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Experimental Analysis and Numerical Simulation of Smart Sandwich Beams Behavior in Honeycomb Magnetorheological Elastomer

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Abstract**—**Composite structures based on magnetorheological elastomers (MREs) are widely used in many industrial sectors, such as automotive, naval, railway, aeronautical, aerospace, and building industries because of their adjustable mechanical properties by an external stimulus. In this work, experimental tests and numerical simulations carried out have shown that the use of these new structures, developed from honeycomb core, and MRE with aluminum skins, make it possible to improve particularly the overall rigidity and to reduce the vibration amplitudes. The results found showed that these hybrid structures have a very good mechanical resistance due mainly to the honeycomb core, and a very good shock absorber due mainly to the core of the MRE. The elaborated composite structure is intended to be used in industrial sectors subject to great efforts and a high amplitude of vibration such as helicopter wings and air turbines.

Keywords**—**Hybrid sandwich structures, magnetorheological elastomer, honeycomb, 3-point bending, mechanical strength.

I. INTRODUCTION

TO improve the performance of the mechanical behavior of structures, engineers make great efforts to design structures with good rigidity, high mechanical strength, high damping and great lightness. Sandwich structures made of composite materials respond well to certain requirements but still remain insufficient. Today, there is a class of so-called smart MRE composite materials that perfectly meet these requirements.

Some works have been done on MRE structures, and very little works are done on MRE-honeycomb structures, among these works are the following: Eloy et al. [1] combined composite materials with an MRE core. They demonstrated that this combination of composite materials, honeycomb core and MRE is an excellent method to reduce vibrations, because it allows changing the modal parameters of the structure without affecting its mass. Li et al. [2] evaluated the mechanical performance of MRE sandwich plates with four types of different panel materials, namely Fiber-Reinforced Polymer (FRP), fiber-reinforced polymer with carbon nanotubes (CNT-FRP), metal and Fiber-Metal Hybrid (FMH) panels. A theoretical model has been proposed. This model will make it possible to determine the static rigidity, the dynamic rigidity, and the damping. The results found showed that the four types of structures possess excellent passive damping and stiffness properties, even without the application of an internal magnetic field. Selvaraj and Ramamoorthy [3] performed a dynamic analysis to evaluate the natural frequencies and damping ratios of laminated composite sandwich beams with a magnetorheological elastomer core reinforced with multi-walled carbon nanotubes (MWCNT-MRE) under different magnetic fields and boundary conditions. The experimental and numerical results show that the incorporation of CNT in the MRE gives high stiffness and also improves the damping characteristics of the structure. Liu et al. [4] propose a modeling method by the feedback control law. This modeling aims to show the compressibility and characterize the failure of the active-passive damping of the magnetorheological elastomer core of the piezoelectric sandwich plate (FGPE-MRE). Gou and Zhu [5] performed a numerical simulation to study the stochastic dynamic behavior of a MRE sandwich plate. The study showed that the MRE sandwich plate has a nonlinear dynamic behavior, including stochastic bifurcations. Li et al. [6] studied the skin effect on the stretching and bending problem in which the two skins are much more rigid than the honeycomb core. Bastola and Hossain [7] have made a synthesis and a comprehensive overview of the magneto-mechanical characterizations of MRE as well as a brief coverage of MRE materials and their fabrication methods. Moreno-Mateos et al. [8] presented an alternative solution based on hard magnetic MRE to provide stiffening responses that can be maintained over time without the need to maintain the external magnetic field enabled by manufacturing novel extremely soft hard magnetic MRE (stiffness of the order of 1 kPa). Bastola and Hossain [9] have provided a complete picture on magnetoactive soft materials (MSMs). They showed fabrication processes, programming and actuation techniques, behaviors, experimental characterizations, and device-related achievements with current state of the art and future perspectives. An experimental analysis of the thermal effect on viscoelastic elastomer by considering magnetic effect was reported by Tourab and Aguib [10]. Nayak et al. [11] studied the dynamic stability of a three-layer rotating symmetric sandwich beam with a MRE core and conductive skins subjected to axial periodic loads by the finite element method.

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In this work, experimental analysis and numerical simulations of the behavior of hybrid sandwich structures in MRE honeycomb in bending were made in order to improve the mechanical resistance and the damping simultaneously.

II. EXPERIMENTAL STUDY

A. Elaboration of the MRE

The studied elastomer is prepared by a mixture of silicone oil, RTV141A polymer, and 30% of iron particles of total mixture, the mixture obtained is mixed for about 15 minutes to obtain an elastomer paste with good homogenization. In order to develop an MRE, this paste is injected into an aluminum mold and subjected to a magnetic field. The constituents in mass fraction of the elastomer produced are given in Table I.

TABLE I
CONSTITUENTS OF THE MRE

$m_{\text{silicone oil}}$ (g)	$m_{RTV(A)}$(g)	$m_{RTV(B)}$(g)	M_{Iron}(g)
1.064	1.0385	0.104	7.559

B. Elaboration and Geometry of the Honeycomb

The chosen honeycomb geometry is based on regular hexagonal cells, Fig. 1.

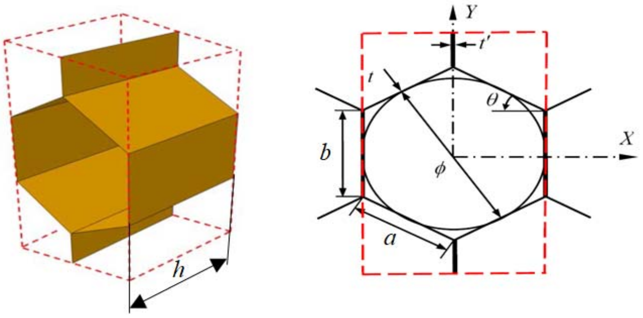

Fig. 1 Representative elementary volume and geometry of a honeycomb

The geometric parameters and mechanical properties of the aluminum honeycomb cell are presented in Table II.

TABLE II
GEOMETRIC PARAMETERS AND MECHANICAL PROPERTIES OF THE HONEYCOMB CELL MATERIAL

$\varphi(mm)$	$a(mm)$	$b(mm)$	$h(mm)$	$t(mm)$	$t'(mm)$	θ
6.35	3,66	3,66	5	1	2	30°
	$\rho_h(Kg/m^3)$			$E_h(MPa)$		ν_h
	2800			72000		0,33

C. Elaboration of Sandwich Beams in MRE-Honeycomb

In order to study the effect of the MRE and the honeycomb on the stiffness and damping of the beam, we developed four different specimens. The first specimen presents a MRE beam (N°1), the second presents a honeycomb beam (N°2), the third presents a hybrid MRE-honeycomb beam with a single layer of MRE (N°3), and the last presents a MRE-honeycomb hybrid beam with a double layer of MRE (N°4), Fig. 2.

Fig. 2 Different elaborated specimens, (1) MRE beam, (2) Honeycomb beam, (3) MRE Honeycomb beam, (4) twin MRE-Honeycomb beam

The hybrid sandwich beams developed previously (Fig. 2) are characterized by the three-point bending test. This test is carried out on Instron 8561 universal testing machine equipped with a 10 kN sensor. The feed rate is 2 mm/min. Data acquisition is performed using software that records displacement as a function of force. Fig. 3 represents the three-point bending test.

Fig. 3 Three-point bending test, Instron 8561 universal testing machine

The results of this set of experimental tests are presented in the form of force-deflection curves for each specimen (Fig. 4). Fig. 4 shows the three-point bending test performed for different engineered beams (Instron 8561 universal testing machine). It is noted that the honeycomb specimen reaches a rapid rupture with a deflection of 5.4 mm, as well as this specimen supports a maximum force of 268 N. On the other hand, the MRE specimen has a deflection value of 53.5 mm and will not reach its breaking point with a maximum supported force less than 100 N. It is also observed, for the two hybrid specimens in MRE and honeycomb that the breaking point increases with a considerable increase in the maximum force applied especially for the case of the MRE-honeycomb-MRE specimen. We have practically the same deflection (3.6 mm for the MRE single layer beam and 3.25 mm for the MRE double layer beam) with a different maximum force (323.6 N for the MRE single layer beam and 548.2 N for the MRE double layer beam).

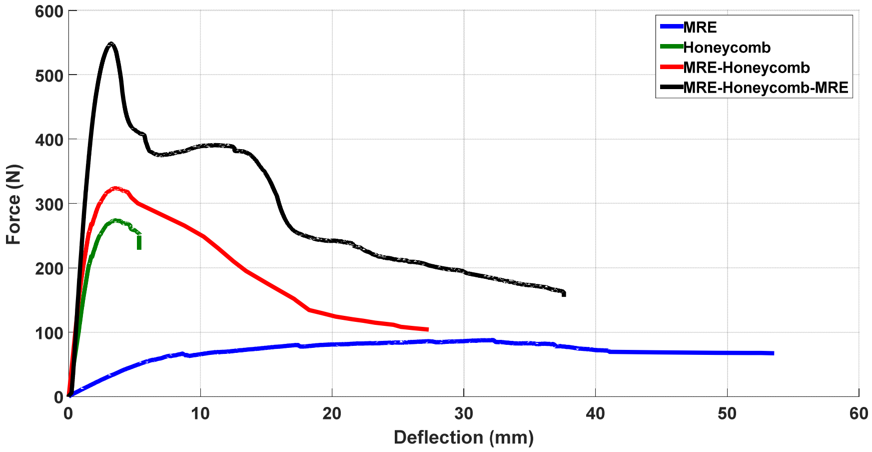

Fig. 4 3-point bending of four elaborated specimens

In conclusion of all the static tests carried out on the four different types of elaborated specimens (Fig. 2), it is found that the hybrid specimens are the most reliable in terms of rigidity and damping and have a better mechanical resistance due to the layer of honeycomb structure and good fracture toughness due to the MRE layer (strength until the MRE layer breaks).

III. NUMERICAL SIMULATION

To evaluate the accuracy and efficiency of our finite element model, we perform three types of calculation: 1) modeling of the honeycomb core by Abaqus shell elements with a very fine mesh to describe the complex geometry of the honeycomb; 2) modeling of the MRE by solid elements of Abaqus with viscoelastic material properties; 3) modeling of the skins by solid elements of Abaqus with the elastic solid properties. To validate the results of our simulation, we consider the same material and geometric data of MRE, honeycomb and skins used in the experimental part. The mechanical characteristics of the MRE were measured experimentally in the Condensed Matter Physics Laboratory of the University of Côte d'Azur - France.

The mechanical and geometric characteristics of the skins are given in Tables III and IV.

TABLE III
PROPERTIES OF THE ALUMINUM SKINS

$\rho_s\,(Kg/m^3)$	$E_s\,(MPa)$	ν_s	$h_s\,(mm)$	$L_s\,(mm)$	$b_s\,(mm)$
2800	72000	0.33	1	200	30

TABLE IV
PROPERTIES OF THE MRE

$\rho_{MRE}(Kg/m^3)$	$E_{MRE}\,(MPa)$	ν_{MRE}	$h_{MRE}(mm)$	$L_{MRE}(mm)$	$b_{MRE}(mm)$
1100	1.7	0.45	2	200	30

The mechanical and geometric characteristics of the honeycomb are given in Table II.

To properly model the bending behavior of the different beams studied, a second-order 3D solid element C3D8R is used to discretize the skin and the core in MRE. A first-order shell element S8R is used to discretize the honeycomb part. The skin of the beam is discretized by 384000 elements and 484605 nodes; the MRE core is discretized by 768000 elements and 872289 nodes, the honeycomb core is discretized by 48120 elements and 149847 nodes. The various simulated beams and their mesh are given by Figs. 5 (a)-(d).

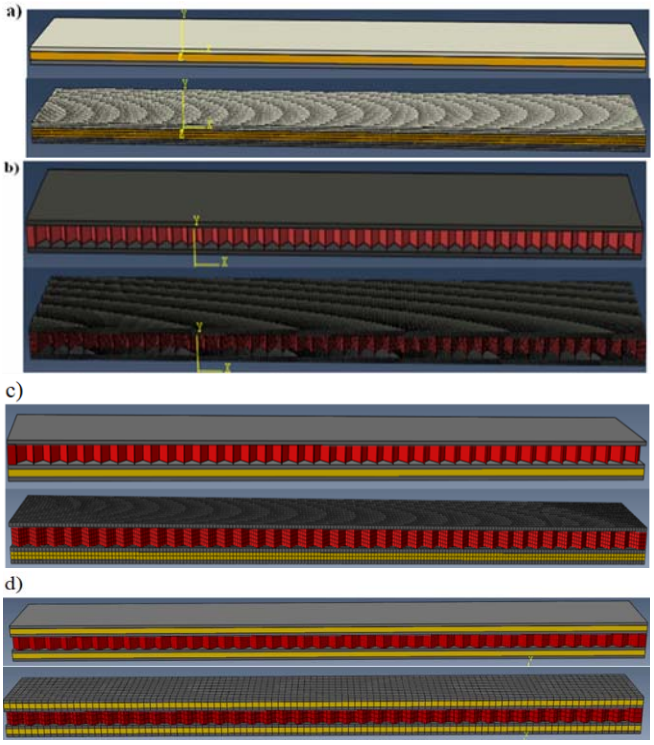

Fig. 5 Different beams studied: (a) MRE, (b) honeycomb, (c) MRE-honeycomb, (d) MRE-honeycomb-MRE

A. Interpretation and Validation of Results

The finite element numerical analysis of the static behavior in three-point bending of the MRE-honeycomb hybrid sandwich beams (Fig. 6) was carried out by simulation using the Abaqus software. Each simulation studied was the subject of several tests of 3 to 5 per specimen. The results in the form of transverse force-deflection curves are summarized in Figs. 8-11 for each beam model.

Fig. 6 presents the results of the three-point bending test carried out on the MRE beam (Fig. 5 (a)). It can be seen that this structure has a very high rupture limit of more than 60 mm with a weak maximum applied force of 89 N. Thus, it can be noted that the difference between the two values of the experimental and numerical deflection, for the maximum applied forces of 87 and 89 N, is 3.5%. Fig. 7 presents the three-point bending test results performed on the honeycomb beam (Fig. 5 (b)). It is observed that this structure has a very short breaking point less than 5.5 mm with a high maximum applied force of 279 N. It can be observed that the difference between the two values of the experimental and numerical deflection, for the maximum applied forces of 279 N. and 274N, is 2.5%. Fig. 8 presents the three-point bending test results performed on the single-layer MRE-honeycomb beam (Fig. 5 (c)). It is noted that this structure has a very high rupture limit more than 27 mm with a high maximum applied force of 334 N. The difference between the two values of the experimental and numerical deflection, for the maximum applied forces of 334 and 323N, is 1.9%.

Fig. 9 presents the three-point bending test results performed on the double-layer MRE-honeycomb beam (Fig. 5 (d)). It is noted that this structure has a very high breaking limit of more than 33 mm with a very high maximum applied force of 546N. The difference between the two values of the experimental and numerical deflection, for the maximum applied forces of 546 and 548N, is 1.6%.

We observe a good agreement between the results obtained by experimental analysis and the numerical results obtained using Abaqus software.

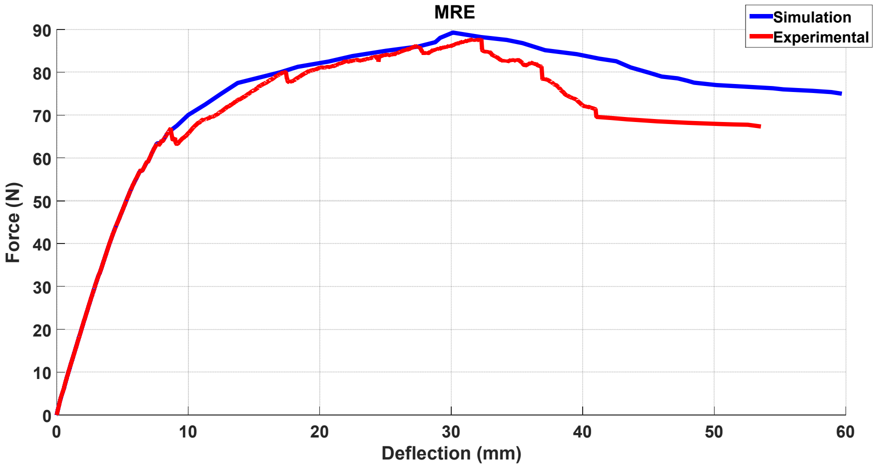

Fig. 6 Comparison between the experimental and numerical results of the MRE specimen

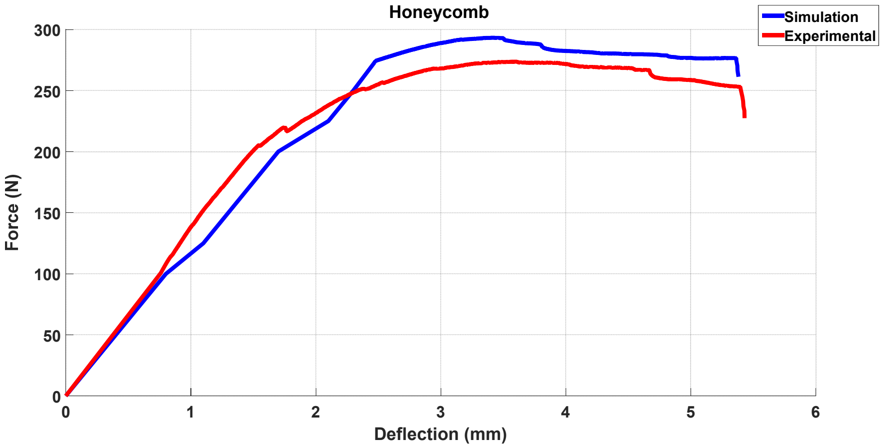

Fig. 7 Comparison between the experimental and numerical results of the honeycomb specimen

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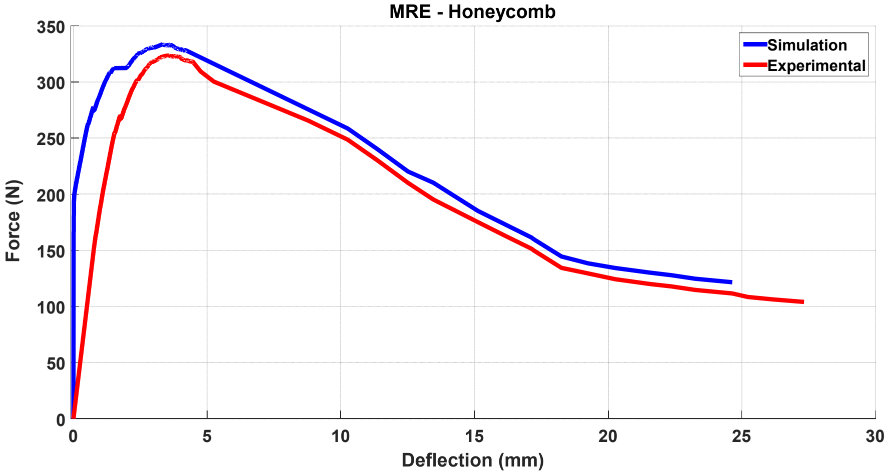

Fig. 8 Comparison between the experimental and numerical results of the MRE-honeycomb specimen

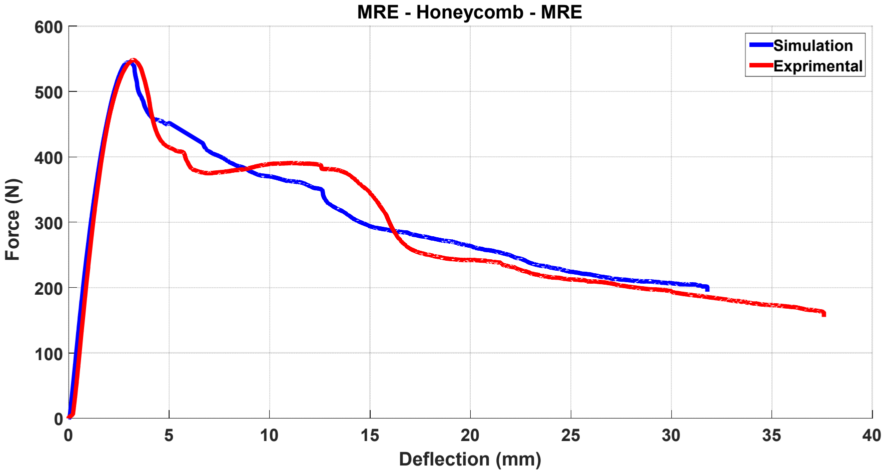

Fig. 9 Comparison between the experimental and numerical results of the MRE-honeycomb-MRE specimen

IV. Conclusion

This research work presents a study on the static behavior of hybrid sandwich beams in honeycomb MRE. The objective is to identify the static behavior in three-point bending of these new structures in smart composite material. The study of the static behavior was made by experimental and numerical methods using Abaqus software (finite elements). The mechanical properties of the beam are adjustable by applying a magnetic field intensity of 0.14T. The resistance of the specimen made of honeycomb core and a layer of MRE is practically 6 times more rigid compared to the rigidity of the specimen in MRE, with an improvement rate of 600%; and 2 times stiffer compared to the resistance of the honeycomb specimen; with a 200% improvement rate. The specimens developed with a honeycomb core and a layer of MRE have a very high breaking limit; this rupture only occurs after a deflection of 35 mm, i.e. with an increase of 600% compared to the rupture limit of the honeycomb specimen where the latter occurs at a deflection of 5.5 mm. It is found that the specimens made of honeycomb core and a layer of MRE provide a great possibility to improve the damping capabilities as well.

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