ANNALS OF FACULTY ENGINEERING HUNEDOARA
– INTERNATIONAL JOURNAL OF ENGINEERING
Tome X (Year 2012) – FASCICULE 2 (ISSN 1584 – 2665)

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ANALYSIS OF ALTERNATIVE COMPOSITE MATERIAL FOR HIGH SPEED PRECISION MACHINE TOOL STRUCTURES

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ABSTRACT: *Structure material plays a vital role in precision machine tools, which are expected to produce the parts within the specified accuracy of shape and dimensions together with the required surface finish. The shape of the work piece depends on the instantaneous relative position of the tool and the work piece and, therefore, of the machine parts which carry them. Hence, a structure which possesses high structural stiffness and high damping is to be selected. Composite materials such as, epoxy granite, exhibit good mechanical properties such as high stiffness and damping ratio at a lesser weight, compared to conventional materials. However, for the same stiffness, the basic dimensions of the structures vary. In this study, the mechanical characteristics of an epoxy-granite beam are studied against the conventional materials such as cast iron and steel with reference to constant stiffness. It is observed that, for same stiffness, the epoxy granite structure offers a considerable weight reduction, along with high damping characteristics.*
KEYWORDS: *structure, material, epoxy-granite, stiffness, damping*

INTRODUCTION

Structural materials used in a machine tool have a decisive role in determining the productivity and accuracy of the part manufactured in it. The conventional structural materials used in precision machine tools such as cast iron and steel at high operating speeds develop positional errors due to the vibrations transferred into the structure. Studies carried out by researchers to build stiff structures by increasing the outer wall thickness for conventional materials indicates an improvement in stiffness, but not matching with the increased mass of the structure. Hence an alternative material which possesses good damping and stiffness has to be developed as structural materials

To meet this challenge, the recent research on high speed precision machine tools aims at developing an alternative material for the structures which exhibit good damping and stiffness characteristics. The best way to obtain both high damping and high structural stiffness is to employ composite structures having high damping characteristics and moderate stiffness. In terms of properties such as chemical resistance, ease of production, workability, high strength-to weight ratio, low thermal conductivity, and damping, plastic and composite materials are increasingly used in the manufacture of machine tools.

Studies carried out on composite machine tool structures proved it to be an alternative for the challenge posed by the conventional materials. Research is on, to study the characteristics exhibited by polymer concrete structures by varying compositions of ingredients in it [1-5]. Results indicate that, the epoxy granite composite structures provide a higher damping ratio and stiff structure. Also, it is observed that the high stiffness, damping and coefficient of thermal expansion characteristics of epoxy granite as compared to other polymer concrete structures and conventional materials makes it more preferable material for precision machine tool structures.

OBJECTIVES AND METHOD OF STUDY

From the literature, it is observed that, many studies were done to find out the suitability of composite materials in replacing the conventional materials. However, a few or no studies were found to compare the material properties when the parts possess constant stiffness. A study of materials based on constant stiffness structures will provide a better comparison of size, weight damping properties etc., for the machine tool structure manufactured using alternative composite material suggested for it. In this study, epoxy granite, steel and cast iron structure exhibiting constant stiffness were modeled analytically and tested numerically. A rectangular beam has been selected for analysis to simulate the machine tool components such as bed, beam and ram. The analytical method was used to arrive at the dimensions of the structures which provide same stiffness. The dimensions calculated analytically were confirmed by testing them numerically. The test specimens of required size were manufactured and their characteristics were studied conducting modal analysis.

ANALYTICAL STUDY

Analytic studies were done to arrive at dimensions for the rods selected. From the first principles for a beam subjected to bending loads, the deflection (y) is given by,

$$y=\alpha.F.L^3/EI \qquad (1)$$

where 'α' is a constant, 'F' is the load applied, 'L' is the length of the beam and 'EI' is the section modulus.

$$\text{The stiffness, } k = F/y = EI/L^3 \qquad (2)$$

Test specimens made of, cast iron (FG 250), steel (C15) and mineral cast (epoxy granite) were selected as structural materials for analysis, with the following assumptions,

(1) The beams have constant stiffness i.e, the beams will produce equal deflection when same load is applied on them.

(2) The length of the beam (L) is a constant and taken as 400 mm.

(3) The aspect ratio, breadth (b) to depth (d) for the beam is taken as 1/2 (ie, d=2b)

Then, for the test specimen the variables are the Young's modulus (E) which is a material property and the depth of the beam (d).

On rewriting equation (2) in terms of depth, d and the Young's modulus we get, the depth is inversely proportional to $(E)^{1/4}$.

The properties of the materials taken for analysis are given in table1.

Table 1: Material properties for the specimen

Material	Density (ρ), kg/m³	Modulus of Elasticity (E), GPa	Poisson ratio, (υ)	Specific weight (E/ρ)
Cast Iron (FG-250)	7100	100	0.3	0.011
Steel (C-15)	7850	210	0.25	0.027
Epoxy Granite	2100	30	0.25	0.015

Now, calculating the depth ratio for the material specimens we obtain,

$$d_{E/G} = 1.35 \text{ times } d_{Cast\ Iron} \text{ and } d_{E/G} = 1.63 \text{ times } d_{steel}. \qquad (3)$$

This indicates that to maintain a constant stiffness for a structure made of mineral cast (epoxy granite) material, the breadth and depth has to be increased by 35% as compared to cast iron and 63% as compared to steel.

Also, it can be observed that, to maintain constant stiffness the required area of cross section for the epoxy granite structure is 1.82 times that of cast iron and 2.66 times that of steel structures. Since, the beams were of constant length, the volume (V) increase for E/G specimen will be same as the increase in cross sectional area.

Hence the mass of E/G specimen ($m_{E/G}$), compared to cast iron and steel will be about 1.82 and 2.66 times its density respectively which gives,

$$(m_{E/G}) \text{ w.r.t cast iron} = 1.82 \times 2100 \times V_{CI} \text{ and } (m_{E/G}) \text{ w.r.t steel} = 2.66 \times 2100 \times V_{steel} \qquad (4)$$

In other words, there will be a reduction in mass by 43.6% and 25.5% for E/G specimen as compared to cast iron and steel specimen respectively.

The dimensions for all the specimens were selected such that when a load of 10 N is applied, the beam will deflect by 0.1mm, so that they will have a constant stiffness of 100 N/mm. The calculated mass and the dimensions for the specimens are shown in table 2.

Table 2: Dimensions for the specimens

Material	Dimensions, bxdxL mm	Mass, kg
Cast Iron (FG-250)	10.8x21.6x400	0.662
Steel (C-15)	8.95x17.9x400	0.503
Epoxy Granite, (E/G)	14.6x29.2x400	0.358

Table 3: Deflections obtained from numerical analysis

Specimen	Deflection (mm)
Cast Iron (FG-250)	0.097
Steel (C-15)	0.098
Epoxy Granite	0.093

NUMERICAL ANALYSIS

To check the dimensions found out using analytical method for cast iron, steel and epoxy granite specimens, the beam structures were modeled numerically using ANSYS 10 software. The dimensions for the specimens obtained analytically were used to model the structural beams. The properties for the specimens used were given in table 1. To obtain the deflections, a load of 10N was applied at the free end of the beam structure modeled, as shown in figure 1. The deflection obtained in the Y-direction is tabulated in table 3. From the deflections obtained, it is observed that, when a load of 10N is applied at the free end of the modeled beams, they deflect by 0.1mm (±7%). Hence we can conclude that, the test beams with the calculated dimensions have a constant stiffness of 100 N/mm.

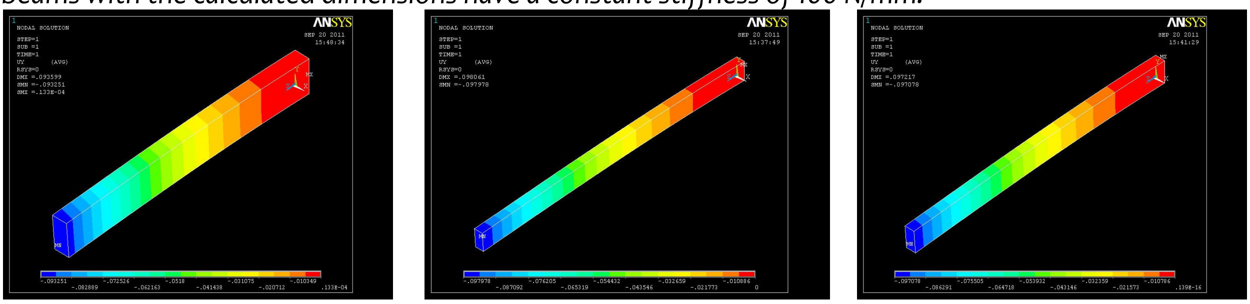


Figure 1. Deflection in structural beams measured using ANSYS 10: (a) Epoxy Granite, (b) Steel and (c) Cast iron

PREPARATION OF TEST SPECIMEN

The epoxy granite specimen was manufactured using the following composition. The coarse (granite material size 0.5-4mm) to fine (material size less than 0.5mm) aggregate material ratio was taken as 88% by weight, 12% by weight of epoxy resin (Araldite LY 556 CS 110KG Q2) including 2% by weight of resin mixture as hardener (ARADUR HY 951 IN 20X 1KG I1) has been used as the matrix material. The test specimen was cured for 24 hours at room temperature.

EXPERIMENTAL SETUP

To analyze the results experimentally, an experimental setup as shown in fig.2 was developed. The epoxy granite, cast iron and steel test specimens of required size has been manufactured as single pieces and fixed into the test set up as shown in figure 3.

To test the constant stiffness characteristics for the structures developed, the deflections were obtained experimentally by applying a load of 10 N in the hanger (weight inclusive of the hanger attached at the end of the beam). The deflections were obtained using a 10 micron Baker make, plunger type dial gauge. The deflections noted down from the dial gauge and weights of the specimen manufactured are given in table 4.

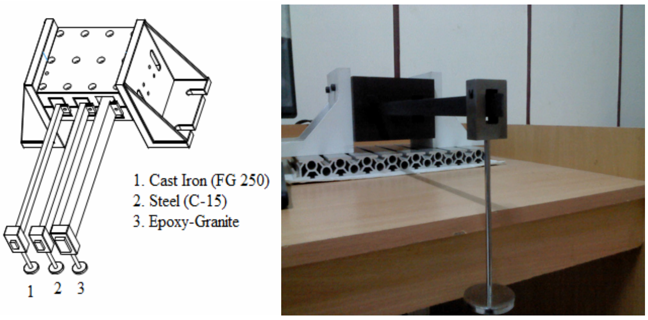


Figure 2. Experimental setup for measuring stiffness

Table 4: Deflections obtained from experiment

Specimen	Deflection (mm)	Stiffness N/mm	Mass (kg)	% mass change w.r.t E/G
Cast Iron (FG-250)	0.094	106	0.687	44.98
Steel (C-15)	0.097	103	0.508	25.59
Epoxy Granite (E/G)	0.096	104	0.378	-

An experimental set up as shown in figure 3 is used to conduct the modal analysis. The components of the set up are as given below.

a) *LabVIEW 8.2 software*
b) *3079, Dytran make, Miniature piezoelectric charge accelerometer, sensitivity 96.72 mV/g*
c) *NI 9234 DAQ*
d) *Impact Hammer: PCB086CO, modally tuned.*
e) *BNC cables*
f) *Connecting wires*

The accelerometer is pasted at the point where the maximum amplitude is observed. The DAQ card takes signals from the accelerometer and the impact hammer. The response of impact on the specimen is obtained through FFT graphs using LabVIEW 8.2 Software.

Figure 3: Experimental setup for modal analysis

RESULTS AND DISCUSSIONS

The stiffness calculated from the deflections obtained through numerical and experimental studies were compared with the analytical value of 0.1mm as shown graphically in figure 4. From the figure we can observe that, the deflections, obtained experimental are close to the values calculated analytically and the deviations are within limits (±6%). Hence, we can approximate that, the specimen manufactured have equal stiffness.

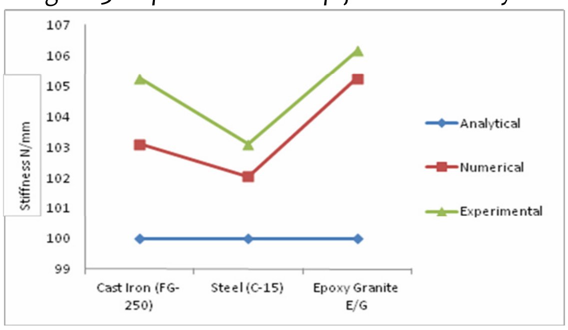


Figure 4. Comparison of Stiffness for test specimens

In figure 5, the mass of the test specimen found analytically and experimentally were compared. The variation in mass for the test specimen manufactured and used for experimental purposes lies within limits of ±5% and is negligible.

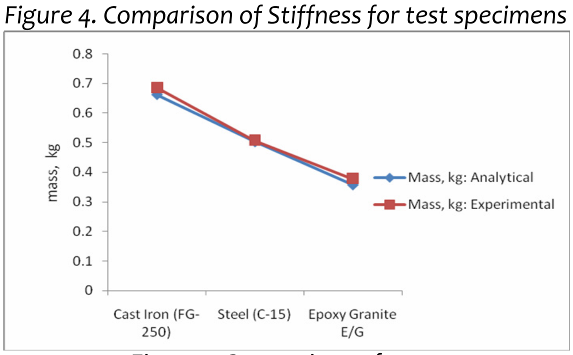
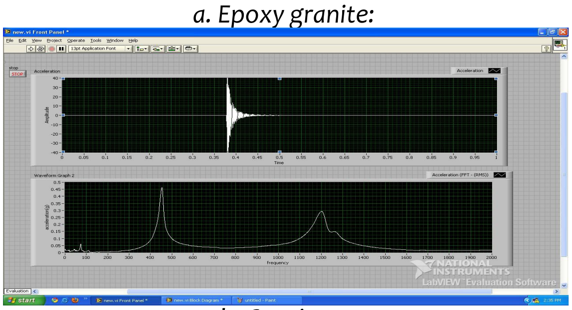


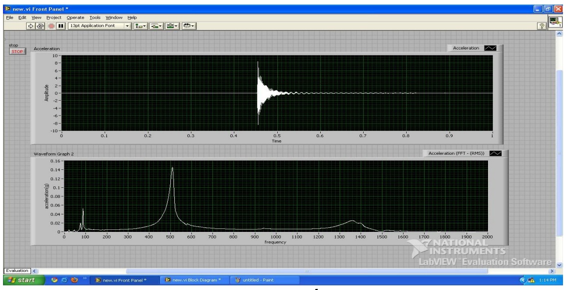
Figure 5.Comparison of mass for different material structures

The weight for the specimen prepared was found out using a balance. A reduction in mass of 44.7% and 17.95% were observed for the epoxy granite specimen when compared to cast iron and steel beams *having same stiffness. The ±8% difference in mass reduction obtained with test specimens obtained as compared to analytically obtained value could be due to the slight variations in dimensions for the specimen prepared. However, the variations are within limits and can be neglected. The reduced mass for epoxy granite structure as compared to conventional materials is an added advantage for high speed machine tool structures. Hence, the use of epoxy granite material for high speed precision machine tool structures is preferable.*

a. Epoxy granite:



b. Cast iron:



c. Steel:

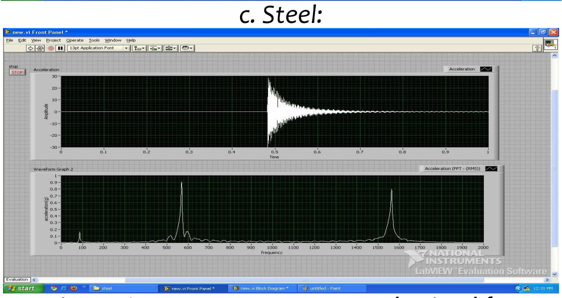


Figure 6: Frequency spectrum obtained for structures from modal analysis

Figure 6a, 6b and 6c shows the frequency response spectrum obtained for the epoxy granite, cast iron and steel test specimens from the modal analysis. The fundamental frequencies and the damping factors, ζ, calculated using the half power band width method expressed as [6]

$$\zeta = (f_2 - f_1)/ f_r \quad (5)$$

The fundamental frequency, damping time and the damping ratios found out for each specimen through modal analysis are tabulated in table 5.

An enhancement in damping ratio for the epoxy granite structure, 22% more compared to cast iron structure and an order higher than that of steel structures having constant stiffness were observed. It is also detected that the epoxy granite structure dampens out the vibrations at a faster rate (0.07seconds) while compared to cast iron (0.1 seconds) and steel (0.32 seconds) structures.

Table 5: Characteristics obtained from modal analysis

Material	Damping Time (Seconds)	Natural Frequency (Hz)	Damping Ratio (ζ)
Epoxy Granite	0.07	80, 450,1200	0.022
Cast Iron (FG-250)	0.1	85, 500,1350	0.018
Steel (C-15)	0.32	87, 570, 1550	0.007

This could be attributed to the ductile nature imparted by the aggregates present in the epoxy granite structure.

These characteristics of epoxy granite material make it a promising alternative material for high speed machine tool structures.

CONCLUSIONS

Test specimens modeled and manufactured with cast iron, steel and epoxy granite materials for constant stiffness helps to compare the properties exhibited by the structures more clearly. From analytical, numerical and experimental studies carried out, it is observed that for same stiffness offered by the structures, the epoxy granite structure offers a sharp reduction in mass along with high damping ratio. It dampens out the vibrations induced at a faster rate compared to steel and cast iron structures. Hence it is a promising alternative material for conventional materials used in high speed precision machine tool structures.

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