Chapter

Impact Analysis of MR-Laminated Composite Structures

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Abstract

Laminated composite structures are being used in many applications, including aerospace, automobiles, and civil engineering applications, due to their high stiffness to weight ratio. However, composite structures suffer from low ductility and sufficient flexibility to resist against dynamic, particularly impact loadings. Recently, a new generation of laminated composite structures has been developed in which some layers have been filled fully or partially with magnetorheological (MR) fluids; hereafter we call them *MR-laminated structures*. The present article investigates the effects of MR fluid layers on vibration characteristics and specifically on impact loadings of the laminated composite beams. Experimental works have been conducted to study the dynamic performance of the MR-laminated beams.

Keywords: laminated composite, MR fluid, vibration, impact

1. Introduction

Laminated composite materials, due to their unique characteristics such as high strength-to-weight ratio, high corrosion and impact resistance, and excellent fatigue strength, are being widely used in aerospace, automobiles, and recently civil engineering applications [1–7]. However, composite structures are highly vulnerable for failure under dynamic loading and, most importantly, impact loads. In the past few years, elements of smart and functional materials have been added to the conventional composite structures to develop a new generation of the laminated composite structures [8]. Researchers have proposed and test many types of smart materials, including piezoelectric, shape memory alloys, fiber optics, and electrorheological (ER) and magnetorheological (MR) fluids, to add the required features, such as controllability, and improve the performance for specific applications [9–14]. These structures have the capability to adapt their response to external stimuli such as load or environmental changes. These new structures have opened new challenges in research communities. The use of MR fluids in composite structures is relatively new as embedding fluids inside a rigid, laminated structure may raise many challenges in fabrication. **Figure 1** shows a typical MR-laminated beam in which some layers are partially replaced by segments of MR fluid. Yalcintas and Dai [15] investigated the dynamic vibration response of three-layered MR and ER adaptive beams both theoretically and experimentally.

Sapiński et al. [16, 17] explored vibration control capabilities of a three-layered cantilever beam with MR fluid and developed FEM model to describe the phenomena in MR fluid layer during transverse vibration of the beam. Sapiński et al. [18] proposed a finite element (FE) model by using ANSYS for sandwich beam

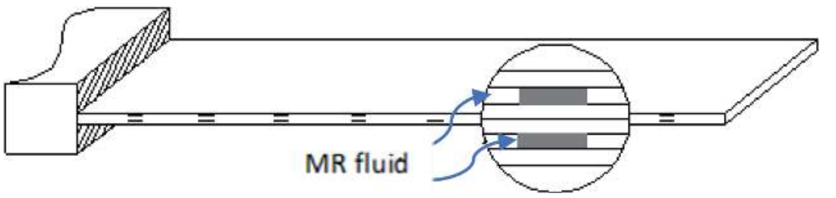

Figure 1.
MR-laminated beam.

incorporating MR fluid. Rajamohan et al. [19] investigated the properties of a three-layer MR beam. The governing equations of MR adaptive beam were formulated in the finite element form and also by Ritz method. Ramamoorthy et al. [20] investigated vibration responses of a partially treated laminated composite plate integrated with MR fluid segment. The governing differential equations of motion for partially treated laminated plate with MR are presented in finite element formulation. Payganeh et al. [21] theoretically investigated free vibrational behavior of a sandwich panel with composite sheets and MR layer. They studied effects of length and width of sheet and also core thickness on frequency. Aguib et al. [22] experimentally and numerically studied the vibrational response of a MR elastomer sandwich beam subjected to harmonic excitation. They studied the effect of the intensity of the current flowing through a magnet coil on several dynamic factors. Naji et al. [23] employed generalized layerwise theory to overcome this challenge and passed behind constant shear deformation assumption in MR layer that is mainly used for vibration analysis of MR beam. Based on layerwise theory, FEM formulation was developed for simulation of MR beam, and results were verified by experimental test. Naji et al. [24, 25] presented a distinctive and innovative formulation for shear modulus of MR fluid. Most recently, Momeni et al. [26, 27] developed a finite element model to investigate the vibration response of MR-laminated beams with multiple MR layers through the thickness of the laminated beam with uniform and tapered cross sections.

The present work intends to study the vibration response of MR-laminated beam with emphasis on impact loadings. The mathematical modeling of MR-laminated beam is similar to the work done by present authors in previous publications [23, 24, 26, 27]. However, here, the modeling has been used mainly to study the effects of impact loading, although for more clarification, basic results for natural vibration have also been provided. Some experimental works have been conducted to illustrate the performance of the MR-laminated beam under practical impact loadings.

2. Review the modeling laminated composite beams with layerwise displacement theory

In brief, laminated composite plates are composed of individual layers, which have been stacked together, usually by hand-layup techniques. Individual layers are composed of fibers, which have been derationed according to property requirement, and matrix, which serves as binder of fibers and transfers the loads to the fibers. Changing the orientation of the fibers optimizes the composite material for strength, stiffness, fatigue, heat, and moisture resistance. Modeling laminated composite structures for conventional applications mainly is conducted by considering the stacked layers as one single layer. The equivalent single-layer (ESL) theories assume continuous displacement through the thickness of the laminate. In general, the stiffness of the adjacent layers in the laminates is not equal; thus, it results in discontinuity in transverse stress through the thickness, which is contrary to the equilibrium of the interlaminar stresses as stated by ESL. In general, ESL theories provide acceptable results for relatively thin laminate. For thick laminate and laminate with material and/or geometric inhomogeneities, such as MR-laminated beams, the ESL theories lead to erroneous results for all stresses.

In smart-laminated structures, due to the material and geometric inhomogeneities through thickness, including MR-laminated beams, it is required to acquire an accurate evaluation of strain–stress at the ply level. Interlaminar stresses can lead to delamination and failure of the laminate at loads that are much lower than the failure strength predicted by the ESL theories.

The accurate modeling of interlaminar stress field in composite laminates requires the displacement field to be piecewise continuous through the thickness direction. Researchers in composite communities have proposed and developed a variety of displacement models to provide sufficient accuracy for interlaminar stresses in composite structures. Layerwise displacement theory developed by Reddy [28] developed a layerwise theory based on the piecewise displacement through the laminate thickness.

The layerwise formulation has the capability to address local through-the-thickness effect, such as the evolution of complicated stress–strain fields in MR-laminated composite structures and interfacial phenomena between the different embedded layers. In this work, the layerwise displacement theory has been used for modeling MR-laminated beam.

The displacement field for a laminated beam based on the layerwise theory is obtained by considering the axial and through-the-thickness displacements as

$$u(x,z,t) = \sum_{I=1}^{N} U_I(x,t)\,\Phi^I(z), w(x,z,t) = \sum_{I=1}^{N} W_I(x,t)\,\Phi^I(z)\,\Phi^I(z) = [1 - \zeta \;\; \zeta] \quad (1)$$

where u and w are displacements along x- and z-directions, respectively. N denotes the total number of nodes through the thickness. The ratio ζ is defined as $\zeta = z/h$, in which h represents the thickness of each discrete layer. Interpolation functions $\Phi(z)$ are defined between any two adjacent layers. For thin laminate, displacements in z-direction between layers are negligible, so $w(x,z,t) = W_o(x,t)$.

2.1 Finite element formulation

For many applications, closed-form solution for MR-laminated beams is either not available or very complex. Therefore, most of the computations are based on finite element models. Finite element formulation has been obtained by incorporating the local in-plane approximations for the state variables introduced in Eq. (1) as follows:

$$U_I = \sum_{i=1}^{Nn} U_I^i(x)\,\phi_i(x) \quad (2)$$

where N_n is the number of nodes and $\phi_i(x)$ are the interpolation functions along the length of the beam, respectively. For details on finite element modeling of composite structures based on layerwise theory, one may refer to the work done by the present author in Ref. [8].

3. Fundamentals of magnetorheological (MR) fluids

Magnetorheological (MR) fluid is a class of new intelligent materials, which rheological characteristics such as the viscosity, elasticity and plasticity change rapidly (in order of milliseconds) subject to the applied magnetic field as shown in **Figure 2**. By applying a magnetic field, the particles create columnar structures

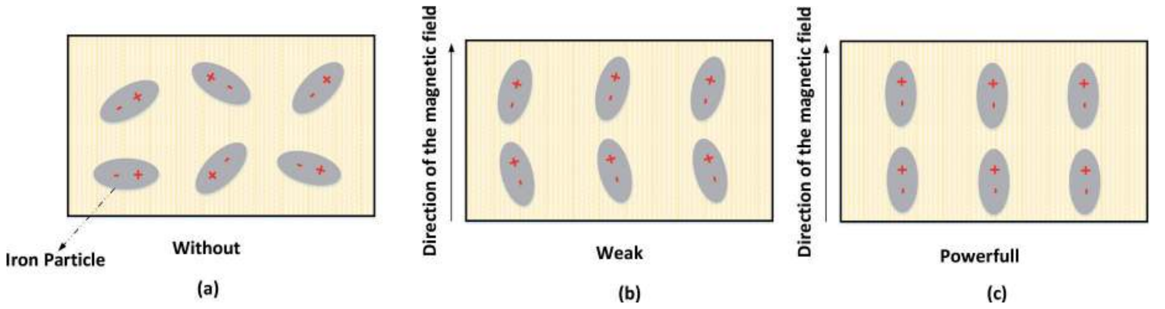

Figure 2.
Structure of MR fluids (a) without magnetic field, (b) with magnetic field, and (c) with magnetic field and shear force.

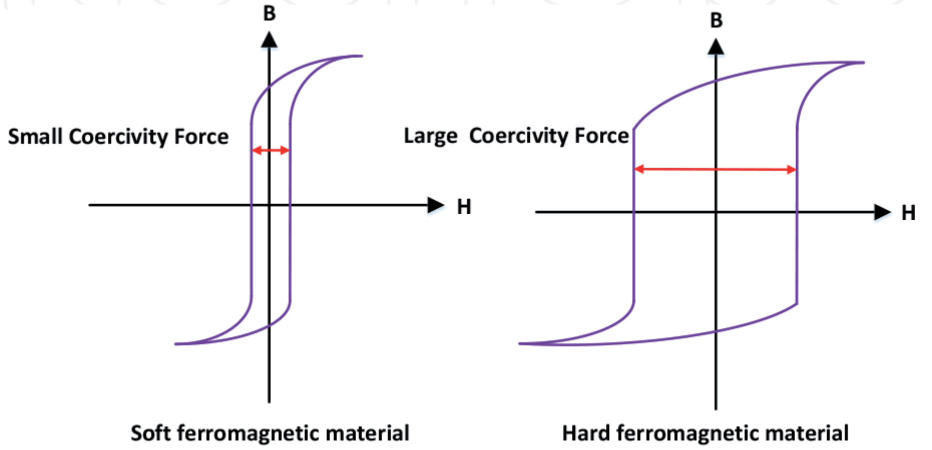

Figure 3.
The comparison between the soft and hard ferromagnetic materials [33].

parallel to the applied field and these chain-like structures restrict the flow of the fluid, requiring minimum shear stress for the flow to be initiated. Upon removing the magnetic field, the fluid returns to its original status, very fast.

Overall, MRF is composed of a carrier fluid, such as silicone oil, and iron particles, which are dispersed in the fluid [29, 30]. Each of the components plays a significant role in the characteristic of MRF.

3.1 Ferromagnetic particles

There are two types of ferromagnetic materials, used in MRFs: the soft material and the hard material [31]. The applied magnetic field intensity (H) and the magnetization of the material (B) are two parameters that show the difference between the two kinds of materials.

Figure 3 shows the H-B hysteresis loops of the soft and hard materials. It is noted that the soft ferromagnetic material has lower remanence and coercivity [32].

The shape of the magneto-soft particles is spherical with a diameter ranging between 1 and 10 μm. One of the most widely used soft materials is carbonyl iron, and that can take up to 50% of the volume of MRF [32]. In order to improve the MRF's dynamic behavior, iron-cobalt and iron-nickel alloys can be used instead of conventional carbonyl iron particles. However, they are more expensive [32].

The hard magnetic material can be made of chromium dioxide (CrO_2), which shows high coercivity and remanence. The size of dispersed CrO_2 is between 0.1 and 10 μm, and it can be easily oriented under the influence of magnetic fields [32].

Commercial MRF	Percent iron by volume	Carrier fluid	Density (g/cm^3)
MRF-122-2ES	22	Hydrocarbon oil	2.38
MRF-132 AD	32	Hydrocarbon oil	3.09
MRF-336AG	36	Silicone oil	3.45
MRF-241ES	41	Water	3.86

Table 1.
Properties of commercial MRFs [34].

It mixes with the soft magnetic material to enhance the rheological behavior and provide more stability to the MRF [32].

3.2 Carrier liquids

The second component of MRF is a carrier liquid providing the continuous medium for the ferromagnetic particles [32]. Although all types of fluids are suitable for this purpose, Ashour et al. [13] recommended a fluid with a viscosity ranging between 0.01 and 1 N/m^2 [32]. Silicon oil and synthetic oil are samples of suitable carrier fluids [32]. **Table 1** provides the samples of carrier fluids with their specifications. As noted in **Table 1**, water is the suitable fluid, which can carry iron particles up to 41% of volume. Hydrocarbon oil and silicone can have the suspended particles between 22 and 36% of the volume.

3.3 Stabilizers

The third element of the MRF is a stabilizer, which are "polymers (surfactants) in nonpolar media." The main roles of the materials as stabilizer are to retain the iron alloy particles suspended in the MRF, extend the service life of the smart fluid, and increase its reliability [32, 35]. There are three types of stabilizers—the agglomerative, the sedimental, and the thermal [32]—as briefly described below:

1. An agglomerative stabilizer is used to prevent the formation of aggregates between the iron particles. Agglomeration usually occurs due to the van der Waals' interactions between the iron particles in the MRF, causing the ferromagnetic particles to stick together. In MRF applications, surfactants should be selected in accordance with the type and concentration of particles. In fine-dispersed concentrations, when the iron particles fill up to 50% of the volume, ionic or nonionic surfactants are recommended. In lower concentrations of iron particles, which only occupy up to 10% of the volume, gel-like stabilizers are also suggested [32].

2. A sedimental stabilizer is employed to prohibit the iron particles from settling down as a result of gravity which decreases the effectiveness of MRFs [32]. The gel-forming and nonionic surfactants, as the sedimental stabilizer, are used to be added to the fluid carrier [35].

3. A thermal stabilizer is utilized to stabilize MRF over a wide temperature range particularly for the long-term applications at high temperature.

Since then, MR fluids have been utilized in various applications, including dampers, brakes and clutches, polishing devices, hydraulic valves, seals, and flexible fixtures. Recently, the application of MR fluids in vibration control has been attracted by many researchers. However, due to the nature of MR fluids, it is very difficult to integrate them with thin-laminated composite structures.

4. Governing equation of MR-laminated beams

Using the displacement field given in Eq. (1) and following a finite element procedure for each element, the governing equation of motion of MR-laminated beam in the matrix form is defined as

$$[m^e]\{\ddot{d}\}_i + \left[k^e(B,f)\right]\{d\}_i = \{f^e\} \tag{3}$$

where $[m^e]$ and $[k^e]$ are the element mass and stiffness matrices, respectively, and $\{f^e\}$ is the element force vector. One may note that when using layerwise displacement theory, depending on the number of layers in the laminate, each node may have many degrees of freedom.

Considering axial displacement given in Eq. (2), the generalized equation of motion of the MR-laminated beam can be obtained by assembling the mass, stiffness matrices, and the force vector as

$$[M]\{\ddot{d}\} + [K(B,f)]\{d\} = \{F\} \tag{4}$$

where $[M]$ and $[K]$ are the MR-laminated beam mass and stiffness matrices, respectively, $\{F\}$ is the force vector, and $[d]$ is the displacement vector.

It should be noted that the stiffness matrix is a complex value since it is the summation of the stiffness matrix of the laminated layer $[K_c]$ and the stiffness matrix of the MR fluid $[K_{MR}(B, f)]$:

$$[K(B,f)] = [K_c] + [K_{MR}(B,f)] \tag{5}$$

One important feature in Eq. (4) is the structural damping which is included in the stiffness matrix. For the sake of simplicity, the complex mathematical modeling is neglected here; however, complete details are available in Ref. [23].

5. Experimental setup for vibration and impact tests

In order to conduct experimental test for MR beams, it is essential to provide a uniform magnetic field all over the beam. For the current work, an electromagnet device shown in **Figure 4**, which was previously fabricated by the current authors at Sharif University of Technology, is used. The length of poles (gap) is 240 mm. The space between the poles (gap) is 40 mm. To ensure that enough magnetic strength is provided, each arm of the electromagnet has 1000 wound turns of copper wire 1.2 mm in diameter. A Hall effect Gauss meter, (Kanetec-TM701) with a suitable probe (TM-701PRB), was used to measure the magnetic flux generated by the electromagnet. The MR fluid selected for this study was MRF-132DG manufactured by Lord Corporation. For more details of the devices, one may consult Ref. [23].

5.1 Modal test

In order to perform modal tests, first a laminated composite plate (800 × 800 mm) made of glass fiber has been fabricated. Glass fiber composite is chosen as its magnetic permeability is zero. The plate was then cut into several strips

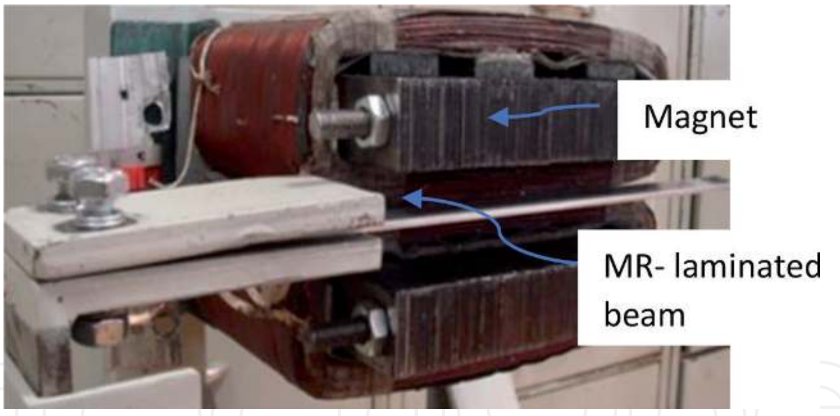

Figure 4.
Experimental setup.

(250 × 30 × 2.0 mm) by water jet to make beams. We used two similar beam strips as top and bottom faces and make a box beam with a 2.4 mm gap between two strips for MR fluid. Therefore, the total thickness of the MR-laminated beam became 4.4 mm. In order to maintain the uniform gap and hold the fluid between two strips, 2.4 mm thick spacer was glued on the inside face of one strip. Some mechanical properties of the glass fiber layers are given as follows:

Density = 200 g/m^3, $E_1 = E_2 = 15.5$ GPa, $G_{12} = G_{21} = 6.5$ GPa, $\rho = 1650$ kg/m^3.

In this work, the complex shear modulus of the MR fluid as function of magnetic field and driving frequency has been considered from the results of the work done by Naji et al. [10].

To study the effects of magnetic field on modal response of the MR-laminated beams, different magnetic fields, from 0 to 2000 Gauss, have been applied to the specimens.

5.2 Impact tests

To conduct the impact tests, the same electromagnet as described in Section 5.1 has been used. However, for impact tests, the specimens are fabricated as box-aluminum beam with length 400 mm and width 30 mm filled by MR fluid. The thickness of each aluminum layer and MR layer was 1 mm. The density of aluminum was 2700 kg/m^3 and that of the MR fluid was 3500 kg/m^3.

The impact tests were performed by dropping a 5.0 g mass from different heights (0.5, 1.0, and 1.5 m) on the tip of the MR-aluminum cantilever beam. In order to investigate the effect of magnetic field on the impact response of the MR-aluminum beam, the impact tests have been repeated for three levels of magnetic fields, 0, 1000, and 2000 Gauss.

6. Results

In the following two subsections, the analytical results and experimental ones followed by brief explanations are provided.

6.1 Modal tests

The results obtained by analytical approach described in Section 4 and the results extracted from the experimental work are given in **Table 2**. The first three

Magnetic field (Gauss)	Mode	Experimental freq. (Hz)	Analytical results freq. (Hz)
0	1	11.0	11.70
	2	66.5	68.10
	3	185.5	187.36
400	1	11.5	12.03
	2	68.5	69.73
	3	187.0	191.49
800	1	12.0	12.39
	2	70.0	71.96
	3	190.5	192.79
1200	1	11.5	11.76
	2	71.5	73.00
	3	192.0	194.50
1600	1	11.0	11.165
	2	73.0	75.34
	3	193.0	197.83
2000	1	10.0	10.18
	2	75.5	78.67
	3	194.5	198.58

Table 2.
Experimental and analytical natural frequencies of MR beam.

natural frequencies which were extracted from the peak of vibration response spectrum subject to three levels of magnetic fields are compared with analytical ones.

As it is shown, the analytical results provide sufficient agreement with experimental ones for most of the cases.

An important feature that one may conclude from these results is noting that intensifying magnetic field increases the natural frequencies of the MR beams.

Increasing the natural frequencies of MR beams by increasing the magnetic field can be explained by noting that increasing magnetic field increases the stiffness of the MR fluid, which leads to increasing the total stiffness of the MR beam and, in turn, increasing the natural frequencies. However, an exception is shifting the fundamental frequency of the MR beam after 800 Gauss, which is in contradiction with intuitive sense. To interpret this phenomenon, one may note that the loss factor at high magnetic field jumps up dramatically [10], so increasing damping is dominated by increasing stiffness of MR fluid, and higher damping dictates vibration behavior.

6.2 Effects of the MR layer thickness

In order to investigate the effect of MR fluid thickness on the modal response of the MR beams, the first three modes have been computed for different thickness ratios of the MR layer to base material under different applied magnetic fields. The results are given in **Table 3**, where h_1 is the thickness of composite laminated which

Mode	Magnetic field (Gauss)	Natural frequencies of five modes for three different magnetic fields			
		$h_2/h_1 = 1/4$	$h_2/h_1 = 1/2$	$h_2/h_1 = 1$	$h_2/h_1 = 2$
Mode 1	0	9.588	9.432	9.261	9.071
	1000	14.381	12.913	12.758	12.308
	2000	10.826	9.537	9.611	9.934
Mode 2	0	40.349	36.217	33.051	30.624
	1000	44.550	40.574	37.539	34.566
	2000	46.026	43.417	41.308	40.204
Mode 3	0	89.108	77.951	68.818	61.086
	1000	99.501	86.666	76.320	68.195
	2000	101.465	89.037	88.784	81.006

Table 3.
Effect of layer ratio on the natural frequencies of MR-laminated beam.

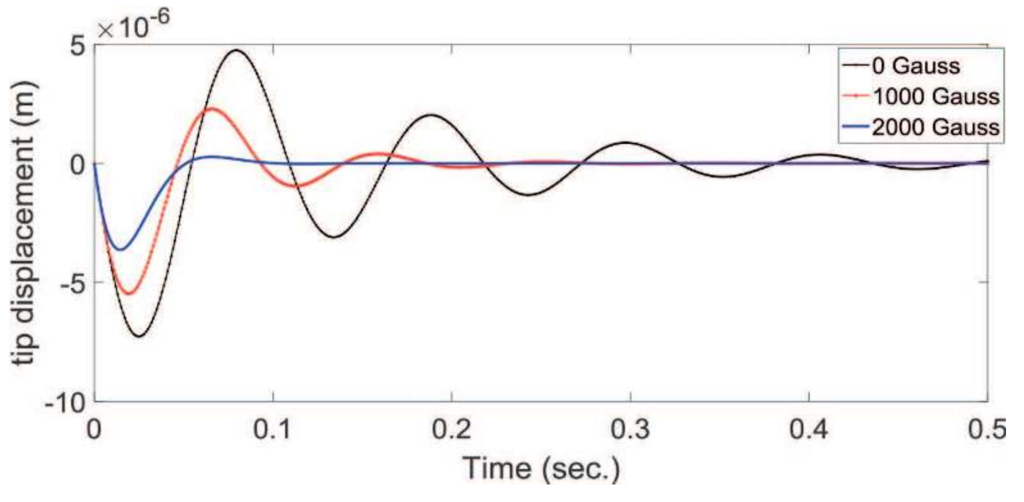

Figure 5.
Impact test for dropping mass from 0.5 m.

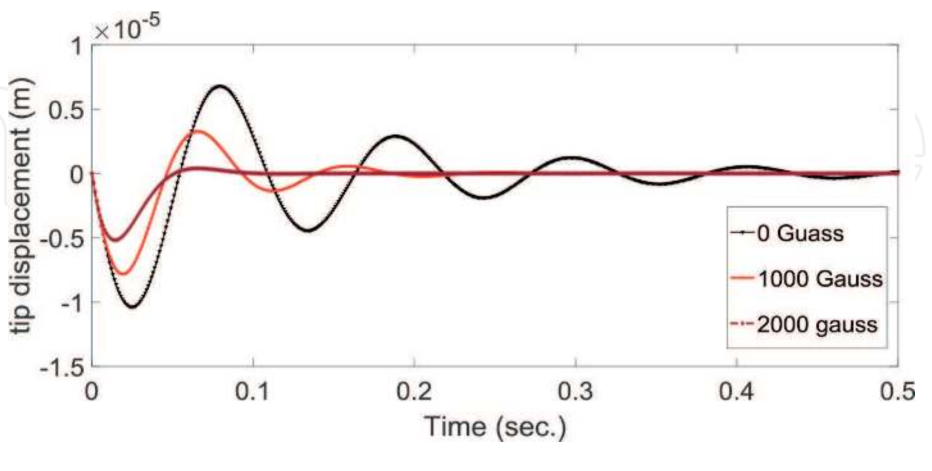

Figure 6.
Impact test for dropping mass from 1.0 m.

is a summation of the upper and lower layers and h_2 is the thickness of MR fluid in middle layer.

The results generally demonstrate that increase in thickness of the MR layer decreases the natural frequencies of all the three modes. This is because in general, the stiffness of MR fluid is lower than the stiffness of the base composite material.

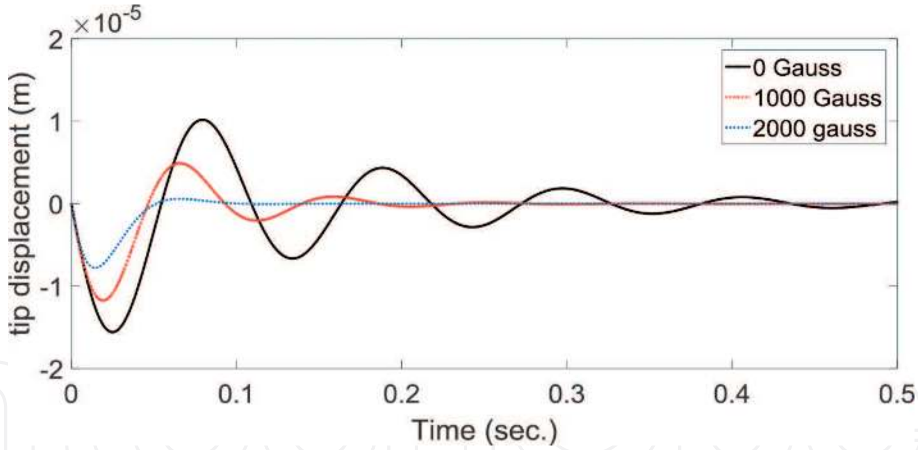

Figure 7.
Impact test for dropping mass from 1.5 m.

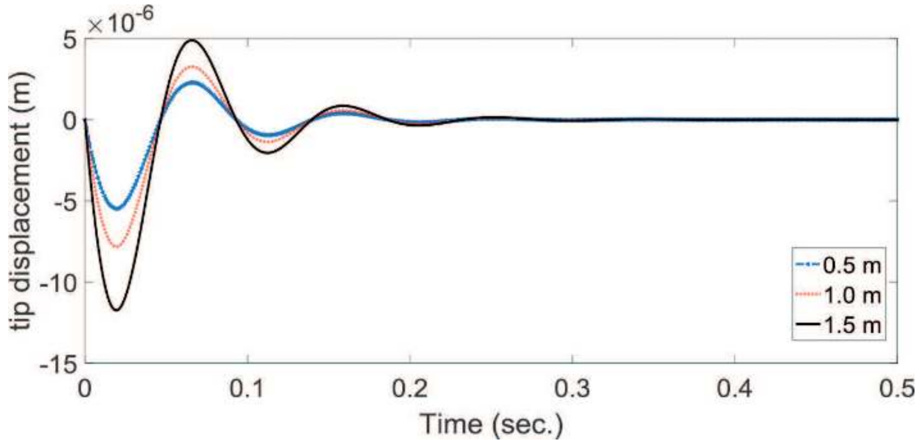

Figure 8.
Impact test for different dropping heights at 1000 Gauss.

6.3 Impact tests

The MR-aluminum beams are subjected to dropping mass as described in Section 5.2. The results for dropping mass from 0.5 m on the tip of the MR beam subject to different magnetic fields are shown in **Figure 5**. As it is observed, increasing the magnetic field makes the MR beam stiffer and thus reduces sharply the settling time.

The impact test results for dropping mass from 1.0 to 1.5 m on the tip of the MR beam for different magnetic fields is shown in **Figures 6** and **7**, where once again it is realized that increasing magnetic field reduces the settling time of the beam response.

To study the effect of magnetic field on the response of the MR beam subject to different impact loads, 1000 Gauss of magnetic field is applied to the MR beam, and its response of different dropping heights is measured and shown in **Figure 8**. As it is observed, increasing the level of impact force increases the amplitude of oscillation.

7. Conclusions

The effect of magnetic field on the vibration and impact responses of the MR beams has been investigated. For modeling purposes, the layerwise displacement theory was employed to overcome some challenges in the modeling of MR beams.

The MR-laminated composite beams in which the top and bottom layers are made of glass-fiber laminated composites and the middle layer, is filled with MR fluids. Experimental tests have been conducted to validate the analytical results and show the performance of the MR-laminated beam for different magnetic fields. It was observed that increasing the magnetic field up to 800 Gauss increases the natural frequencies of the MR-laminated beam. However, beyond the 800 Gauss, the fundamental frequency of the MR-laminated beam begins to drop. The influence of MR layer thickness on the vibration behavior of MR-laminated beam was examined. Adding thickness of the MR layer affected decreases the natural frequencies of the first three modes.

In another study, a three-layered aluminum beam composed of aluminum layers at the top and bottom and the middle layer filled with MR fluid has been investigated for impact loadings. It was realized that increasing the magnetic field reduces the settling time of vibration for MR-aluminum beam. Also, for a constant magnetic field, increasing the level of impact load leads to increasing the amplitude of vibration as it was expected.

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