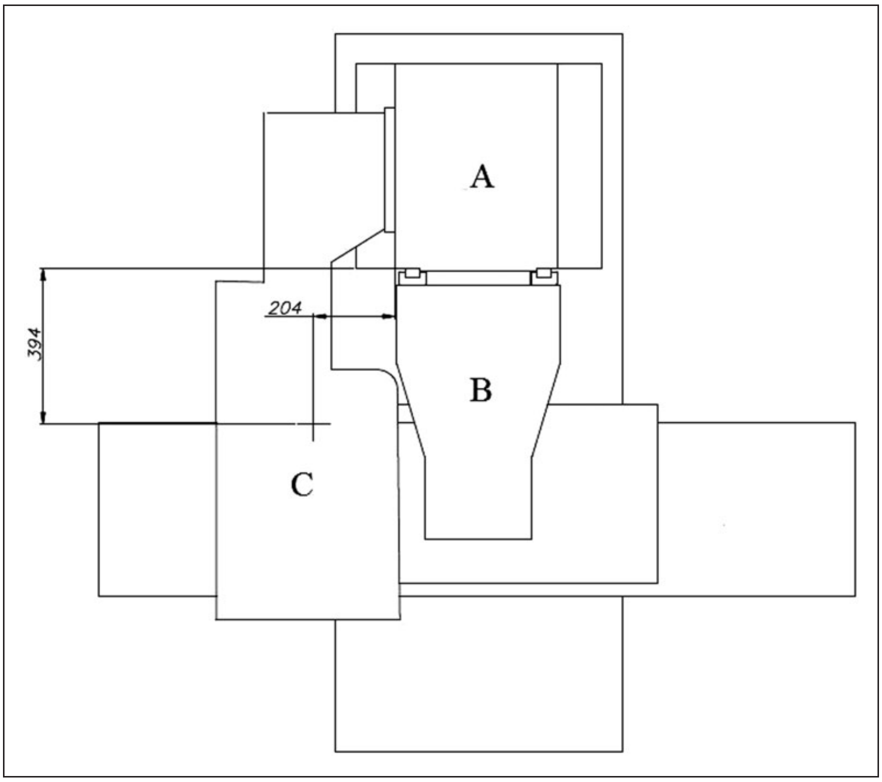

Figure 7. Schematic diagram showing the CG of ATC from the column.

Table 4. ATC Forces and moments due to ATC.

Location of loading	Reaction force (N)	Reactive moment (N-m)
Vertical face of ATC bracket		
X	0	431 (CW)
Y	685	2 (CCW)
Z	55	958 (CW)
Six holes on ATC bracket		
X	95	271 (CW)
Y	4415	12 (CCW)
Z	0	10 (CW)

ATC: automatic tool changer.

WORKBENCH 15 software. The material properties used for analysis are: Young's modulus (E)=110 GPa, Poisson's ratio = 0.28, and density (ρ) = 7200 kg/m^3. The geometrical model of the column is meshed with higher order three-dimensional tetrahedron elements (Solid 187). The meshed model consists of 323,857 elements and 542,713 nodes. After applying the free–free boundary condition, first 12 modes were extracted where the first six modes correspond to rigid body modes while the modes from 7 to 12 represent structural modes. The natural frequencies obtained by experimental and numerical analyses are presented in Table 1. Mode shape 1 as shown in Figure 4(a) is the first bending mode about Y-axis at 397 Hz. Mode shape 2 as shown in Figure 4(b) corresponds to the first torsional mode at 410 Hz. Mode 3 converges spindle head guide way to moving out of phase causing bulging of side walls at 418 Hz. The natural frequencies and mode shapes determined by the FEA are found to be in good agreement with the experimental data as shown in Table 1. Thus, the validated finite element model has been used for further studies on static and dynamic simulation of the column structure.

Static analysis of the existing VMC column by finite element method

A finite element method has been employed for the evaluation of static and dynamic performance of the VMC column subjected to different loading conditions. As a primary investigation, the effect of cutting forces on the VMC has been modeled and analyzed. In addition to cutting forces, which occur only during machining, inertial loads acting on the column due to automatic tool changer (ATC) or tool magazine and the weight of spindle head need to be considered for a complete analysis of a VMC column as a part of a typical machine tool. The finite element model validated by the experimental modal analysis is used to perform static structural analysis considering the following loads:

1. Cutting forces for different machining operations.
2. Cutting forces, ATC forces, and 10% of spindle head weight.

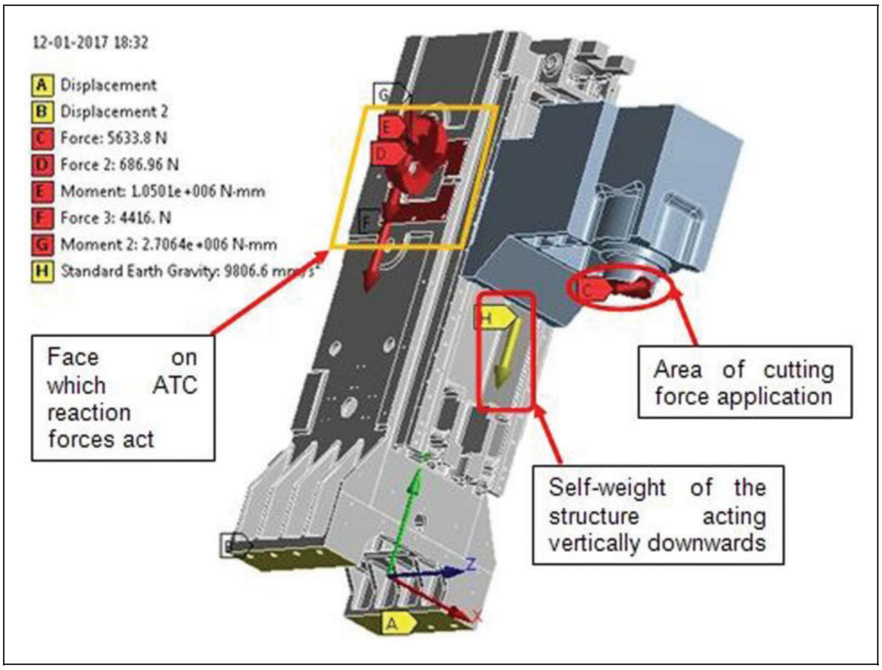

Figure 8. Loading and boundary conditions.
ATC: automatic tool changer.

Table 5. Comparison of results of static analysis.

	Cast iron column		Epoxy granite column	
Loading condition	Deformation at spindle head nose (μm)	Maximum principal stress (MPa)	Deformation at spindle head nose (μm)	Maximum principal stress (MPa)
Cutting forces, ATC forces and 10% spindle head weight	76.8	7.9	277	8.0
Cutting forces, ATC forces and spindle head weight during failure of counterbalance system	82.3	7.8	293.9	7.8

ATC: automatic tool changer.

3. Cutting forces, ATC forces, and 100% of spindle head weight (during failure of counterbalance system).

Static analysis considering only cutting forces for different machining operations

It is essential to investigate the static performance of VMC column subjected to the extreme cutting forces in various directions. A typical magnitude of cutting forces associated to the type of cutting operation and the direction of feed is shown in Table 2.

Further, the position where the spindle head is at the extreme top of the column is considered so that the column experiences the maximum bending moment as shown in Figure 5(a).

Static analysis has been carried out considering the assembly of column and spindle head where spindle head was assumed rigid by applying hybrid modeling technique.[30] The column was constrained in order to arrest displacements in "X" and "Y" directions at the bolt locations in the bottom flanges. The "Z" displacement was arrested at the resting face. The cutting forces were applied at the spindle end at the mounting of the milling cutter. The model was meshed constantly with tetrahedron elements followed by the mesh convergence in order to find the optimal mesh size. Static structural analysis of the column has been carried out for three worst-case conditions specified in Table 2. The deformation at spindle head nose and the maximum principal stress distribution for cast iron column considering milling feed along Y-axis are shown in Figure 6.

The maximum deformation of 85.8 μm was observed for milling feed along Y-axis as shown in Table 3. A combination of milling operation and the feed along Y-axis has been considered for further analysis of VMC column.

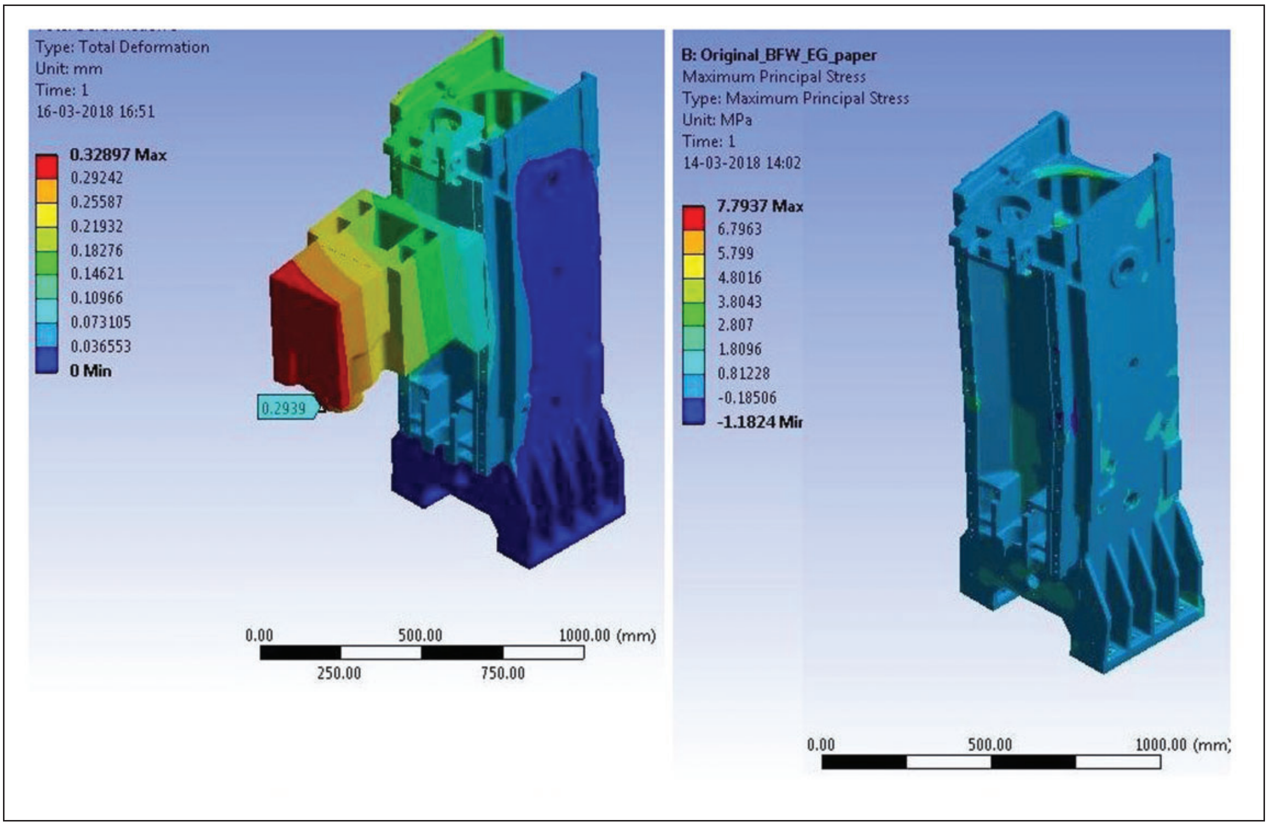

Figure 9. Deformation pattern and stress distribution in CI column for case II loading.

Influence of ATC and spindle head on column

In addition to cutting forces, which occur only during machining, inertial loads acting on the column due to automatic tool changer (ATC) or tool magazine and the weight of spindle head need to be considered for analysis. The ATC has a capacity of holding a maximum of 24 tools and it is attached to the side wall of the column. The ATC weighs about 4500 N whose center of gravity (CG) lies at an offset from the column face and tends to produce a moment that bends the column sidewise. Since the geometry of a typical ATC is complex, a simple bracket structure, which has an equivalent mass with location of CG as that of the actual ATC was modeled as shown in Figure 7. The FEA has been carried out to determine the reaction forces and moments induced on the column and are shown in Table 4.

Furthermore, in addition to ATC forces, the weight of spindle head of 4000 N also needs to be considered for a complete analysis of a VMC column. The spindle head moves over the linear motion guide ways on the column through ball screw and nut assembly. In order to prevent the loading on ball screw, the VMC column has a counterbalance system, which takes up to 90% of the spindle head weight and only 10% of the spindle head weight acts on the column. The present analysis considers the following two cases in addition to cutting force and ATC weights: (I) Working of counter balance system causing only 10% of spindle head weight acts on column (40 kg); (II) Failure of counter balance system causing 100% of spindle head weight to act on the column (400 kg). The loading and boundary conditions for the second case are shown in Figure 8. The FEA has been carried out by considering the above two cases for the existing cast iron structure and the results are tabulated in Table 6.

Although cast iron is the primary choice for machine tool industries due to its better good damping with relatively high material strength and the better machinability among the structural metals, the inherent problems such as chattering has been detected in the machine tool structure during machining. It adversely affects the tool life, machining integrity, surface quality, and geometric accuracy of the workpiece. Therefore, the present work focuses on replacing cast iron with EG for the VMC column. The FEA has been carried out by considering the above two cases with EG as a structural material and the results are summarized in Table 5. The material properties used for EG are Young's modulus $(E) = 30\,\text{GPa}$, Poisson's ratio $= 0.25$, and density $(\rho) = 2300\,\text{kg/m}^3$. The design of EG column has been developed through various modifications considering cast iron column design as a reference. The very first design of a EG column, which has a resemblance with the cast iron column shows higher deformation as compared to the cast iron structure. The deformation at spindle nose for EG column (case II) is found to be 293.9 µm, which is approximately 3.6 times higher than the deformation value of CI column (82.3 µm) as shown in Figure 9. The increase in deformation is attributed to the modular ratio of 3.6 between cast iron and epoxy granite material. A need for the use of additional strength using steel reinforcement has been recognized as the stiffness of EG column found to be significantly lower than the cast iron column structure.

Design and analysis of steel-reinforced epoxy granite VMC column by FEM

In order to achieve equivalent stiffness as that of cast iron, the basic dimensions of EG made column need to be increased, which lead to the changes in functional dimensions of the column. However, changes in functional dimensions are not desirable for the ease in assembly. It leads to the reinforcement of the EG structure with a material having higher Young's modulus in order to achieve the required cumulative static stiffness of the structure. The present work focuses on improving the static characteristics of EG column with steel reinforcements. Nine different reinforcement configurations have been explored to arrive at the equivalent static stiffness.

The longitudinal circular stiffeners in the existing cast iron column are removed for analysis since it is difficult to fabricate such complex parts using EG material. Initially, the column has been reinforced with four 6 mm square rods (design configuration-I) in the front face of the column along the tension side. The FEAs have been carried out by applying cutting forces, ATC, and spindle head weight. The number of steel rods have been increased gradually in the EG structure in order to increase the cumulative structural strength using reinforcement. The column has been reinforced with 12 vertical rods placed closer to the vertical places throughout the column (design configuration-II). However, increasing the number of steel rods along the vertical axis of the column was found to be an insignificant approach in order to increase the structural stiffness. Therefore, steel rods in the form of horizontal stirrups (design configuration-III) have been introduced at equal intervals in order to increase the lateral stiffness of the EG column. Nevertheless, the addition of steel rods either in vertical or lateral directions in the EG column structure was found to be insignificant in order to increase the static stiffness of the column. Therefore, the wall thickness of the EG column has been increased from 18 mm to 30 mm (design configuration-IV). The result shows a considerable improvement of 40% when compared to the previous design. Design configuration-V was achieved by increasing the size of the steel rod from 6 mm to 12 mm and by having the EG wall thickness as 30 mm.

The steel reinforcements as part of previous design configurations were made by welding square rods at multiple locations. Welding at multiple locations induces residual stresses and also increases the complexity in producing the steel reinforcements in large numbers. In order to overcome such manufacturing infeasibility, standard L-sections, T-sections, and flats have been tried out in design configuration-VI. L-sections of dimension $3 \times 40 \times 40\,\text{mm}^3$ form the external structures, which are held together by interconnecting flats at equal intervals. In order to improve the torsional strength of the structure, cross ribs have been provided at the centers. Two T-sections of dimension $6 \times 40 \times 40\,\text{mm}^3$ were attached closer to the front face. Further, the wall thickness of column has been increased to 50 mm in order to achieve better static stiffness. Although the structural deformation at the nose of the spindle head was found to be decreased due to the above series of modifications in the EG column structure, a necessity of further design has

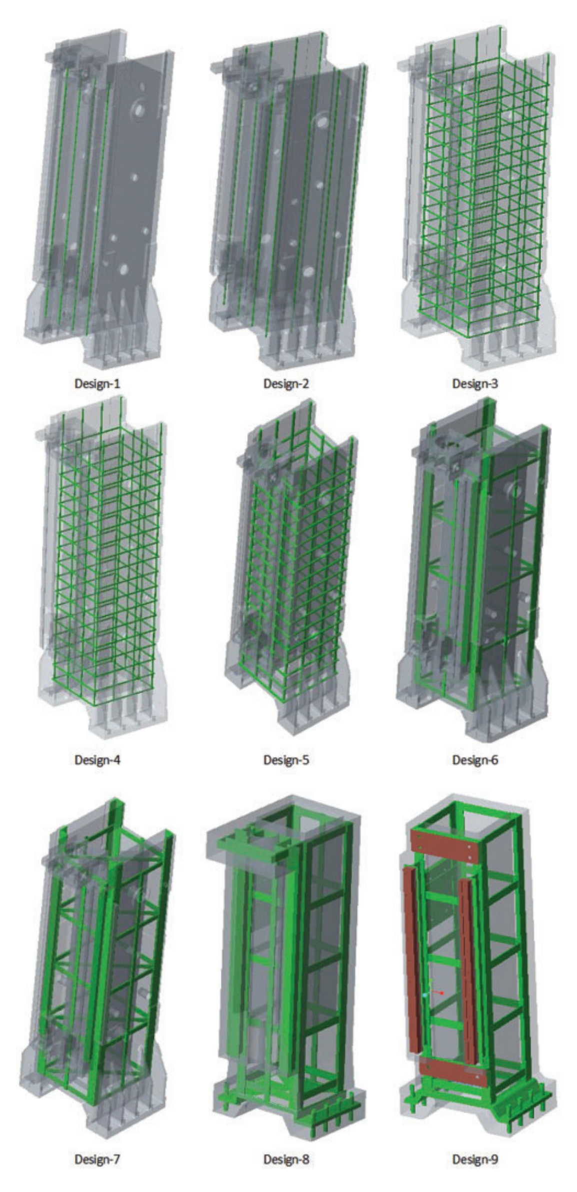

Figure 10. Design configurations of VMC.

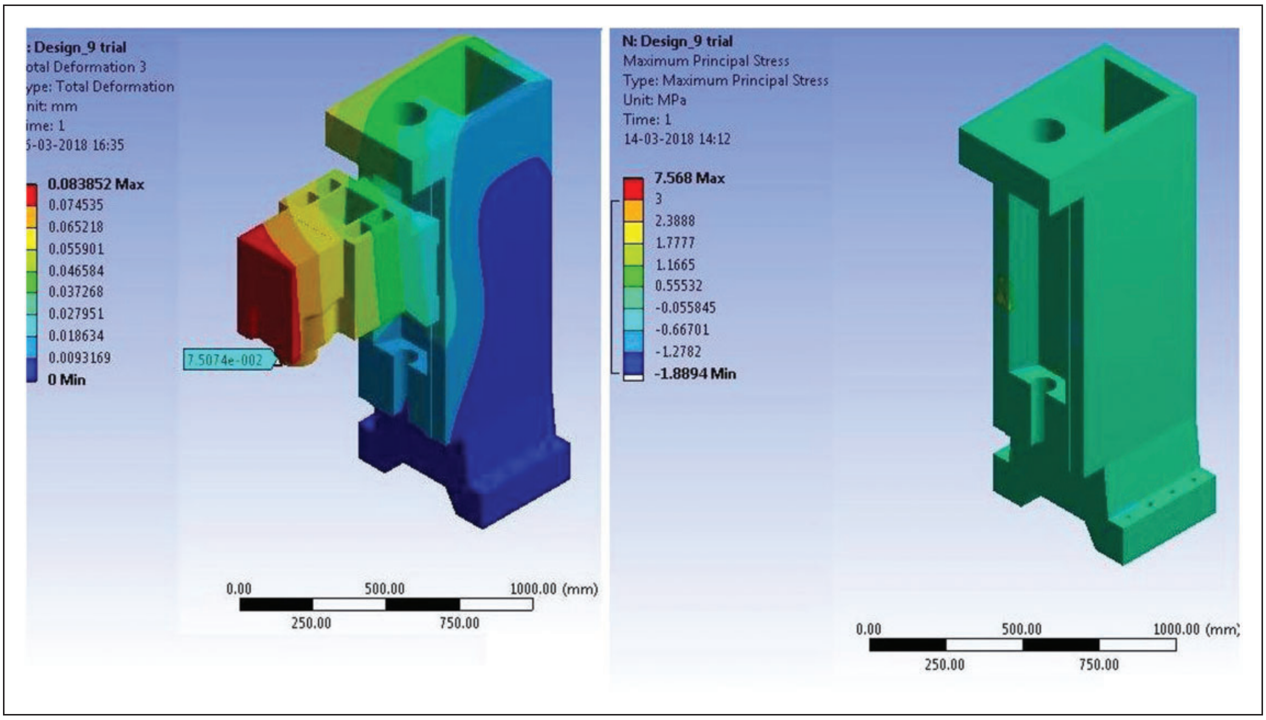

Figure 11. Deformation at spindle head nose and stress plot for milling feed along *Y*-axis.

Table 6. Results of various design configurations of VMC Column.

Design configuration	Column wall thickness	Size of square rod (mm × mm)	Reinforcement configuration	Deformation at spindle head nose (μm)	Maximum principal stress (MPa)	Total mass (kg) (mass of reinforcement)
Cast iron	18	–	–	82.2	7.8	660
Epoxy granite	18	–	–	294.8	7.8	212
Design I	18	6 × 6	Four rods on tension side	449.6	7.7	183 (2)
Design II	18	6 × 6	12 vertical rods	445.9	16.0	186 (5)
Design III	18	6 × 6	12 vertical rods with 17 horizontal stirrups	432.7	23.6	192 (13)
Design IV	30	6 × 6	12 vertical rods with 17 horizontal stirrups	268.2	12.6	247 (13)
Design V	30	12 × 12	12 vertical rods with 17 horizontal stirrups	255.8	10.1	263 (35)
Design VI	50	Nil	L-section (mm) – 3 × 40×40 T-section (mm) – 6 × 40×40 Flats are used for interconnection	146.1	10.6	466 (35)
Design VII	60	Nil	L-section (mm) – 6 × 50×50 T-section (mm) – 6.5 × 50×50	136.3	10.8	532 (59)
Design VIII	60	Nil	L-section (mm) – 6 × 50×50 T-section (mm) – 9 × 75×75 25 mm plate for ATC mount 20 mm plate for platform	75.9	7.1	619 (138)
Design IX	60	Nil	Two 20 mm plates for lead screw mount in addition to the standard sections used in design VIII	75.2	7.5	542 (161)

ATC: automatic tool changer.

been identified to match it to the existing cast iron structure. The wall thickness of the column was further increased to 60 mm along with the increase in the dimensions of standard L-sections and T-sections to $6 \times 50 \times 50\,\text{mm}^3$ and $6.5 \times 50 \times 50\,\text{mm}^3$, respectively. As a result, design configuration-VII was evolved, which has a platform of 20 mm thickness. FEAs have been carried out for design configuration-VII, which leads to the necessity for further design modifications.

Table 7. Comparison of results of modal analysis.

	Natural frequency (Hz)	
Mode number	CI column	Design configuration-IX
1	92	89
2	109	103
3	245	274
4	375	471
5	403	487

Steel pipes of ID 18 mm have been welded as reinforcement in order to bolt the column to the base of the VMC. The T-section provided earlier has been increased in size to $9 \times 75 \times 75\,\text{mm}^3$ as the entire spindle head weight is supported by it. An extension has been provided at the top to facilitate the attachment of lead screw mount bearings.

The deformation of design configuration-VIII was comparable (75.9 μm) to that of the cast iron column; however, the manufacturing aspects needs to be improved for the ease of the manufacturing of the EG column. The lead screw mount needs to be machined to closer tolerance so that its positioning of the same can be maintained accurately. However, machining epoxy granite to such close tolerances can be tedious and time consuming. As a solution, the lead screw mounts were made of cast iron material and were attached to the EG column. In order to

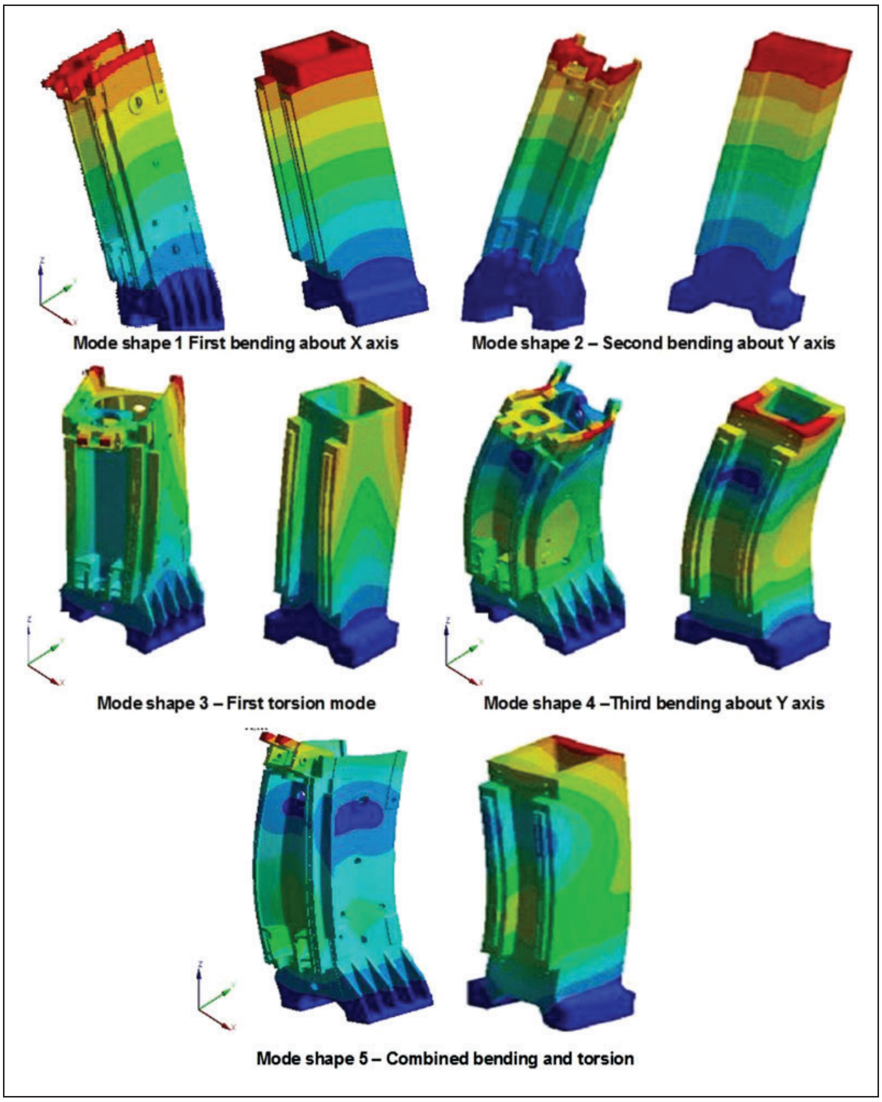

Figure 12. Mode shape–CI column and design configuration IX.

facilitate the lead screw mount attachment, plates were welded to the steel reinforcement. Further, two bars were machined and welded to the T-section, which serves the purpose of mount for LM guideways in order to avoid finishing of the EG structures for the required close tolerances. The platform has been made hollow to facilitate the removal of core and to reduce the weight of steel reinforcement. Further, 40-mm-thick plate was attached to the side wall of column over which ATC could be mounted. Design configuration-IX obtained is shown in Figure 10 and the deformation plot at the spindle head nose is shown in Figure 11. The total deformation of design configuration-IX was 62 µm, which was found to be comparable to that of the cast iron column. The details of steel forms used in all the design configurations are mentioned in Table 6.

Modal analysis on steel-reinforced epoxy granite column (design configuration-IX)

It is essential to perform modal analysis for the proposed configuration (design configuration-IX) in order to characterize the dynamics of the structure accurately. A fixed–free modal analysis was carried out by using FEM to determine first five natural frequencies and mode shapes of the structure. The column was constrained using eight bolt holes at the bottom and modal analysis was carried out for both CI column and design configuration-IX and the results are shown in Table 7. The mode shapes of the same are shown in Figure 12.

Design configuration-IX has the first mode at 89 Hz as forward bending motion along the Y–Z plane; second mode at 103 Hz as the lateral bending motion along the X–Z plane; third mode at 274 Hz as the twisting motion about Z-axis; fourth mode at 471 Hz as the second lateral bending motion along the X–Z plane; fifth at 487 Hz as the second forward bending motion along the Y–Z plane. Similar mode shapes were observed for CI column also with the frequencies as shown in Table 7.

The results reveal that the natural frequencies for the first two modes are close and significant improvements for design configuration-IX were observed in the range of 12–20% for the higher order modes. The increase in natural frequency is attributed to the reduction in mass of the structure of about 118 kg and the improvement in the structural stiffness.

Conclusion

This study presented the investigations on the alternative composite material (epoxy granite) to be used in the vertical machining center column in order to improve the static and dynamic characteristics. EG provides better damping capacity than cast iron. But for its use in machine tool column, it requires steel reinforcement to provide equivalent stiffness as that of a cast iron column. Experimental modal analyses have been performed in the existing cast iron column in order to find out the natural frequency and mode shapes. To validate the model, the natural frequencies of the CI column are also found through numerical technique and the results are validated by experimental evaluation. Initially, static analysis has been carried out on the existing VMC column by considering only cutting forces and maximum deformation of 85.8 µm occurs for milling feed along Y-axis and it is considered for further analysis. Further analyses have been carried out by considering 10% and 100% ATC weight along with cutting forces and the results show that the deformation of the VMC column made with cast iron and epoxy granite material was found to be 82.3 µm and 293.9 µm, respectively. In order to achieve equivalent stiffness as that of cast iron column, nine different design configurations were evolved iteratively and numerical investigations were carried out. The proposed final configuration with standard steel sections is found to have a static stiffness equivalent to that of the existing cast iron column and natural frequencies of about 12–20% higher than the cast iron structure. The results reveals that a design configuration with standard steel sections and provisions for external attachments is found to be equivalent to cast iron column in terms of static stiffness. Thus, it can be a viable solution to use these structures in the manufacturing of machine tools in order to improve the performance of the machine tool thereby increasing its machining characteristics.

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