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APPLICATION OF DESIGN OF EXPERIMENTS AND FINITE ELEMENT METHOD FOR MULTI-MATERIAL CANTILEVER BEAM CHARACTERIZATION

Eduardo D. Telli
Mechanical Engineering Post-Graduate Program, Federal University of Rio Grande do Sul, Sarmento Leite 425, Porto Alegre CEP 90050-170, Brazil
edtelli4667@gmail.com

Gustavo P. Mezzomo
Post-Graduation Program in Design and Manufacturing Processes, University of Passo Fundo, BR 285 Km 292,7 | Campus I, Passo Fundo CEP 99052-900, Brazil
gpmezzomo@yahoo.com.br

Daniel M. De Leon
Ignacio Iturrioz
Mechanical Engineering Post-Graduate Program, Federal University of Rio Grande do Sul, Sarmento Leite 425, Porto Alegre CEP 90050-170, Brazil
daniel.leon@ufrgs.br
ignacio@mecanica.ufrgs.br

Abstract. *Regarding the automotive industry innovative and comprehensive approaches to lightweight construction, the use of composite materials is increasingly being adopted, as less material can achieve the same level of strength. Limitations of the application of this material includes stability issues for too thin regions, material cost and susceptibility to damage by friction and machining. A promising approach to overcome these limitations is the use of multi-material systems, which combine high-strength steels and fiber-reinforced plastics in the same component. Since beams are common structural elements often chosen as a representative problems, this work aims to explore the behavior of a multi-material cantilever beam composed of steel and unidirectional epoxy-fiberglass composite, unified by an interface element called 'pad', which is tied to the composite beam and slides without friction on the steel beam surface. Using finite element method, a 3D multi-material cantilever beam model under flexural load was built with fixed length and width while the design variables were thicknesses of the composite and steel beams. A Design of Experiments technique was applied for 80 simulations runs, recovering reaction forces global stiffness of the whole assembly. Furthermore, a parametric analysis was carried out to find which dimensionless number describes the structure behavior. Results shows that the bending stiffness ratio of the beams strongly dictates the behavior of reaction forces as well as the resulting stiffness. Finally, this work concludes that a logarithmic or 6-degree polynomial function can describe the results found.*

Keywords: *Composite, Multi-material, FEM, DOE, Bending Stiffness*

1. INTRODUCTION

In the ever-evolving field of automotive engineering, the pursuit of lightweight construction has become a paramount objective. Reducing the weight of vehicles offers numerous benefits, including improved fuel efficiency, enhanced performance, and reduced carbon emissions. However, the continuous drive for increased safety, comfort and electrification trend has led to increased vehicle weight. This presents a challenge for the automotive industry, particularly considering upcoming regulations focused on climate protection (Hovorun et al, 2017).

To address these challenges, innovative and comprehensive approaches to lightweight construction are necessary. One promising avenue is the utilization of high-strength materials, which have the potential to offset the weight increase associated with safety, comfort, and electrification requirements. Among these materials, composites are widely adopted, as they possess exceptional strength-to-weight ratios, meaning that less material can achieve the same level of structural integrity (Kaw, 2005),(Jones, 2018). By incorporating composites materials into vehicle components, manufacturers can often achieve substantial weight reductions without compromising safety or performance (Pfeffer, 2020).

However, there are certain limitations to consider when employing high-strength materials in automotive lightweight construction. Once a minimum cross sectional area of a general component is reached, stability issues may arise, affecting the structural integrity and overall safety of the vehicle. Moreover, high-strength composites, although lighter and stronger than conventional materials such as steel, are more expensive and more susceptible to damage caused by friction, machining processes and interlaminar stresses (Dikshit, 2017). These limitations necessitate careful consideration of the potential of composite materials and the need for effective strategies to overcome these challenges.

A promising approach is to combine high-strength steels with fiber-reinforced plastics in the same component, namely multi-material system. As it is addresses in (Kromm, 2002) and (Linghoff, 2009), multi-material problems are diversely present in literature, with a wide range of applications that goes beyond this work's scope. By strategically integrating these materials, it is possible to overcome the inherent limitations of individual materials while profiting from their individual advantages. Thus, the use of multi-material systems holds great potential for achieving optimal weight reduction while maintaining structural integrity, safety, and cost-effectiveness.

Many automotive components are often considered as cantilever beams in early calculations, as they are fundamental structural elements. This kind of structure plays a crucial role in various parts, including suspension systems, steering systems, and chassis components. As a representative problem for automotive applications, the behavior of multi-material cantilever beams becomes a subject of interest.

The objective of this study is to explore the behavior of a multi-material cantilever beam composed of high-strength steel and unidirectional epoxy-fiberglass composite. By statically examining the mechanical response of this integrated system, valuable insights can be extracted to enhance the understanding of multi-material interactions and optimize this kind of structure in the automotive industry.

The beam considered consists of a combination of steel and unidirectional epoxy-fiberglass composite, interconnected by an interface element referred to as a "pad", which serves as a sliding, frictionless connection between the composite beam and the steel beam, ensuring their unified performance. Finite element method (FEM) is used, and the thickness of the composite and steel parts are parametrically and individually varied through a Design of Experiment (DOE) scheme. Finally, this work uses parametric analysis to numerically characterize the system and carry out conclusions about what drives the mechanical response of the multi-material component.

2. METHODOLOGY

2.1 Applied Materials

The properties of materials considered in this study were determined from mechanical testing performed in previous works following ASTM norms as (D3039/DM, 2014) and (D3410/DM, 2021). For the composite part, the material properties adopted was related to a composite of approximately 55% E-Fiberglass and 45% epoxy resin in volume with a uniform density of $\rho = 1820$ kg/m³. All the fibers were aligned longitudinally, characterizing a transversely isotropic material. As for the high-strength steel, isotropic properties of G92600 steel were considered for its widely application in industry. The engineering constants and density adopted in this work are summarized in Table 1.

Table 1. Materials properties adopted for both composite and steel.

Composite Properties	
E_1 [GPa]	40.76
E_2=E_3 [GPa]	10.4
$\upsilon_{12} = \upsilon_{31}$	0.29
υ_{23}	0.4
ρ [kg/m3]	1820
G_{12}=G_{31} [GPa]	4.1
G_{23} [GPa]	37.14
Steel Properties	
E[GPa]	200
G[GPa]	76.92
υ	0.3
ρ [kg/m3]	7850

2.2 FEM model

The use of FEM for analyzing composite structures have some particularities over the use for analyzing isotropic materials as steel and aluminum (Barbero, 2023). A schematic view of the modelled problem can be visualized in Figure 1. It is composed of two cantilever beams united by a component called Pad, which, by the model assumption, is glued at the interface with the composite beam and slides without friction at the steel interface. At one end, all degrees of freedom (DOF's) are constrained to zero while at the other end, bending force F_t was applied. Rigid beam elements (RBE) were used to apply displacement boundary conditions in two nodes, allowing the recovering of reaction forces for the steel beam, F_s, and composite beam, F_c.

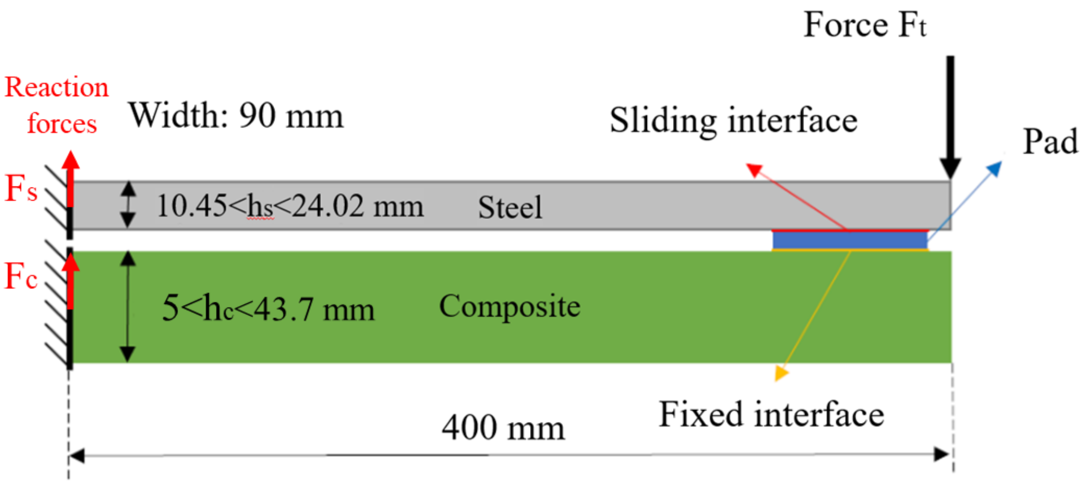

Figure 1. Static non-linear problem schematic representation.

The FEM model is shown in Figure 2, where the coordinate system, mesh quality and applied boundary conditions can be visualized. 3D linear elements were implemented in a non-linear static analysis which considers large displacements and contacts. Rigid beam elements were used to apply displacement boundary condition in two separate nodes, one for each beam. At the other end, load F_t of 1000 N was distributed along 32 nodes on the upper surface of the steel. For arbitraty reasons, nominal conditions of steel and composite thickness h_s and h_c are set to 10.45 mm and 43.7mm, respectively.

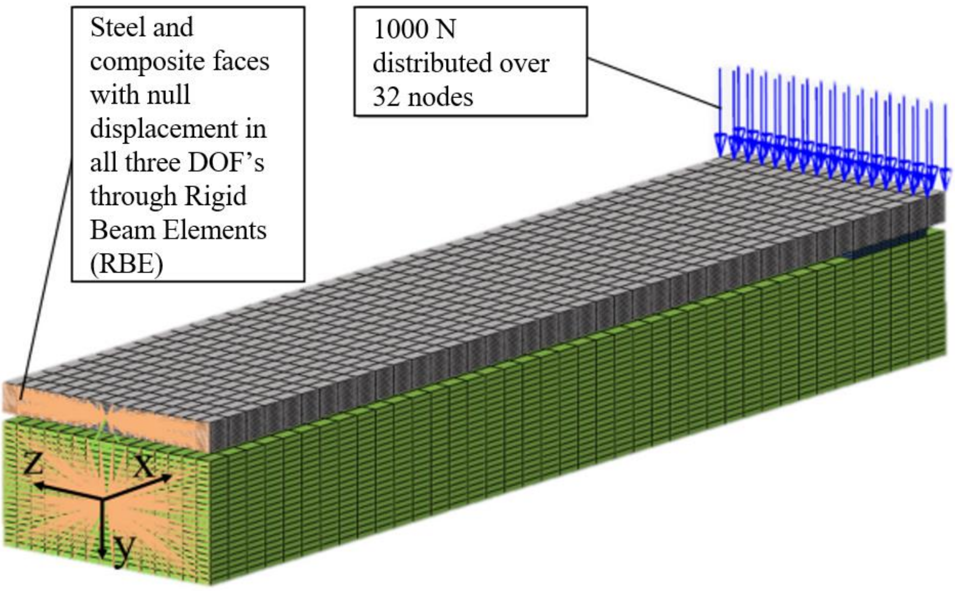

Figure 2. FEM model indicating coordinate system, mesh quality and boundary condition details.

2.3 DOE scheme

Design of Experiments (DOE) is a widely known technique for maximizing information extraction in scientific experiments. More specifically, for computational experiments a specific DOE methodology stands out called space-filling designs (Joseph, 2016). The combination of this type of DOE with FEM is particularly efficient for exploring the mechanical response of a structure with varying geometric parameters. In this work, a DOE approach was implemented to identify driving factors of some important mechanical responses as reaction forces and stiffness.

These algorithms aim to globally explore a computational system's response. It is important to mention that the DOE technique does not claim to find minimum/maximum of a design space. The main goal of a DOE procedure is to indicate to the designer preferred choices and give insights of the system's response.

Specifically in this work, the algorithm Modified Extensible Lattice Sequence from Altair© was applied with two variables: Steel thickness h_s and composite thickness h_c. The limit values for each variable and the number of simulated conditions (runs) are described below:

- h_c (15 runs): Minimum: 5mm; Maximum: 43.7 mm.
- h_s(50 runs): Minimum: 10,45mm; Maximum: 24.02 mm.

3. RESULTS

In Figure 3, two Design of Experiments (DOEs) are presented in terms of reaction forces and thickness of composite or steel beams. In the same graph, there are points indicating the reaction force in the steel beam, referred to as Fs, and in the composite beam, Fc. Similarly, the thickness variation can be either for the steel, hs, or for the composite, hc..

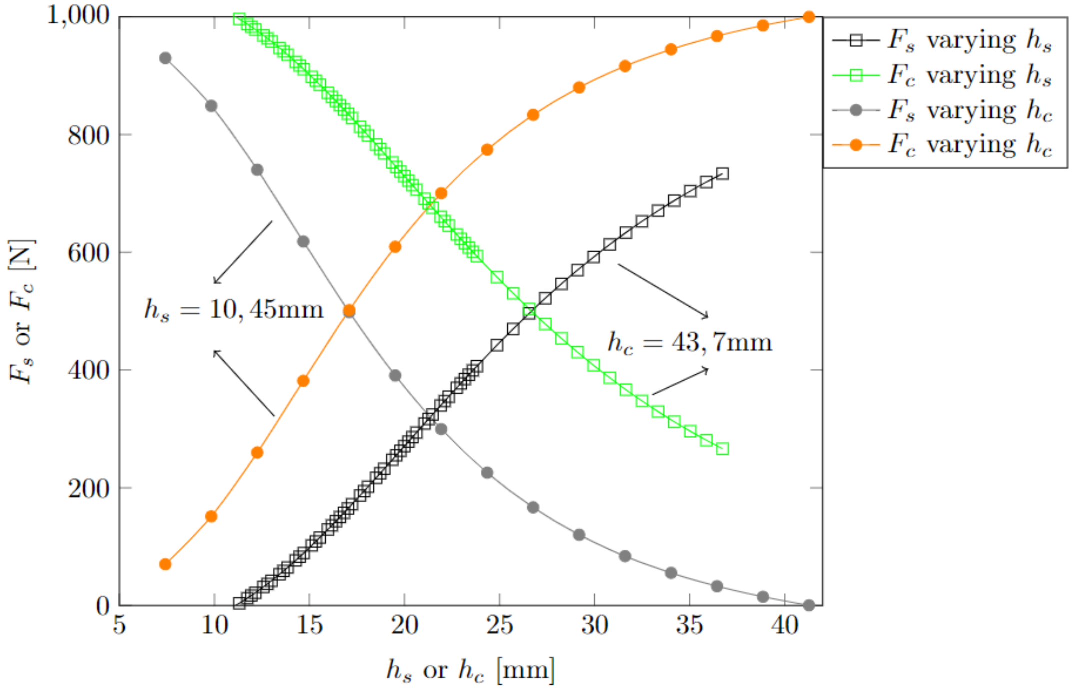

Figure 3. Steel and composite beams reaction forces F_s and F_c for a given thickness h_s or h_c.

It is possible to observe the behavior of the force distribution when the system's geometry is modified. In both DOEs, it can be noted that there is a point where the forces are equally distributed (about 500 N in each beam): in the case where the composite thickness varied (with h_s fixed at nominal condition of 10.45 mm), this occurs at a value of 17 mm, and in the other case, when the steel has a thickness of 26.5 mm (with h_c fixed at its nominal condition of 43.7 mm). Furthermore, each of the curves has a different sensitivity to the thickness parameter. The light gray and light green curves are more inclined in the range between 10 and 25 mm of composite thickness, while the other curves demonstrate less sensitivity to this parameter and have a constant slope between values of 17 and 28 mm.

Values of reaction moment in the two beams were also extracted from the same routines, and the behavior was identical to the graph in Figure 3, except the different magnitude of the vertical axis; therefore, they are not displayed here. The points where the curves of each study intersect indicate equal reaction force distribution between both beams. Regarding the resulting stiffness, the results are displayed in terms of thickness in Figure 4. It is demonstrated that changing the thickness of the steel beam has a much more significant impact than changing the thickness of the composite. This difference in slope can be explained by the Young modulus ratio $E_{1c}/E_s = 0.2038$, allowing to reason that steel is inherently about 5 times stiffer (material wise) than the composite.

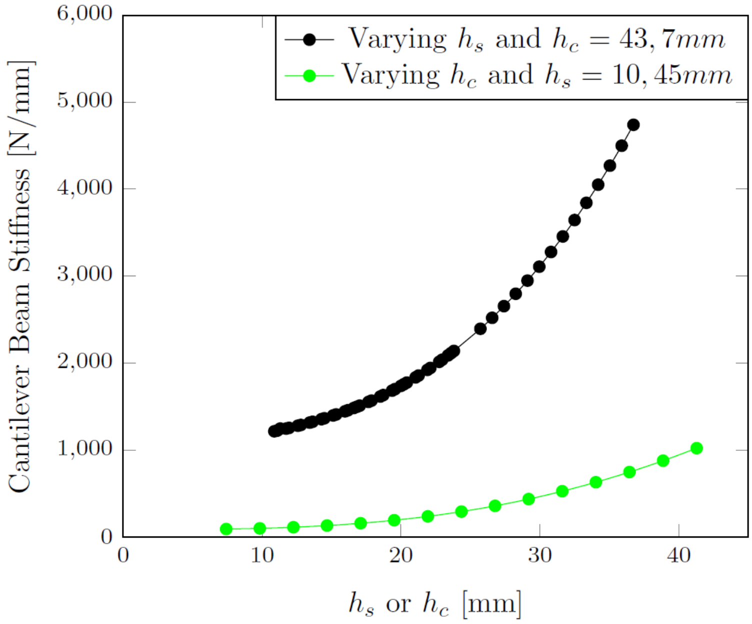

Figure 4. Cantilever Beam Stiffness in function of thickness of the steel, h_s, and composite, h_c.

3.1 Parametric study

In order find ways to better characterize the behavior seen in Figures 3 and 4, a parametric analysis was carried out to find a dimensionless parameter that drives the multi-material beam mechanical response. The behavior of beams under bending are generally described by the bending stiffness, which is the Young modulus E [MPa] multiplied by the second moment of inertia I [mm4]. Since each one of the beams has its own bending stiffness, it is possible to analyze the results from the DOE in terms of the bending stiffness ratio $(EI)_c/(EI)_s$.

The results from the Figure 3 have been grouped through the bending stiffness ratio and plotted in Figure 5: reaction force points from the same beam are now part of the same curve. It can be concluded that this balance between system forces is mapped for all stiffness ratios and can be approximated with good precision by either a logarithmic function or a 6-degrees polynomial function. Thus, the need to plot a response surface in three axes (reaction force, composite thickness, and steel thickness) is eliminated. Finally, representing the characteristics of the hybrid beam through the moment ratio $(EI)_c/(EI)_s$ carries more information than representing it purely in terms of thickness.

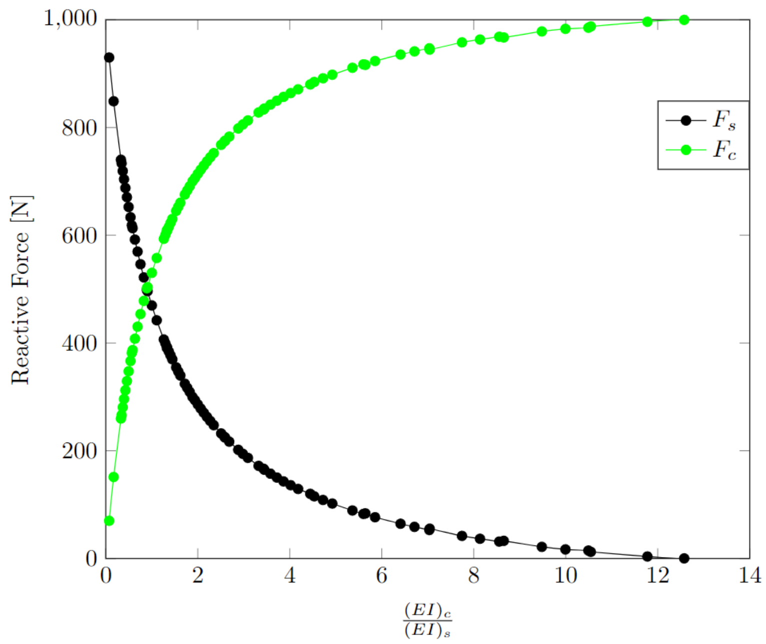

Figure 5. Reaction forces in both steel (Fs) and composite (Fc) beams versus bending stiffness ratio.

4. CONCLUSIONS

This work describes a thorough investigation on the behavior of a hybrid cantilever beam and give insights on the balance between system responses by varying the amount of each material in the overall structure. The FEM model and DOE scheme used in this work were described. Results includes an identification of sensibility of the reaction forces and stiffness when the thickness of each beam was changed. Moreover, a parametric analysis was useful to identify a driving factor of the problem, the bending moment ratio. Thus, the work contributes to multi-material component studies by exploring different tools that can be used in the future during project development.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE