

Numerical modeling and mechanical analysis of composite beam design for hybrid CNC systems

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ABSTRACT

This study evaluates the mechanical performance of a composite beam designed for a hybrid CNC cutting system equipped with both laser and plasma heads. A parametric 3D CAD model was developed in Siemens NX 1899 and analysed using Simcenter 3D Structure 2020.1 with Simcenter Nastran. Static simulations were conducted. Six design variants were tested, varying in shell thickness (2.4–7.2 mm), beam width (170–200 mm), and reinforcement configuration (none, vertical, cross). The preferred configuration variant (Test 6: 4.8 mm shell, 200 mm width, cross stiffeners) achieved a maximum Z-axis displacement of 0.0209 mm and an average displacement of 0.0298 mm at a mass of 22.45, thereby satisfying the adopted stiffness and mass criteria. These findings suggest the suitability of composite as a structural material in hybrid CNC systems, offering enhanced precision, energy efficiency, and operational reliability.

Keywords: computerized numerical control systems, beam of cutting plotter, composite materials, FEM structural analysis, parametric analysis.

INTRODUCTION

Recent developments in advanced manufacturing technologies, along with the ongoing drive to enhance production efficiency by increasing operational speeds, have intensified interest in the application of composite materials in CNC systems designed for lightweight, high-performance operation. In particular, machines that combine modular laser and plasma cutting heads require beam structures that offer both mechanical rigidity and preferred mass, to ensure positioning precision. Traditional materials, such as cast iron and steel, despite their high stiffness, significantly increase the system's inertia and energy consumption, limiting the speed and responsiveness of CNC operations. This study investigates the mechanical performance of a composite beam for CNC systems, focusing on displacement under static operational loads.

Overview of CNC machines and their components

Composite materials are currently a highly popular engineering solution used across a wide spectrum of technical applications. Their widespread recognition results from their highly advantageous properties compared to conventional monolithic material structures [1]. Composite materials are composed of two or more constituents (phases) with differing physicochemical properties, and their combination allows for achieving superior performance characteristics. Depending on the selected components and the manufacturing process, the final product may exhibit high mechanical properties (strength, hardness, wear resistance) [2], thermal properties [3], electrical properties [4], optical properties [5], acoustic properties [6], or tribological properties [7]. The attributes of composite materials contribute to their widespread industrial

use, for example in the aerospace sector (fuselages, wings, thermal shields, turbines), automotive industry (body components, suspension systems) [8], construction (concrete reinforcement rods, composite beams and columns) [9], energy sector (wind turbine blades, protective structures) [10], medicine (implants, prosthetics) [11], marine engineering (ship hulls) [12], and sporting goods (skis, tennis rackets) [13].

CNC machines are highly automated systems used to perform various manufacturing processes across different industrial sectors. Numerically controlled machines are characterised by high precision, accuracy, efficiency, and repeatability of operations, while also reducing the likelihood of human error and minimising material waste. Their use reduces the need for manual labour, limiting the operator's role to programming and supervising the machine's correct operation. The range of CNC machines is extensive and includes milling machines, lathes, drilling machines, cutters (water, laser, plasma), grinders, welders, presses, and even 3D printers, among many other devices. There are also multi-function machines capable of performing different types of processing (e.g., drilling and cutting) on a single workstation. Additionally, CNC machines can be integrated into a coordinated technological system with transport elements, enabling the comprehensive execution of production processes [14]. Numerically controlled machines consist of several basic components, including the controller, drive system, tool for performing material processing, coolant system, supporting frame with a working area, sensor system, and safety system. Depending on the machine's intended application and technical advancement, its structure may also incorporate a range of additional elements such as tool systems, workpiece clamping systems, and cooling systems [5].

Loads and design requirements for CNC beams

The proper functioning of CNC machines requires maintaining appropriate environmental conditions, particularly stable ambient temperature (typically between 18 °C and 22 °C) and humidity (typically between 40% and 60%) in the machine's installation area. Inadequate environmental conditions contribute to the emergence of dimensional deviations due to the thermal expansion of machine components, which negatively impacts the precision of the machining process.

Incorrect humidity levels promote corrosion and may also lead to failures in control systems or disrupt signal transmission due to moisture condensation. Another critical condition for the correct operation of CNC machines is proper leveling and the use of vibration dampers (adjustable anti-vibration feet), which are especially important during dynamic machine operation. Even slight floor unevenness can cause excessive load on the guideways and bearings, leading over time to increased mechanical wear and reduced positioning accuracy. Vibration sources may originate from the machine's own components or external factors, such as other machines or transport systems in the vicinity [15]. Disruptions in the proper functioning of CNC machines may also result from electromagnetic radiation generated by the machine's components or by neighbouring equipment. Such disturbances can cause malfunctions in electronic systems, reducing machine precision. The adverse effects of electromagnetic interference originating from CNC machine components are mitigated during the design stage through the selection of appropriate subassemblies and safety systems. Interference caused by neighbouring devices can be eliminated through careful placement of the machine or the use of barriers and shields that limit electromagnetic emissions. Among the factors contributing to CNC machine malfunctions, contamination should also be noted. Material processing generates various types of dust, which settle on the elements of the head movement systems (e.g., guideways), interfere with cooling systems, or cause disruptions in optical measurement systems. It is essential to maintain both the CNC machine and the workstation in a clean condition and to perform regular maintenance and service activities [16].

CNC cutting machines can be used for cutting, marking, or engraving various types of materials such as metals, wood, plastics, and composites. Depending on the cutting technology used in the machine, it is possible to distinguish between laser cutters (cutting with a laser beam), plasma cutters (cutting with a stream of ionized gas), waterjet cutters (cutting with a high-pressure water stream), and oxy-fuel cutters (cutting with a jet of heated gas under high pressure). The main components of a CNC cutting machine include the supporting structure with a working table, the drive system for moving the cutting head along the X, Y, and Z axes together with a guide lubrication system, a cooling and dust extraction system,

and the controller with associated software [17]. The beam of the CNC cutting plotter is one of the primary structural elements, enabling precise and stable movement of the cutting head along the X and Y axes using the drive system. During machining operations, the beam is exposed to a range of thermal and dynamic loads that negatively affect the positioning accuracy, movement trajectory of the head, and the durability of the structural component. The main loads affecting the beam of the CNC cutting plotter include inertial forces generated during motion, vibrations, and thermal expansion. Static loads result from the mass of the beam and the attached tooling, while dynamic loads are generated during acceleration, deceleration, and direction changes. Vibrations are particularly important and are caused both by the beam's natural frequencies and by vibrations generated during machine operation. Thermal effects are associated with local heating of the component during operation, which contributes to thermal expansion. The combined effect of these various loads leads to permanent geometric deformations of the beam, which disrupt the precision of the machine's operation [18].

Materials used in CNC beams

The negative impact of these loads on the beam is mitigated during the design phase by carefully selecting the geometry and materials for the component. The primary requirements for the beam include ensuring high strength while minimizing mass. High stiffness is essential for maintaining precise movement trajectories and minimizing geometric deviations, while low mass allows for faster beam motion, reduced moment of inertia, and lower dynamic forces [19]. Among the basic materials used in CNC plotter beams are aluminium alloys (e.g., GJL-250 or GJS-500-7), structural steels (e.g., S235 or S355), and cast irons (e.g., AW-6082 or AW-7075). Table 1 presents an overview of the mechanical and thermal properties of the materials commonly used in CNC plotter beams.

The interest in the use of composites in CNC machines is related to the elimination of the disadvantages associated with conventional materials, while focusing on the integration of only their advantages. The main justification for the use of composite materials in the construction of CNC plotter beams is the possibility of creating components with favorable strength properties

while minimizing their mass. Composite structures can exhibit high resistance to vibration and long operational lifespans, which also translates into reduced operating costs due to lower energy consumption required to move the beam. The composite materials that can be used to manufacture CNC plotter beams are primarily fibre-reinforced composites, especially carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). In particular, CFRP composites are characterized by an exceptionally favourable stiffness-to-mass ratio, very low thermal expansion, and high fatigue resistance and vibration damping. The use of CFRP enables a significant reduction in the inertia of the beam's drive system, which allows for higher accelerations and greater precision of motion trajectories [24].

Recent research on hybrid and composite structures in machines

Recent research highlights a growing trend towards the replacement of conventional metallic structural elements in CNC and precision machine tools with composite and hybrid materials designed to improve stiffness-to-mass ratio and vibration damping. Publication [25] demonstrated that hybrid CFRP–mineral-cast beams can be successfully implemented in machine tool crosshead assemblies, achieving approximately 21% mass reduction with preserved static stiffness and a 26% increase in specific stiffness compared to steel references. The publication also emphasised the manufacturability of such designs by embedding or casting CFRP tubes within mineral composites, which reduces thermal deformation and enhances damping performance. These findings confirmed that relatively simple CFRP beam geometries can be effectively integrated into machine tool frames to achieve both dynamic stability and energy efficiency.

Complementary developments concern steel–polymer concrete composite frames, which combine high stiffness with superior damping. Study [26] presented a novel design of a vertical lathe based on a steel–polymer concrete frame, where the polymer filling increased the modal damping ratio of a steel beam by 239% and reduced the dominant resonance amplitude by 81%. The experimental prototype exhibited up to 83% reduction in the relative tool–workpiece frequency response amplitude compared with a purely steel frame, demonstrating a tangible improvement in

Table 1. Mechanical and thermal properties of CNC plotter beams materials [20–23]

Parameter	Cast Iron		Steel		Aluminium	
	GJL-250	GJS-500-7	42CrMo4	S355	AW-6082	AW-7075
Density [g/cm ³]	~ 7.2	~ 7.1	~ 7.85	~ 7.85	~ 2.7	~ 2.8
Tensile strength [MPa]	250–350	500–600	750–1300	470–680	260–310	360–540
Young’s modulus [GPa]	103–118	165–178	~ 210	~ 210	~ 70	~ 72
Thermal expansion coefficient [10 ⁻⁶ /K]	11–12	~ 12.5	10–14	~ 12	~ 23	21–25
Thermal conductivity [W/(mK)]	44–58	~ 35.2	34–45	45–50	170–220	130–160

machining stability. These results substantiate that polymer concrete infill in steel beam or frame structures can substantially suppress chatter and vibration without compromising stiffness, offering a pathway for lighter yet dynamically robust CNC constructions.

A further contribution by [27] employed the rigid finite element method (RigFEM) to model steel–polymer concrete beams and frames. The authors showed that RigFEM allows for low-dimensional dynamic modelling with a reduction of degrees of freedom by up to 99.8% compared with a conventional three-dimensional FEM discretisation employing deformable solid elements, while maintaining a prediction error below 5% for natural frequencies. Such methodology provides an efficient computational tool for early-stage design parametric analysis of hybrid and composite structures, particularly when multiple geometric or material variants must be evaluated. In the context of CNC beam design, RigFEM offers a promising approach for rapid parametric studies of composite cross-sections and reinforcement layouts while preserving accuracy in mode shape prediction.

Publication [28] investigated the application of granite-based composite material (GCM) in a five-axis CNC vertical machining centre. Their results indicated that substituting grey cast iron with a lightweight mineral composite containing epoxy resin and carbon-fibre fillers produced a structure with only one-third of the density of cast iron but capable of withstanding compressive stresses up to 125.8 MPa. Finite-element simulations of the GCM bed showed reductions of 68.9% in maximum stress and 72.6% in strain, along with a 20–30% increase in natural frequencies. These gains directly translated into higher precision and reduced vibration levels during high-speed spindle operation, validating the industrial relevance of mineral and hybrid composites in advanced CNC architectures.

Together, these studies confirm a consistent trend in contemporary machine tool engineering: composite and hybrid beam structure, ranging from CFRP-reinforced members to mineral or polymer concrete infills, provide measurable advantages in mass reduction, vibrational behaviour, and thermal stability. Despite these advances, however, existing works primarily address static or low-frequency behaviour of machine frames and crossheads, whereas systematic analyses of CFRP or hybrid beams in hybrid CNC cutting systems combining laser and plasma processes remain largely unexplored. This identified gap further justifies the present study, which aims to perform a detailed numerical evaluation of a composite CFRP beam under representative static operational loading.

Identified research gap and aim of the present study

The primary objective is to develop and parametric analysis a composite beam structure that ensures high stiffness and minimal deformation under operational loads while maintaining low mass. Specific objectives include:

- Numerical simulation of the beam’s structural response under representative operational loading conditions by means of static finite element analysis.
- Parametric analysis of shell thickness, beam width, and reinforcement configuration in order to minimise mid-span deflection while satisfying the assumed mass constraints.

The central hypothesis posits that a composite beam, when properly parametric analysed in terms of shell thickness, internal geometry, and reinforcement layout, can outperform or match traditional metal counterparts in structural performance, while significantly reducing system mass.

MATERIALS AND METHODS

Research object

The object of the numerical study was a component of a CNC plotter in the form of a composite beam, designed to simultaneously carry two cutting heads – one for laser cutting and the other for plasma cutting. To analyse the mechanical parameters of the beam, a 3D CAD model of the entire CNC plotter was developed using the Siemens NX 1899 environment. The development of the plotter model was based on defined geometric assumptions. These included a working area of 1500×3000 mm, maximum overall machine dimensions of $2085 \times 1832 \times 3550$ mm, a steel frame structure made of $100 \times 100 \times 10$ mm square profiles, the capability to mount two cutting heads, and the inclusion of safety enclosures. In the numerical model only those components that directly influence the mechanical behaviour of the beam were represented explicitly. A simplified CAD model of the complete plotter is shown in Figure 1 for context, while the subsequent sections focus exclusively on the composite beam, which is the actual object of the mechanical analysis.

Beam parametric analysis and strength properties

The subject of the numerical analysis was a composite support beam for cutting heads, made of carbon fiber. The selected material is characterized by a density of 1800 kg/m^3 and a Young's

modulus of 290 GPa in the X direction, 23 GPa in the Y direction, and 23 GPa in the Z direction. The adopted dimensions of the beam were $200 \times 300 \times 1996$ mm. The beam was designed to accommodate a Raytools Fiber BM06K 6 kW laser head and a Berkers PB80 plasma torch. The composite beam model was subjected static structural simulations in Simcenter 3D Structure 2020.1 with Simcenter Nastran, using the Laminate Composites module. This module enabled the definition of the composite's layer structure and the preliminary verification of the model's strength. The static strength analysis of the beam was performed in the Simcenter 3D Structure environment due to the fact that the CAD model of the beam was created in NX, and Simcenter is an integrated software that facilitated and accelerated the work by defining the basic geometry for static studies. The simulations were initiated by preparing the numerical model, which included importing the CAD geometry, generating the finite element (FEM) file representing the idealised structure, defining the geometry within the FEM environment, and assigning material properties and interaction definitions for the composite components. Bonded contact interfaces were defined between the composite beam, the guide rails and the mounting brackets, ensuring full continuity of displacements at the joints and preventing sliding or separation between the connected components. The internal wall stiffeners were modelled as closed-section ribs, located at the joints between the vertical wall and the top and bottom walls.

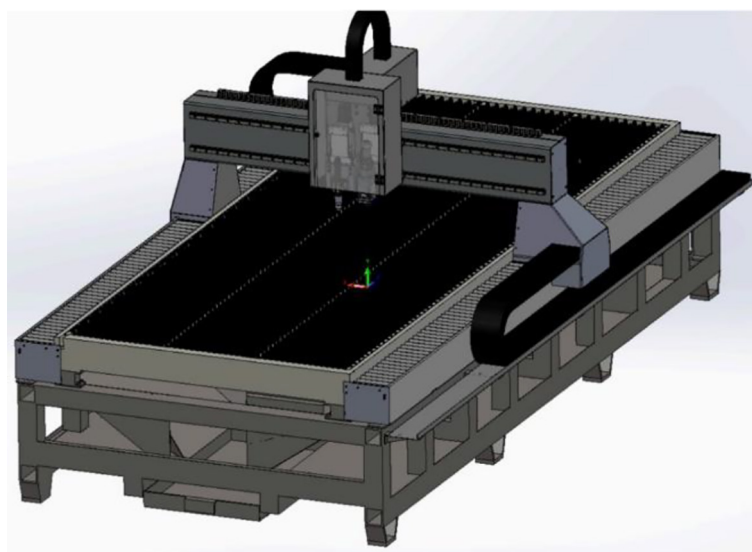


Figure 1. CNC Plotter CAD model

The assembly and simplification of the developed model allowed for the application of a mesh. By simplification, the author mainly meant replacing fasteners with appropriate ties in the FEM analysis. According to the methodology of analyses using finite element methods, this does not adversely affect the reliability of the results. The procedure involved selecting the type of elements to be used in the model. In Simcenter Nastran the composite beam was discretised using CQUAD8 elements, i.e. 2D eight-node quadrilateral shell elements with quadratic interpolation. Each node possesses six degrees of freedom (three translational and three rotational components), which allows the element to capture both membrane and bending behaviour of laminated shell structures. Subsequently, the element size and total number of elements were selected, with special attention paid to avoiding over-refinement of the mesh. The number of elements included in the model was gradually increased until consistent results, in line with the assumed criteria, were obtained. The initial mesh consisted of approximately 90 000 elements with a characteristic in-plane element size of about 9.2 mm in the central regions of the beam. The mesh was then gradually refined, keeping the same geometry and boundary conditions, until the change in maximum mid-span displacement between successive meshes fell below 2%. The final mesh contained approximately 135 000 elements, corresponding to a characteristic element size of about 7.5 mm.

The reinforcements were connected to the outer shell of the beam using glued joints (Glue contact). The “glue joint” used in the model was not a simplification defined outside the solver, but rather a standard feature of the Simcenter 3D / NX Nastran environment used to model glue joints between component surfaces. In the program interface, this connection was defined as Surface-to-Surface Gluing, while on the solver side it is stored as a BGSET card, which describes the pairs of surfaces intended for gluing. In the analyzed model, the composite beam was constructed from several separate geometric parts that are bonded in the actual structure; therefore, glue joints were defined between the corresponding surfaces of the individual components. This modeling approach allows for the representation of the interaction between the bonded parts without the need to explicitly model the volume of the adhesive layer itself, treating the joint as an idealized, continuous surface

connection. The modeling method adopted was justified by the nature of the analyzed structure, as the beam consisted of several parts interacting via adhesive joints, and the goal was to represent their combined load-bearing behavior in a computationally efficient manner consistent with the solver’s capabilities.

During the simulation, forces were applied to the four central bolts of the upper and lower guide rails to simulate the least favourable loading scenario caused by the mass of the cutting heads. The brown vectors represent the degrees of freedom constrained by bonding (Figure 3A). In order to simulate fixed supports at the ends of the beam, limited degrees of freedom were used, restricting displacements in the X, Y and Z directions and rotations around all axes to reproduce rigid mounting in the frame and prevent rigid body movements during the simulation. The rigidity of this connection is crucial for maintaining the appropriate tolerances during the working movement of the CNC machine. To complete the simulation, the assembly was fully constrained, and the edges resulting from the model being cut were permanently fixed. As shown in Figure 3B, both beam ends were modelled as fixed supports, corresponding to the connection to the machine columns, while the loads were applied at the bolt locations of the upper and lower guide rails to simulate the combined mass and inertia of the cutting heads.

The orange arrows in Figure 2 and Figure 3 represent bonded elements, while the blue arrows represent boundary conditions for fastening. Fixed supports (20×20 cm area) were used on both sides of the beam to provide a reaction opposite to the load resulting from the beam. During the static force simulation, force was applied to the four center bolts of the upper and lower guides to simulate the least favorable case of load by the weight of the heads. Figure 4 shows a diagram of the conditions used for the static test. The geometric features of beam are shown in Figure 5.

To achieve a beam structure with the required strength and mass, a parametric analysis process was carried out. This involved modifying selected geometric parameters and analysing the resulting central deflection values. The main parameters considered during the simulation included: the outer thickness of the composite, the beam width, and the type of structural reinforcements used. During the analysis, both the total mass of the beam and the maximum mid-span deflection were

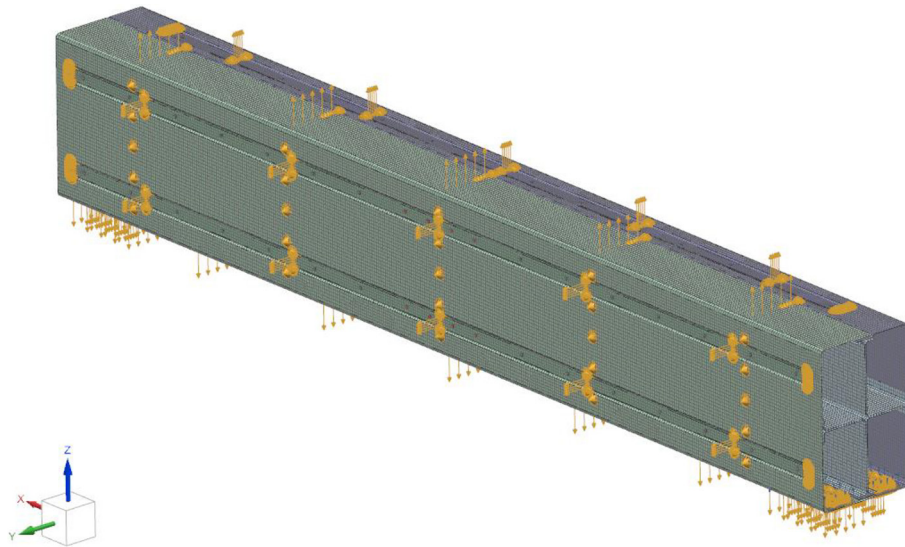


Figure 2. Interactions between elements

evaluated. The parametric analysis focused on examining how changes in geometric characteristics affect the deformation behaviour of the beam. All simulations were conducted using Simcenter 3D Structure 2020.1 with Simcenter Nastran, employing a typical structural analysis procedure – SOL 101. Parametric analysis was conducted through an iterative parametric study that systematically varied the shell thickness, beam width, and reinforcement configuration. For each design variant, the deflection at mid-span under service loading and the total beam mass were evaluated, with design goals of a maximum deflection of less than 0.25 mm and a beam mass of less than 25 kg. The final configuration was selected as the first variant to meet both criteria. The analysis

included six variants of the beam design, each differing in specific parameters, including the type of reinforcement used (either crosswise or vertical). The logic behind the selection and adjustment of each variant is described in Table 2.

RESULTS OF PARAMETRIC ANALYSIS OF BEAM STIFFNESS

The six design variants differed in the combination of composite shell thickness, beam width and reinforcement layout. Tests 1–3 considered beams without internal stiffeners and shell thicknesses of 2.4–4.8 mm, with beam width in the range 170–200 mm. Test 4 introduced vertical

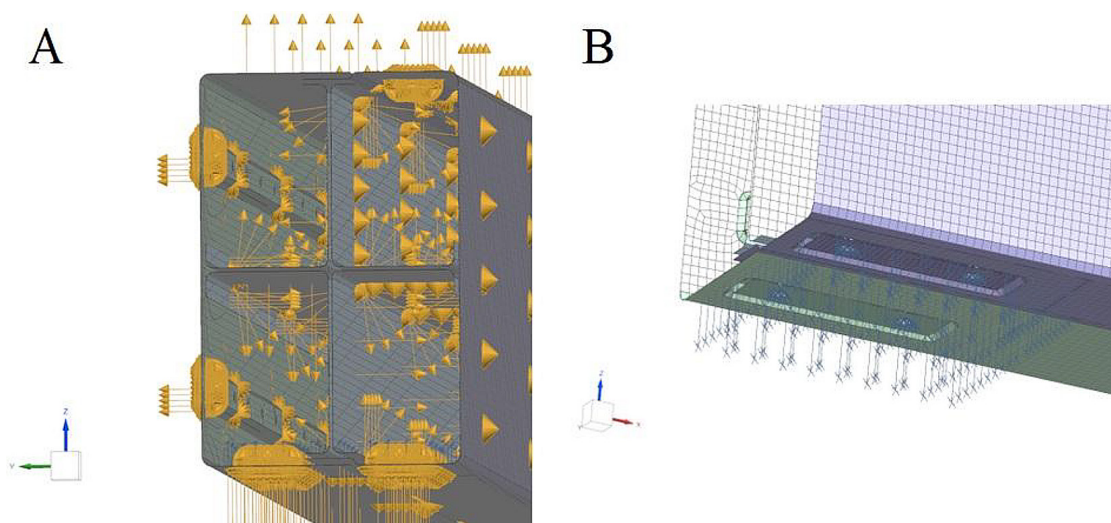


Figure 3. A. Constrained degrees of freedom. B. Fixing the edges of the model

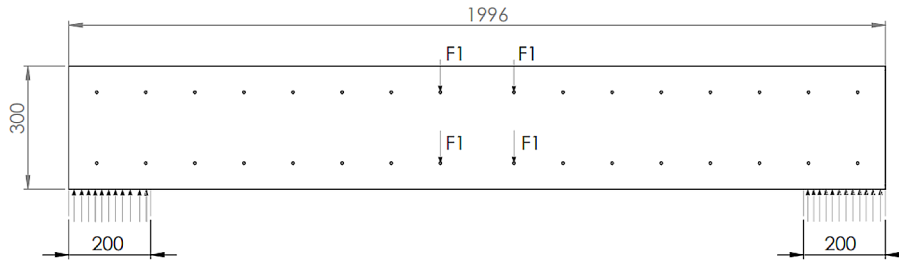


Figure 4. Diagram of the conditions used for the static test

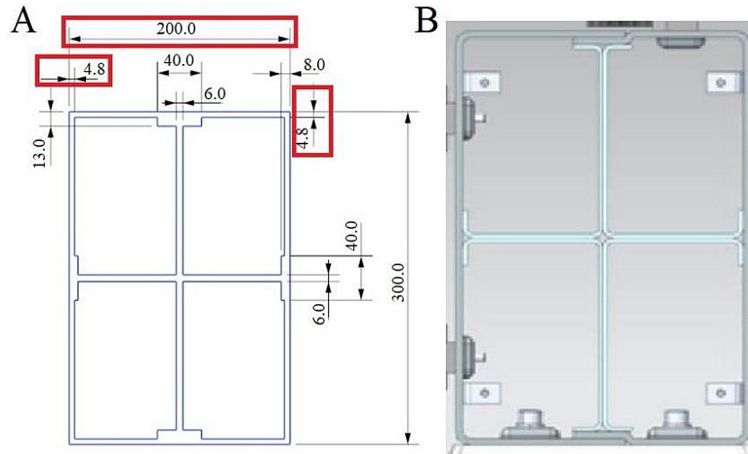


Figure 5. A. The geometric features of cross-sectional view composite beam. B. Cross-sectional view of the CAD model of the composite beam

stiffeners and Test 5 increased shell thickness up to 7.2 mm, which substantially reduced mid-span deflection but increased mass. Test 6 introduced cross-type stiffener and returned the shell thickness to the target value of 4.8 mm, while maintaining the beam width of 200 mm, resulting in a configuration that met the assumed design criteria. Figures 6–9 present, respectively: Z-axis displacements and average displacements obtained for 1 and 6 test cases. Figures 6–9 are only a graphical representation of the results obtained during the analyses, demonstrating the values for the first and last beam design variants considered. A comprehensive overview of all the results obtained for each of the analysed variants is presented in Table 3.

The analysis of Test 1 indicated that the shell thickness should be increased. Test 2 showed that the beam width should be increased while retaining the previous shell thickness. Based on Test 3, it was concluded that additional structural reinforcement should be introduced to further improve stiffness. Test 4 therefore implemented vertical stiffeners in the structure, which improved stiffness but increased the total composite mass.

Test 5 suggested that further increasing the shell thickness could enhance stiffness, but this resulted in exceeding the target mass criterion. Test 6 demonstrated that replacing the vertical stiffeners with a cross-type reinforcement layout while returning the shell thickness to the target value and maintaining the beam width allowed both stiffness and mass criteria to be satisfied simultaneously. The evolution of the results across Tests 1–6 therefore reflects a targeted design process in which the shell thickness, beam width and reinforcement layout were iteratively adjusted in order to achieve a favourable stiffness-to-mass ratio while meeting the assumed geometric and load-related constraints.

As part of the optimisation procedure, six numerical variants (Test 1–Test 6) were analysed, representing different structural configurations of the composite beam. Although all variants satisfied the assumed maximum deflection criterion (< 0.25 mm), this parameter was not treated as the sole or decisive classification factor. In the case of Test 5, configuration was excluded due to exceeding the allowable composite shell thickness, which reached 7.2 mm compared to the

Table 2. Design logic of the variants considered during parametric analysis

Variant	Conclusions from the analysed version implemented in the next variant	Parameter			
		Composite shell thickness [mm]	Beam width [mm]	Application of stiffener in the structure	Composite mass [kg]
		Target: 4.8	Target: 200.0	Target: Cross	Target: <25.00
Test 1	Wall thickness of the beam should be increased.	2.4	170.0	None	7.56
Test 2	Beam width should be increased, while maintaining the previous composite shell thickness.	4.8	170.0	None	13.78
Test 3	Additional reinforcement should be introduced.	4.8	200.0	None	14.51
Test 4	Composite shell thickness should be increased.	4.8	200.0	Vertical	19.25
Test 5	Change the shell thickness and modify both the reinforcement design and the element's width.	7.2	200.0	Vertical	25.83
Test 6	Solution was meeting the criteria	4.8	200.0	Cross	22.45

target value of 4.8 mm, resulting in an excessive total composite mass. The configuration analysed as Test 6 was selected as the solution, which met the all criteria, because it satisfied simultaneously the requirements related to composite shell thickness, beam width, reinforcement layout and total composite mass. Consequently, the selection of Test 6 resulted from a multi-criteria assessment accounting for stiffness, mass, geometric constraints and load conditions, rather than from deflection values alone.

DISCUSSION

The mechanical performance of the composite beam investigated in this study aligns with

prior findings on lightweight beam structures for high-precision manufacturing systems, such as those developed for 11th-generation LCD panel production [29]. In both cases, composite demonstrated a substantial advantage in terms of stiffness-to-mass ratio, enabling mass reduction while maintaining structural stiffness, as confirmed by the agreement between numerical and experimental results reported in [29], while maintaining or improving structural rigidity. The present beam, designed for hybrid CNC cutting applications, achieved comparable performance enhancements, exhibiting minimal static deflection, under the adopted loading scheme. The comparison with the literature indicates that changes in shell thickness and reinforcement layout are associated with differences in deformation behaviour, which

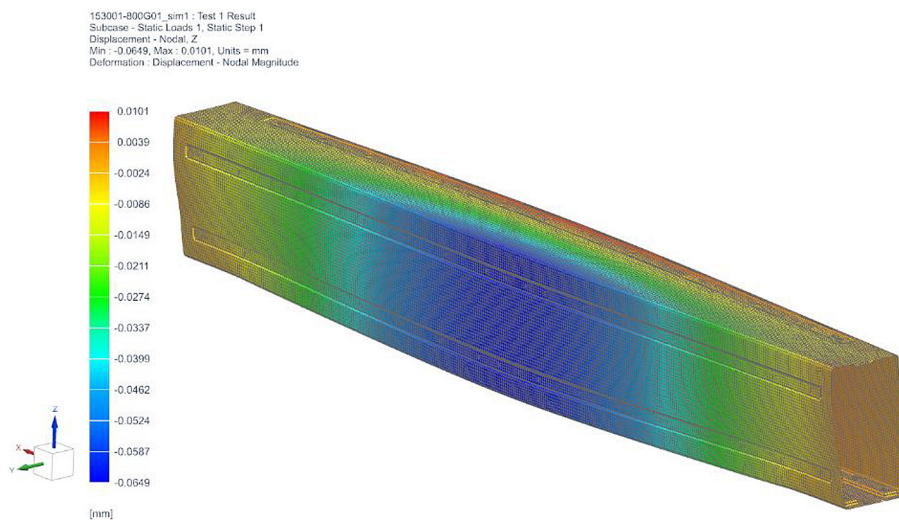


Figure 6. Z-axis displacements for Test 1

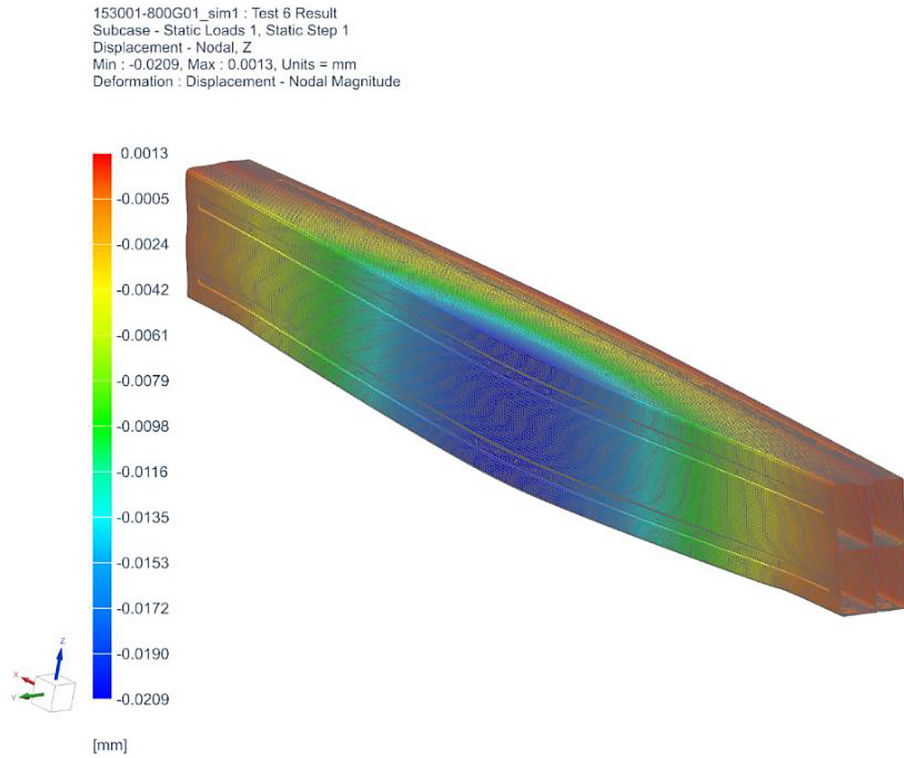


Figure 7. Z-axis displacements for Test 6

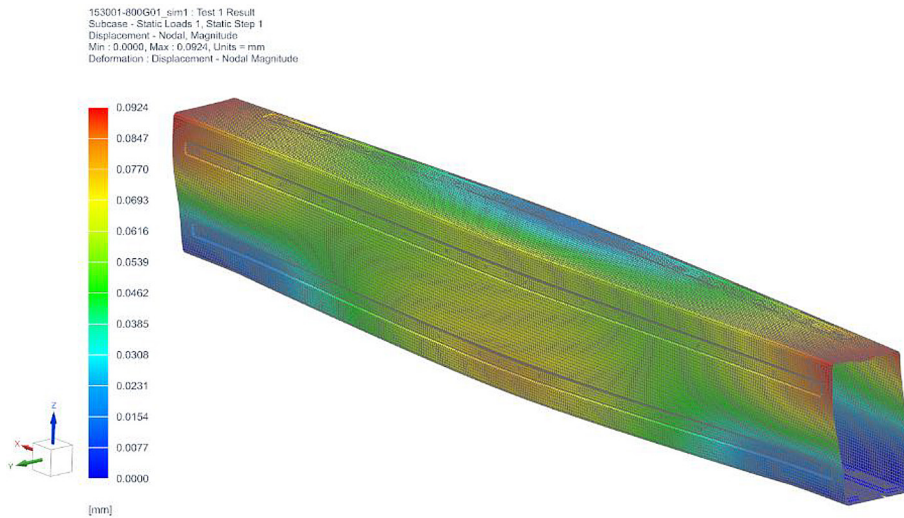


Figure 8. Average displacements for Test 1

supports the effectiveness of composite structures in mitigating deflection without compromising structural integrity. Moreover, the favourable stiffness-to-mass characteristics obtained in the present study support the broader applicability of composite beams in motion-sensitive manufacturing environments where energy efficiency, low inertia and structural precision are critical.

The growing interest in lightweight structural solutions for machine tools is also confirmed by

the study [30], where investigated hybrid and composite materials for moving components of machine tools, including CFRP-based structures. Their results demonstrated that lightweight materials can provide a favourable combination of high stiffness and reduced mass compared to conventional materials such as steel or cast iron, while additionally offering improved vibration damping characteristics. In particular, CFRP structures were shown to maintain high stiffness with a significant

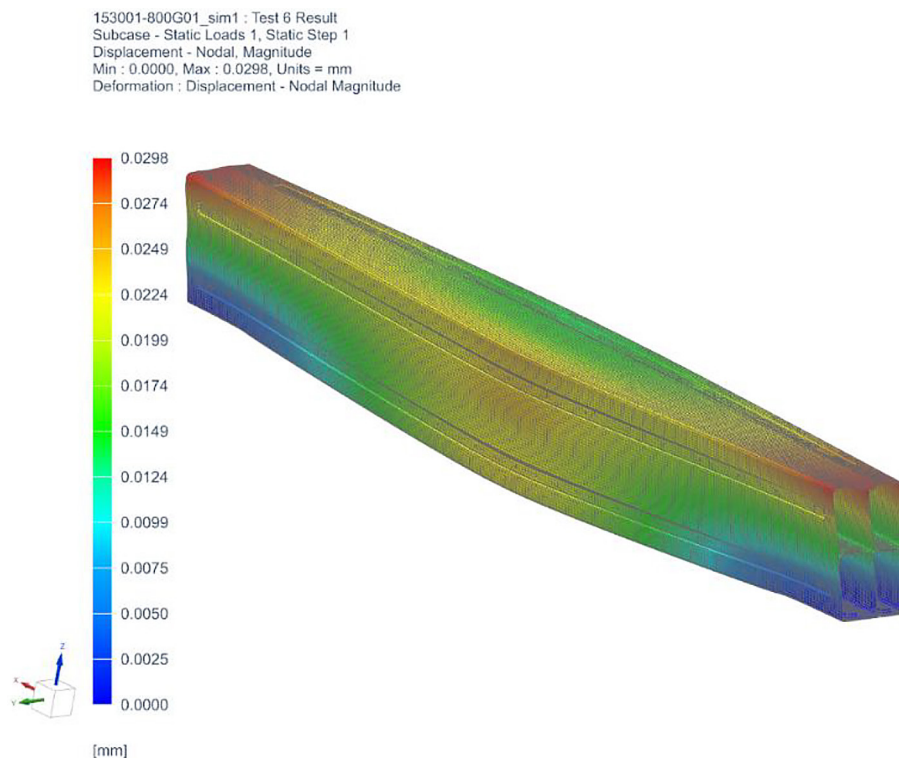


Figure 9. Average displacements for Test 6

Table 3. Summary of results for individual tests

Test	Z-axis displacements [mm]		Average displacements [mm]
	Min.	Max.	
Test 1	-0.0649	0.0101	0.0924
Test 2	-0.0293	0.0035	0.0523
Test 3	-0.0294	0.0046	0.0456
Test 4	-0.0251	0.0046	0.0415
Test 5	-0.0160	0.0022	0.0255
Test 6	-0.0209	0.0013	0.0298

reduction in weight, which directly contributes to lower energy consumption and improved machining efficiency. Although the present study focuses on static structural analysis, the findings are consistent with the conclusions of study [30], indicating that appropriately designed lightweight composite structures can effectively meet the mechanical requirements of machine tool components. This supports the use of composite beams in CNC systems as a viable alternative to traditional materials, especially in applications where low mass and high structural stiffness are critical.

The findings of this study reinforce the growing consensus on the role of composite design in enhancing the structural performance of CNC beam systems. Similar to the approach presented

by [31], where topology optimisation was applied to CNC crossbeam structures to reduce mass and deformation while maintaining stiffness, this work also focused on parametric analysing the beam’s geometry and composite structure to improve stiffness and stability, under service loads. The present research demonstrates that the use of composite combined with laminate parametric analysis can achieve comparable improvements with greater mass reduction.

This study aligns with [32] approach, which emphasized enhancing CNC beam performance through structural innovation. Both designs aim to reduce deformation and improve the load-carrying capability of the beam by adjusting the stiffness distribution within the beam structure. Research [32] proposed a modified beam rail arrangement aimed at improving rigidity and load-carrying capability by reducing the influence of overturning moments observed in conventional designs. Similarly, the parametric analysis of the composite beam in this study focused on minimizing deflection through shell thickness adjustment and reinforcement placement. Both approaches confirm the critical role of beam structure in machine tool precision, and together they offer complementary evidence that design innovation, whether through the structural

arrangement of the beam, including its cross-sectional layout, support configuration and stiffener placement or advanced materials, can lead to substantial gains in rigidity, energy efficiency, and long-term accuracy in CNC beam machine tools.

The parametric analyzed composite structure met mechanical performance targets for stiffness, with performance comparable to the 16% stiffness improvement reported by [33] through topology optimization. The parametric analyzed design (Test 6) maintained structural deflection below 0.25 mm while reducing mass to 22.45 kg, confirming the effectiveness of design modifications without requiring formal topology parametric analysis. Compared with the solutions discussed in the cited literature, the present beam combines low displacement values with relatively low structural mass, indicating that appropriate selection of shell thickness and reinforcement arrangement can effectively improve the stiffness-to-mass ratio. These outcomes align with the conclusions of [33] whose topology-optimized beam achieved a 16% increase in stiffness, consistent with the trend of stiffness improvement reported in [33].

The results demonstrate that through parameter parametric analysis of shell thickness and reinforcement layout, among six evaluated variants, the final configuration achieved displacements below 0.25 mm and a total mass of 22.45 kg. Compared to the steel crossbeam optimized by [34] which achieved a 14.2% reduction in deformation through stiffener design and dimensional parametric analysis, the composite beam exhibited a favourable combination of low mass and limited deformation under static loading. These results indicate that material substitution, combined with tailored geometric reinforcement, offers an effective strategy for improving the structural performance of beam structures in high-speed CNC systems. The conclusions regarding composite beams directly stem from the conducted simulations.

CONCLUSIONS

This study set out to evaluate the mechanical performance of a composite beam structure designed for hybrid CNC cutting systems, in which modular laser and plasma heads operate on a shared motion platform. This viability is confirmed by specific results: parametric analyzed static performance with deflections <0.0313 mm at 22.45 kg mass. The principal objective was to

validate whether a composite beam, when properly parametric analyzed, could deliver equivalent or superior structural performance compared to conventional metallic alternatives, while significantly reducing mass. The parametric studies conducted showed that the specified composite beam configuration meets the accepted design criteria for maximum deflection and weight, and can therefore be considered a sufficiently strong solution in mechanical terms and suitable for use in the actual structure. The configuration obtained should be interpreted as functioning well and sufficient in terms of design, ensuring the assumed values. The analyses carried out were not aimed at obtaining an optimal solution, but at determining a structure that will be implemented in practice, intended for testing in real conditions.

The results of the numerical simulations confirm the validity of the research hypothesis. The composite beam, parametric analyzed in terms of shell thickness, geometric configuration, and reinforcement layout, exhibited high stiffness under operational loading. Static structural analyses demonstrated low levels of deflection.

Parametric analysis of key geometric parameters led to a final configuration that satisfied both mechanical performance targets and mass constraints, confirming that mass reduction does not inherently compromise structural reliability when composite materials are employed.

The results confirm the technical viability of composite beams for CNC systems, encouraging broader adoption in applications where mass reduction and precision are critical. The integration of composite into beam systems enables increased acceleration, improved trajectory accuracy, and reduced energy consumption, directly addressing the performance limitations of traditional steel or cast iron constructions.

Further work should include experimental validation of the numerical model, long-term fatigue testing under cyclical loading, and thermal stability assessments under variable environmental conditions. In addition, extended numerical investigations should be conducted, including modal and dynamic analyses, to evaluate the vibrational behaviour of the composite beam and its response under operational conditions. Additionally, the incorporation of embedded sensor systems within the composite structure may offer promising avenues for real-time monitoring and predictive maintenance, enhancing the reliability and operational intelligence of future CNC platforms.

It should be emphasised that the composite beam under investigation was designed from the outset with the intent of physical manufacture as a functional prototype, meaning that the assumed geometry, layer configuration, and joint solutions reflect technological constraints applicable to actual composite fabrication processes, including lamination and adhesive bonding. The adhesive joints included in the numerical model reflect the intended adhesive joints between the composite coating and are represented in the finite element model by adhesive contact conditions and appropriate division of the coating areas. This work focuses on the mechanical feasibility of the beam's application under the adopted static load assumptions, therefore no detailed planning of the manufacturing process and its optimisation was undertaken. The results of the research confirm that the design under consideration is feasible and can be further analysed in real conditions. The analysis of additional machine subsystems is planned as part of future research. The presented results provide the necessary basis for the production of a prototype and subsequent optimisation of the technological process.

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