A SYNOPSIS REPORT
on

Design of 1-3/0-3 viscoelastic composite layer for augmented active/ passive constrained layer damping of structural vibration

for
A Thesis
to be submitted
for the award of the degree
of

Doctor of Philosophy

by

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Under the guidance of

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1. Introduction

Viscoelastic materials have elastic as well as viscous properties and possess the capability of energy-dissipation through the conversion of mechanical energy into heat during their deformation under the external dynamic loads. This energy-dissipation property of viscoelastic materials has long been utilized for suppression of structural vibration. Generally, the viscoelastic materials are attached to or embedded in the host structure and dissipate energy passively from the overall vibrating structure so that a passive damping of structural vibration appears. The attachment of viscoelastic materials to the host structure may be in different ways [1-4]. As a particular case of passive damping of bending mode of vibration of thin-walled structures, the viscoelastic materials are commonly used in the form of a layer either freely attached to the surface of host structure or constrained between the host structure-surface and a constraining layer. These two kinds of attachments of the viscoelastic materials in the layer-form are commonly known as free/unconstrained layer damping (UCLD) and passive constrained layer damping (PCLD) treatments. The PCLD is also called as the constrained layer damping (CLD).

In the UCLD treatment, the passive damping appears due to the extensional deformation/strain of the viscoelastic layer [5] although a little contribution of the thickness deformation of the viscoelastic layer to the total damping has also been reported [6]. A substantial number of studies on this UCLD treatment of structural vibration have been addressed in the literature [7-14]. All these studies show low damping capacity of the UCLD treatment, and thus the viscoelastic layer is generally used through the PCLD/CLD arrangement for achieving greater passive damping. The PCLD/CLD treatment is constituted by adding a constraining layer over the free surface of the viscoelastic layer in the UCLD treatment. Since both the top and bottom surfaces of the viscoelastic layer in the PCLD/CLD treatment are constrained by the stiff surfaces of the substrate and constraining layer, the damping in flexure mode of vibration arises mainly due to the transverse shear deformation/strain of the constrained viscoelastic layer. It is reported that the damping capacity of the PCLD/CLD treatment is indicatively greater than that of the UCLD treatment [15], and thus the PCLD/CLD treatment is widely utilized for attenuation of vibration of flexible engineering structures in automobiles, aircraft, ships, machine tools, etc. [2-4, 16-18]. The concept of this CLD treatment was proposed by Swallow [19], while its first mathematical formulation was addressed by Kerwin [20]. Subsequently, various theoretical models of the PCLD/CLD treatment of structural vibration have been addressed over the years particularly for investigating its damping capability as well as the corresponding mechanisms [21-29].

Besides the development of different theoretical models of the PCLD/CLD treatment, a substantial number of studies in the quest of its augmented damping capacity have also been reported in the literature [30-44]. In the quest for further improvement of damping capacity of the PCLD/CLD treatment, the active materials are utilised for the constraining layer along with a suitable controller. According to an appropriate control strategy, the active constraining layer mainly acts as an actuator for controlling the deformation of the constrained viscoelastic layer so that the damping treatment not only becomes adaptive to the changes in the structural vibration characteristics but also appears with augmented energy dissipation capability. This advancement of the CLD treatment was first introduced by Baz and Ro [45] through the proposition of the active constrained layer damping (ACLD) treatment. Subsequently, it (ACLD treatment) is developed through various theoretical and experimental studies over the years [46-63]. A review of literature in this context of free (UCLD)/constrained layer (PCLD/CLD/ACLD) damping treatment of structural vibration is presented in the dissertation.

1.1 Motivation and objectives of present research

A literature review was performed with an objective of understanding the state-of-art research in the broad area of structural vibration control using viscoelastic materials. This literature survey reveals a substantial number of research reports on the passive damping of structural vibration using the viscoelastic materials in layer-form through the UCLD or CLD/PCLD arrangement. The CLD/PCLD treatment provides superior passive damping over that in the UCLD treatment [15]. So, most of the available studies on the passive damping of structural vibration have been carried out using the CLD/PCLD arrangement. In these studies on the PCLD/CLD treatment, the mathematical modelling and experimental verification of damping in the treatment have been addressed for different kinds of structures. Along with these theoretical and experimental studies, the research in the quest of improved damping capacity of the CLD treatment has also been reported using standoff/spacer layer [41-43], segmented constraining layer [30], segmented damping layer [31-32], multiple damping layers [37-40], partial PCLD [33-36], closely spaced axial beams through VE layer [44], etc. Further improvement of damping capacity of the CLD treatment is achieved by the concept of ACLD [45]. The damping in the ACLD treatment is indicatively higher than that in the CLD treatment [45], and thus an exhaustive research on the ACLD treatment for various structures has been observed [46-64]. Similar to the CLD treatment, several design modifications of the ACLD treatment have also been reported by many researchers, particularly for its (ACLD) improved damping capacity. In these design modifications, the popular ones are SACL damping [54], segmented ACLD [55], EACL damping [56, 59], HCL damping [57], pre-compressed layer damping [58], stand-off layer damping [59] and partial ACLD [60-64]. Through these studies, the CLD/ACLD treatment has gained the credential as the eminent mean to exploit the damping properties of the viscoelastic materials for suppression of structural vibration. It is observed from the available studies on the CLD and ACLD treatments that the damping arises mainly due to the transverse shear strains of the constrained viscoelastic layer since the in-plane strains in the same damping layer appear with negligibly small magnitudes. If these in-plane strains appear with reasonable magnitudes along with the transverse shear strains within the constrained viscoelastic layer, then the damping capacity of the CLD/ACLD treatment is expected to improve. But, for achieving this coincidental occurrence of transverse shear strains and in-plane strains with their reasonable magnitudes, it is required to distribute the stiffness and damping properties of the constrained layer in an appropriate manner. Although it is not an easy task, the foremost option is to tailor the properties of the constrained layer using the passive inserts in a predefined manner. It basically infers the design of viscoelastic composite (VEC) layer for the improved damping in the CLD and ACLD treatments. The research using such passive inserts within the viscoelastic layer of CLD or ACLD arrangement has not yet been reported in the literature. Thus, the main objective of this research is identified as the design of VEC layers using the passive inserts for augmented CLD and ACLD treatments of basic structural elements like beams, plates and shells. These augmented CLD and ACLD treatments are aimed to arrive through the reasonable in-plane strains of the viscoelastic phase of the constrained layer along with its (viscoelastic phase) enhanced transverse shear strains.

In the application of CLD treatment for control of vibration of a structure, the modal damping does not appear in an adequate manner for all the modes of vibration within a range of operating frequency. This discrepancy may be alleviated by distributing the materials for damping and/or constraining layers in an appropriate manner through the segmentation of either of the constraining layer [30, 44] and CLD layer [34, 36]. A parallel strategy may also be implemented without segmentation of the CLD treatment where it is required to distribute the damping and stiffness properties of the constrained layer in an optimal manner for the appearance of sufficient modal damping for any of the modes of vibration within the operating frequency-range of interest. The research in this direction has not yet been reported in the literature. So, the second objective of the present research is identified as the design of a VEC layer in the CLD treatment for improved modal damping according to a predefined relative importance of different modes of vibration within a frequency-range of operation. Since the primary importance of damping is to reduce the amplitude of vibration at resonance, the relative importance of the modes of vibration would be based on the corresponding resonant amplitudes of vibration before deciding the distribution of properties of the damping layer.

In the ACLD treatment, the primary role of the piezoelectric constraining layer is to control the transverse shear deformation of the constrained viscoelastic layer for the effective active-passive damping of structural vibration. When this control of deformation is required to vary in the space coordinates at any instant of time, the active constraining layer is to be taken in the form of patches [60-64]. This form of constraining layer not only benefits the appropriate actuation of deformation of the constrained layer but also facilitates to overcome the discrepancy of poor flexibility and conformability of the piezoelectric actuator. However, with the advent of the flexible and conformable piezoelectric fiber composites (PFCs), the active constraining layer may be used in the layer-form while the variation of actuation in the space coordinates can be achieved by the use of the patches of surface-electrodes. The research in the line has not yet been addressed in the literature. So, another objective of this research is identified as the design of an ACLD treatment using the patches of surface-electrodes for active-passive control of structural vibration within an operating frequency range.

In order to fulfil the aforesaid objectives in this research, the following theoretical studies have been carried out:

(a) Design of a 1-3 VEC layer for improved free/constrained layer damping treatment of beams.

(b) Active-passive damping treatment of beams using a new 1-3 VEC layer.

(c) Optimal passive damping in circular cylindrical sandwich shells with a three-layered VEC core.
(d) A design of ACLD treatment for vibration control of circular cylindrical shell structures using three-layered VEC.
(e) Augmented CLD treatment of plates through the optimal design of a new 0-3 VEC layer.
(f) Performance of a graphite wafer-reinforced viscoelastic composite layer for active-passive damping of plate vibration.

2. Summary of the present research

This section presents a summary of the research work carried out for the thesis, and this includes the statements and salient results of the problems.

2.1 Design of a 1-3 VEC layer for improved free/constrained layer damping treatment of beams

A 1-3 VEC layer is designed in a combination of 2-2 VEC and pure viscoelastic material (VEM) layers as shown in Fig. 1. The 2-2 VEC is comprised of the thin rectangular graphite-wafers embedded within the viscoelastic matrix. This 1-3 VEC layer (Fig. 1(b)) is utilized instead of the traditional monolithic VEM layer in the UCLD/PCLD arrangement over the top surface of a substrate beam (Fig. 2), and the corresponding changes in the passive damping characteristics of the treatment (UCLD/PCLD) are studied. A finite element (FE) model of the overall beam is developed, and its (overall beam) static and dynamic analyses are carried out under the transverse load. In the static analysis, the distributions of transverse shear strain (γ_{xz}) and extensional strain (ε_x) over a transverse (xz) plane of the UCLD/PCLD treated beam are analysed in the presence and the absence of the graphite-inclusions within the viscoelastic layer. A corresponding result for the PCLD treated beam (Fig. 2(b)) is shown in Fig. 3 where it is clear that the maximum magnitudes of the strains in the viscoelastic layer indicatively increase due to the graphite-inclusions. Similar

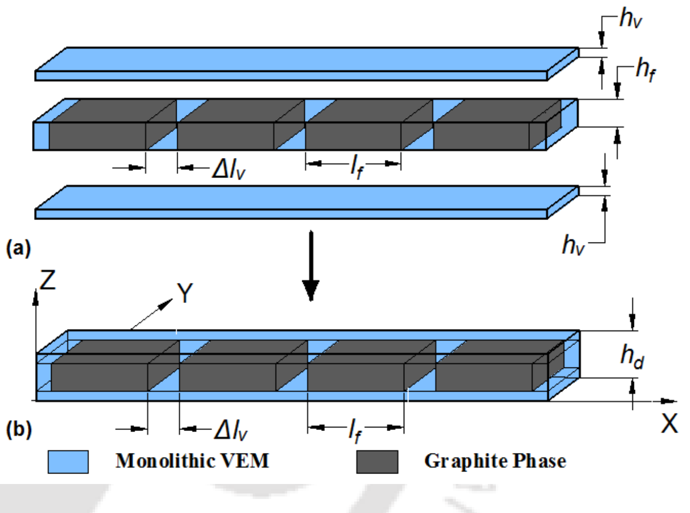

Fig. 1. Schematic diagrams of (a) 2-2 VEC and pure VEM layers, and (b) 1-3 VEC layer.

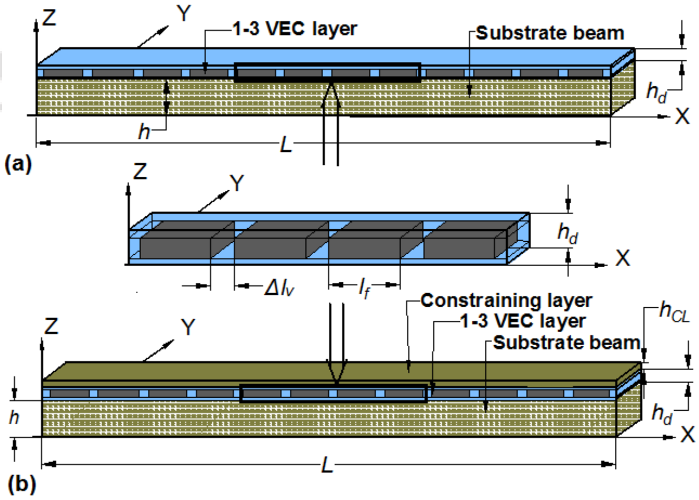

Fig. 2. Schematic diagram of a substrate beam integrated with an (a) layer of UCLD treatment and (b) layer of PCLD treatment.

observations are also obtained for the UCLD treated beam (Fig. 2(a)), and the same are furnished in the dissertation. These static results provide an initial estimation of improved damping capacity of the UCLD/PCLD treatment.

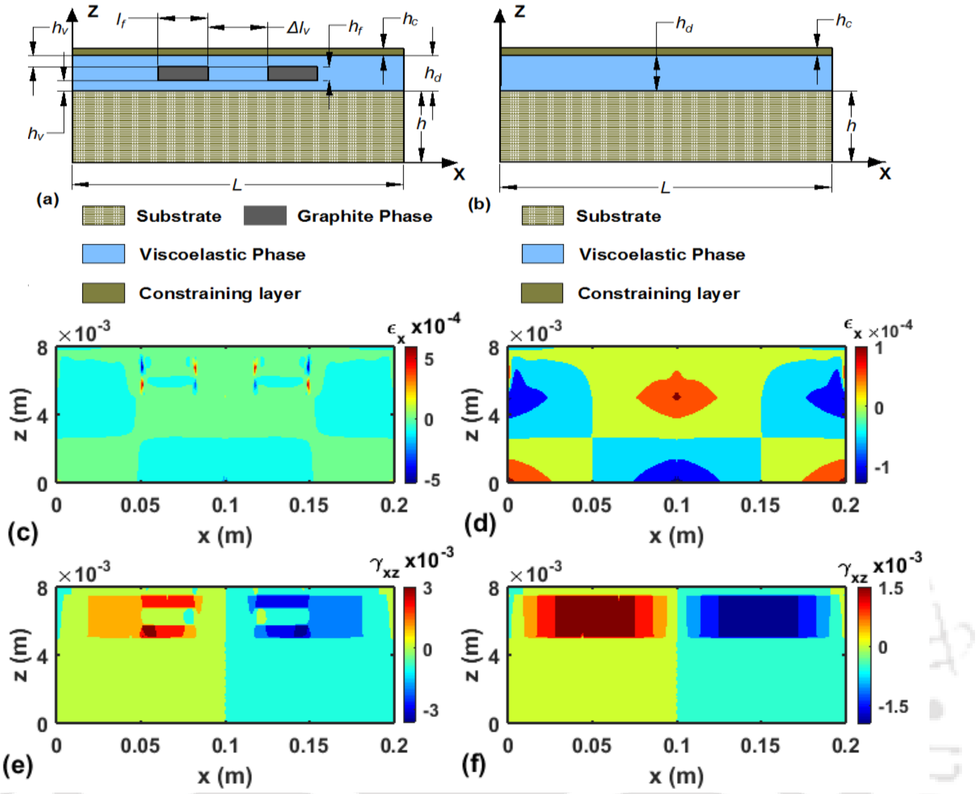

Fig. 3. Transverse (xz) plane of the PCLD treated beam with (a) 1-3 VEC layer or (b) pure VEM layer; distributions of extensional (ε_x) and transverse shear (γ_{xz}) strains on the xz-plane (c), (e) with and (d),(f) without graphite-inclusions.

This estimation of improved damping is further investigated through the evaluation of the modal loss factor of the overall beam for different sets of values of geometrical parameters in the arrangement of the graphite-inclusions within the viscoelastic layer. All these results are presented in the dissertation. These dynamic results reveal that the passive damping in the overall beam increases indicatively due to the graphite-inclusions. But, the augmented passive damping in the overall beam significantly depends on the different geometrical parameters in the arrangement of graphite-inclusions within the 1-3 VEC layer. So, based on these results, an appropriate geometric configuration of the inclusions within the viscoelastic layer is decided, and the frequency responses of the overall beam under a transverse harmonic load are

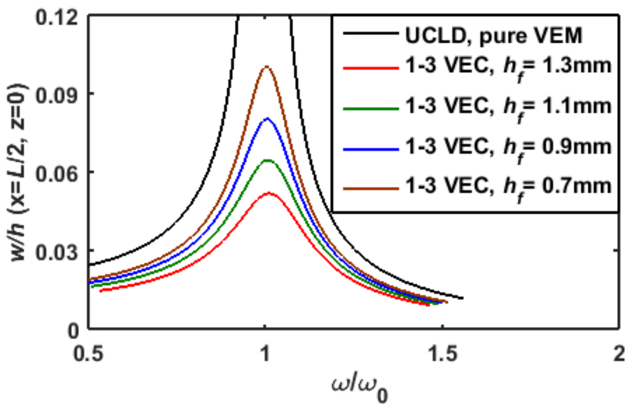

Fig. 4. Frequency responses of the overall beam integrated with pure VEM/1-3 VEC layer.

evaluated. Figure 4 shows these frequency responses of the UCLD treated beam for different values of thickness (h_f) of the 2-2 VEC layer within a constant thickness of the 1-3 VEC layer. As displayed in this figure, the damping in the overall beam increases significantly for the graphite-inclusions within the unconstrained viscoelastic layer. Similar frequency responses for the PCLD treated beam, and other important results are furnished in the dissertation to investigate the damping mechanisms and the damping capacity of the UCLD/PCLD treatment using the new 1-3 VEC layer.

2.2 Active-passive damping treatment of beams using a new 1-3 VEC layer

The active-passive damping in the ACLD treatment of vibration of a simply-supported beam is studied using the new 1-3 VEC layer (Fig. 1(b)). The passive constraining layer of the overall beam (Fig. 2(b)) is replaced by a monolithic piezoelectric layer (PZT5H), and it is activated by supplying the external voltage across its thickness according to the velocity feedback control law. An electro-elastic FE model of the overall beam is developed. Using this FE model, first, a bending analysis of the overall beam is carried out, and it is observed that the characteristics of strains ($\gamma_{xz}, \varepsilon_x$) in the constrained 1-3 VEC layer do not alter due to the active constraining layer instead of the passive one. But, the magnitudes of the strains in the VEC layer change. These observations provide an estimation of the improved active-passive damping in the ACLD treatment as the traditional monolithic VEM layer is replaced by the 1-3 VEC layer, and it is subsequently substantiated by evaluating the modal loss factors η and η_s for total damping and damping due to the shear strain of the viscoelastic phase, respectively. Figure 5 shows a result of the variations of modal loss factors (η, η_s) with the gap (Δl_v) between any two consecutive graphite-wafers of the 1-3 VEC layer (Fig. 1). The same figure also shows similar results in the absence of the graphite-inclusions. The vertical gap between the curves for η and η_s indicates the contribution of the extensional strain of the viscoelastic phase to the total damping in the overall beam. The results in Fig. 5 reveal indicative damping due to the extensional strain of the viscoelastic phase when the graphite-inclusions are added. Concurrently, the damping caused by the shear strain indicatively increases due to the graphite-inclusions. As a result, the total active-passive damping (η) in the overall beam increases significantly due to the passive inclusions. Similar results for the effects of different geometrical parameters of the 1-3 VEC layer on the active-passive damping in the overall beam are presented in the dissertation. Also, an appropriate geometric configuration of the 1-3 VEC layer is addressed for effective active-passive damping in the overall plate. The corresponding

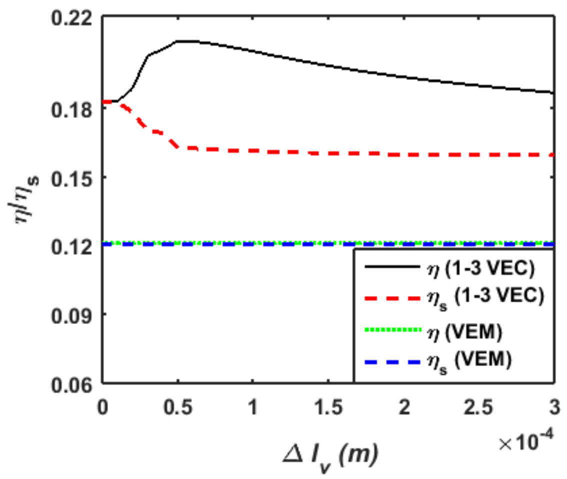

Fig. 5. Variations of modal loss factors (η , η_s) with the gap (Δl_v) in 1-3 VEC layer.

active-passive control capability of the ACLD treatment for control of forced harmonic vibration of the overall beam is also presented in the dissertation. Additionally, an iterative procedure is also proposed for solving quadratic eigenvalue problems.

2.3 Optimal passive damping in circular cylindrical sandwich shells with a three-layered VEC core

The concept of 1-3 VEC layer is implemented for passive control of vibration of a circular cylindrical shell. The overall shell is made in the form of a sandwich shell with the core of monolithic viscoelastic material as shown in Fig. 6(a). To achieve the 1-3 VEC layer at the core, the graphite-strips are inserted through the middle surface of the viscoelastic core as shown in Fig. 6(b). The physical configuration of this composite core is attributed in the form of a cylindrical laminate of two monolithic VEM layers over the inner and outer surfaces of the middle 2-2 VEC layer (Fig. 6(c)) so that it may be called as the three-layered VEC core. The graphite-strips are utilized for two main objectives. The first one is to achieve improved passive damping at all the modes of vibration of the cylindrical sandwich shell. The second one is to achieve this improvement of modal damping according to the assigned relative importance of excited modes of vibration within a frequency-range of operation. It is observed in the use of pure VEM core that few modes of vibration are prominently excited to large resonant-amplitudes. So, it is required to provide sufficient damping to these modes following the relative importance of corresponding

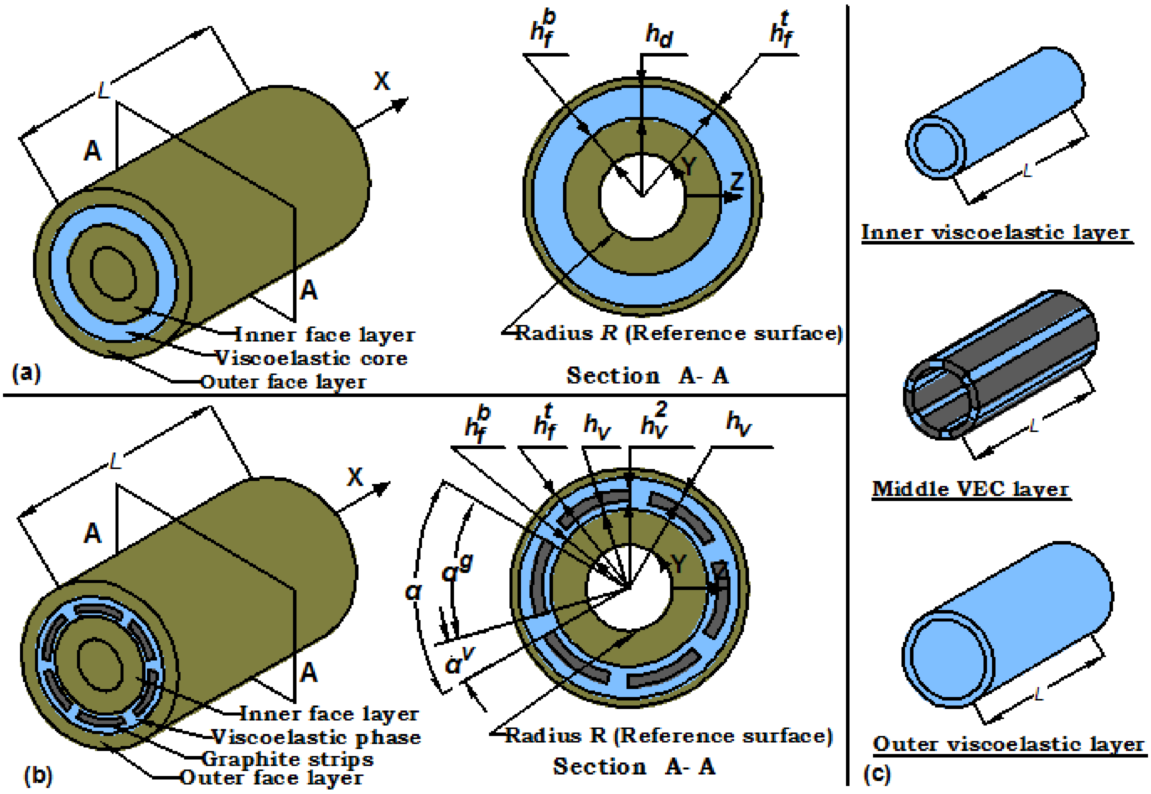

Fig. 6. Schematic diagrams of (a) sandwich shell with single-layered viscoelastic core, (b) sandwich shell with three-layered viscoelastic composite core and (c) layers of three-layered viscoelastic composite core.

resonant-amplitudes, and it is now aimed through inserting the graphite-strips within the viscoelastic core in the form of a three-layered VEC core.

The study with these objectives is carried out by developing an FE model of the sandwich shell based on the layer-wise shear deformation theory and Sander's shell theory. Using this FE model, first, the mechanisms of passive damping are illustrated through the study of strain-distributions in the VEC layer for different modes of vibration of the sandwich shell. These results are furnished in the dissertation where it is estimated that the improved passive damping may appear through both the shear and extensional strains of the viscoelastic phase in the three-layered VEC core. This estimation of augmented damping is subsequently corroborated by the evaluation of the variations of modal loss factors of different modes of vibration with the number (n_f)/thickness ($r_c = h_v^2 / h_c$)/spacing (α^v) of graphite-strips. These dynamic results are detailed in the dissertation where an indicative augmentation of passive damping in the shell is observed. Also, the indicative influences of the geometric parameters in the distribution of graphite-strips are observed. So, the graphite-strips are introduced with their optimal size and circumferential distribution by means of maximizing the weighted average loss factor ($\bar{\eta}$) of all the modal loss factors of excited modes within the operating frequency range. The relative importance (weights) of the excited modes within this weighted average loss factor is assigned in proportion to the resonant-amplitudes appeared in the use of pure VEM core. A numerical result for deciding the optimal parameters in the distribution of graphite-strips for the unsymmetrical sandwich shell is shown in Fig. 7 where, first, a suitable

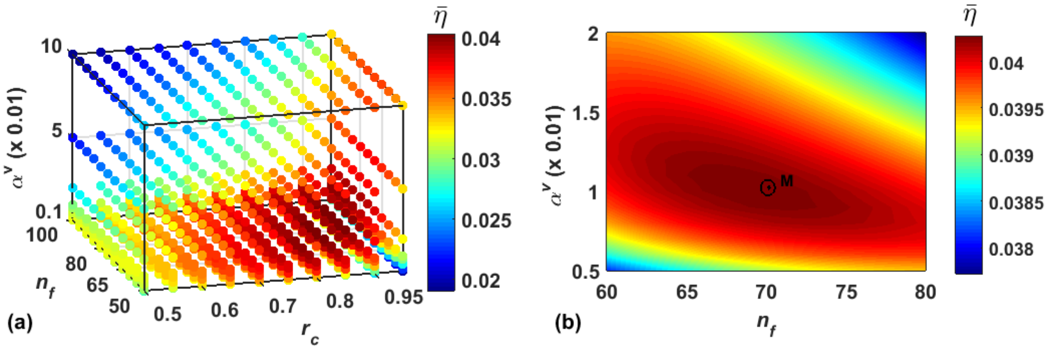

Fig. 7. (a) Variation of $\bar{\eta}$ for unsymmetrical sandwich shell at different grid points of 3D mesh with the axial directions of r_c, α_v, n_f ; (b) contour plot for variation of $\bar{\eta}$ in 2D plane of α_v and n_f at r_c = 0.85 (M-point for maximum $\bar{\eta}$).

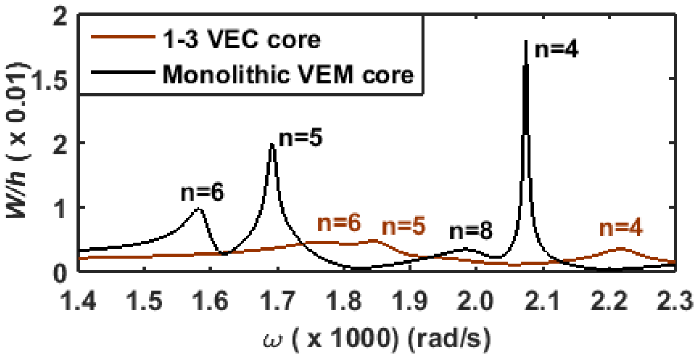

Fig. 8. Frequency responses of the unsymmetrical sandwich shell with monolithic VEM core or VEC core (n is the circumferential mode number for the longitudinal mode number of 1).

value of the thickness (r_c) is decided primarily on the basis of physical aspects of fabrication of the VEC (Fig. 7(a)) and then the other two parameters (n_f, α^v) are optimized (Fig. 7(b)). Similar results for the symmetrical sandwich shell are also presented in the dissertation. Based on these optimal configurations of the three-layered VEC core, the forced frequency responses of the symmetrical and unsymmetrical sandwich shells are evaluated within a frequency-range of interest. A corresponding result for the unsymmetrical sandwich shell is shown in Fig. 8 where the change in the response due to the inclusions indicates the fulfilment of the aforesaid objectives and the same is detailed in the dissertation. Apart from these results, the improvement of modal loss factors in proportion to the assigned modal weights is presented in the dissertation. The numerical accuracy in computation of model loss factor using complex mode-shape or modal strain energy (MSE) method is also furnished in the dissertation.

2.4 A design of ACLD treatment for vibration control of circular cylindrical shell structures using three-layered VEC

An ACLD arrangement for effective control of several modes of vibration of circular cylindrical shell structure is presented using the new three-layered VEC. The three-layered VEC is considered to be distributed throughout the outer convex surface of a host circular cylindrical shell. For superior active-passive damping in the overall shell, the VEC layer is considered to be fully constrained by the piezoelectric layer, while the conformability of this piezoelectric layer with curved host-surface is ensured by the use of vertically/radially reinforced 1-3 PFC layer. The inner fully electrode-surface of this 1-3 PFC constraining layer is grounded while its outer surface is considered to be printed with electrode-patches as shown in Fig. 9. The electric potential over every electrode-patch is supplied by taking the feedback of local velocity that is sensed at its (patch) middle point. The first objective in this arrangement of ACLD treatment is to accomplish augmented active-passive (ACLD) damping of shells using the new three-layered VEC. The second objective is to control several modes of vibration of the shell using the ACLD treatment in layer-form.

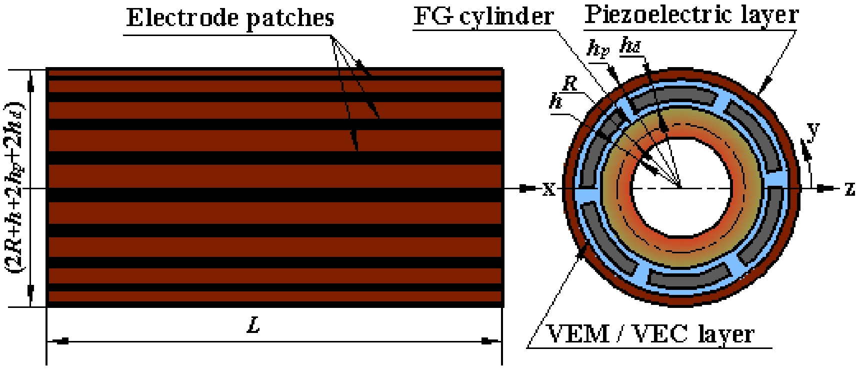

Fig. 9. Schematic diagram of the host FGM shell integrated with the ACLD layer over its outer surface.

The host circular cylindrical shell is considered to be made of a functionally graded material (FGM) with the metal and ceramic constituents. Its (FG shell) properties vary from inner ceramic rich surface to outer metal rich surface for the consideration of a high temperature at the inner concave surface. The overall FG shell is considered to vibrate in the presence of this temperature for an applied harmonic mechanical excitation within a range of operating frequency. For effective control of all the modes of vibration of the shell within the operating frequency-range of interest, a fruitful strategy for the arrangement of the patches of surface-electrode is proposed, and the corresponding controlled frequency responses of the overall shell are evaluated through the development of its (overall FGM shell) geometrically nonlinear coupled thermo-visco-electro-elastic incremental FE model based on the layer-wise shear deformation theory, Sander's shell theory and GHM model for viscoelastic material. The responses of the overall shell are evaluated considering its small deformation, but the nonlinear formulation is carried out to account the coupling between the thermal deformation and the amplitude of vibration of the overall shell. A result for the controlled frequency responses of the overall shell is shown in Fig. 10 for different values of the thickness (h_v^2) of the middle 2-2 VEC layer within a constant thickness of the constrained three-layered VEC. The numbers indicate circumferential modes (n) of resonance. The symbols Ω and W indicate the dimensionless operating frequency and the maximum transverse displacement-amplitude, respectively. This result shows a significant improvement of the active-passive (ACLD) damping in the overall shell for the

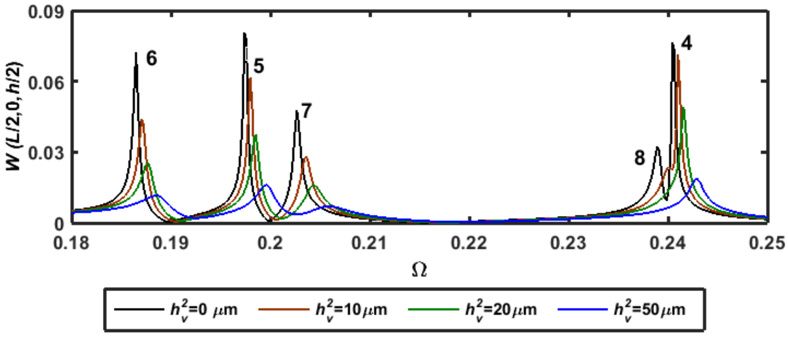

Fig. 10. Frequency responses of the overall shell for different thickness (h_v^2) of 2-2 VEC layer within the constrained layer of constant thickness.

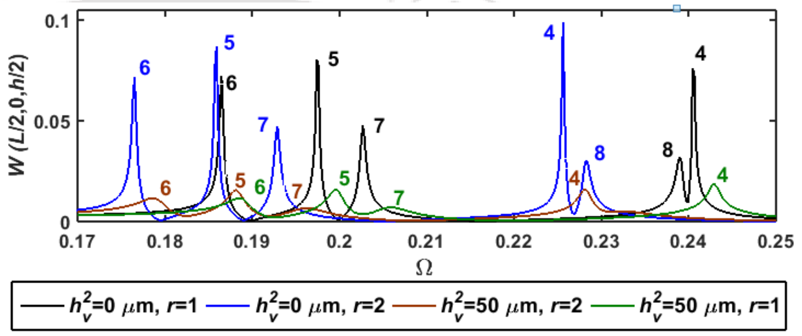

Fig. 11. Frequency responses of the overall FG shell for different values of the volume fraction index (r) of host FG shell.

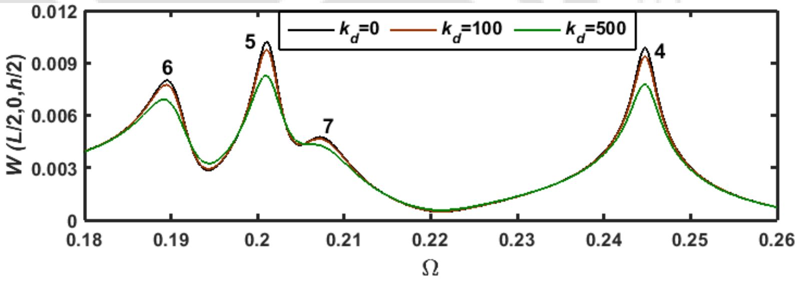

Fig. 12. Frequency responses of the overall shell for different values of control-gain (k_d).

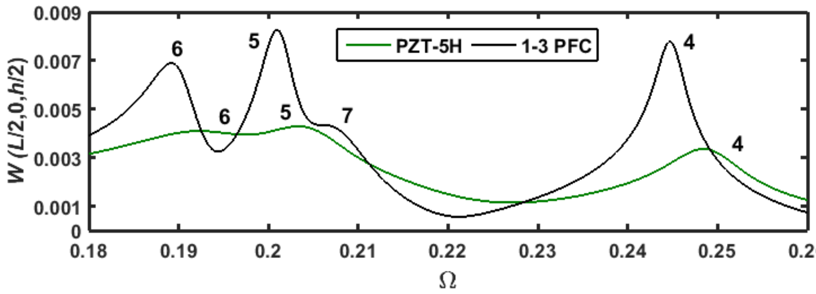

Fig. 13. Frequency responses of the overall FG shell for the PZT-5H or the 1-3 PFC constraining layer.

inclusions of graphite-strips ($h_v^2 \neq 0$) within the monolithic VEM ($h_v^2 = 0$). This characteristic of the active-passive damping holds for any volume fraction (indicated by the index r) of the ceramic/metal constituent of the FG shell as shown in Fig. 11. The active-passive damping in the shell can also be increased by increasing the velocity-feedback control gain (k_d) as demonstrated in Fig. 12. It is also observed that the performance of the 1-3 PFC as the material of the active constraining layer is a little inferior to that of the monolithic PZT5H (Fig. 13). Still, the 1-3 PFC is chosen because of the requirement of the highly conformable piezoelectric constraining layer for the curved host-surface. Other important results and also the effects of temperature in the FG shell on the control capability of the ACLD layer are presented in the dissertation.

2.5 Augmented CLD treatment of plates through the optimal design of a new 0-3 VEC layer

In the PCLD/CLD and ACLD treatments using 1-3 VEC layer, the augmented damping arises due to the enhancement of certain strain components in the viscoelastic phase. These strain components lie in the transverse plane over which the graphite-inclusions are discontinuously distributed. However, in the quest of improved PCLD/CLD treatment of structural vibration through the enhancement of all the strain components in the viscoelastic phase, a new 0-3 VEC layer is designed. It (0-3 VEC layer) is constructed by inserting a rectangular array of the thin rectangular graphite-wafers through the middle surface of a pure viscoelastic layer. The geometrical construction of this VEC layer may be described by a stack of two pure viscoelastic layers over the top and bottom surfaces of a middle 1-3 VEC layer as shown in Fig. 14(a). As all the layers are combined into a single layer, a 0-3 VEC layer can be obtained. The performance of this 0-3 VEC layer as a damping layer in the CLD treatment is investigated by integrating it (0-3 VEC) as a constrained layer over the top surface of a substrate plate as shown in Fig. 14(b). As the overall plate undergoes bending deformation, the viscoelastic material within the in-plane axial gap between any two consecutive rectangular graphite-wafers is expected to experience extensional/compressional strain. Concurrently, the viscoelastic material in the transverse gap between any two successive horizontal surfaces of stiff elements experiences the transverse shear strains. So, the transverse shear and in-plane extensional strains are supposed to appear within the viscoelastic phase with reasonable magnitudes. The corresponding passive damping in the overall plate is analysed by developing an FE model of the overall plate (Fig. 14(b)) based on the layer-wise shear deformation theory. First, a

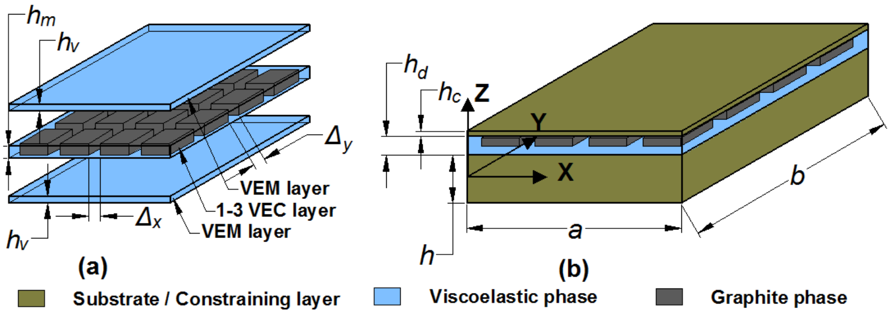

Fig. 14. Schematic diagrams of (a) the component layers of 0-3 VEC, (b) PCLD arrangement over the top surface of a substrate plate using 0-3 VEC layer.

bending analysis of the overall plate is performed, and the characteristics of the transverse shear and in-plane strains within the constrained 0-3 VEC layer are studied. A corresponding result for the distribution of a shear strain (γ_{xz}) over a horizontal plane above the top surfaces of the graphite-wafers is shown in Fig. 15. This result shows the improvement of the maximum magnitude of the transverse shear strain (γ_{xz}) due to the insertion of graphite-wafers. Similar results for all the transverse shear and in-plane strains within the constrained 0-3 VEC layer are presented in the dissertation. These results indicate the improvement of maximum magnitudes of all the strains in the viscoelastic phase of the 0-3 VEC layer. The corresponding improvement of passive damping is substantiated by computing the modal loss factor of the overall plate for its fundamental bending mode of vibration. The effects of different geometric parameters of the 0-3 VEC layer on the passive damping in the overall plate are studied, and it is observed that some of the geometrical parameters in the arrangement of the graphite-wafers indicatively influence the passive damping in the overall plate. So, these geometrical parameters are optimally configured for maximum modal loss factor of the overall plate. These results are detailed in the dissertation. Based on these results for optimal configuration of the 0-3 VEC layer, the forced frequency responses of the overall plate are evaluated. A corresponding result is shown in Fig. 16 where the frequency responses of the overall plate are presented for the presence and the absence of graphite-wafers in the viscoelastic layer. This result shows an indicative improvement of passive damping in the plate due to the insertion of an array of graphite-wafers in an optimal manner. Other important results are also furnished in the dissertation to illustrate the damping characteristics

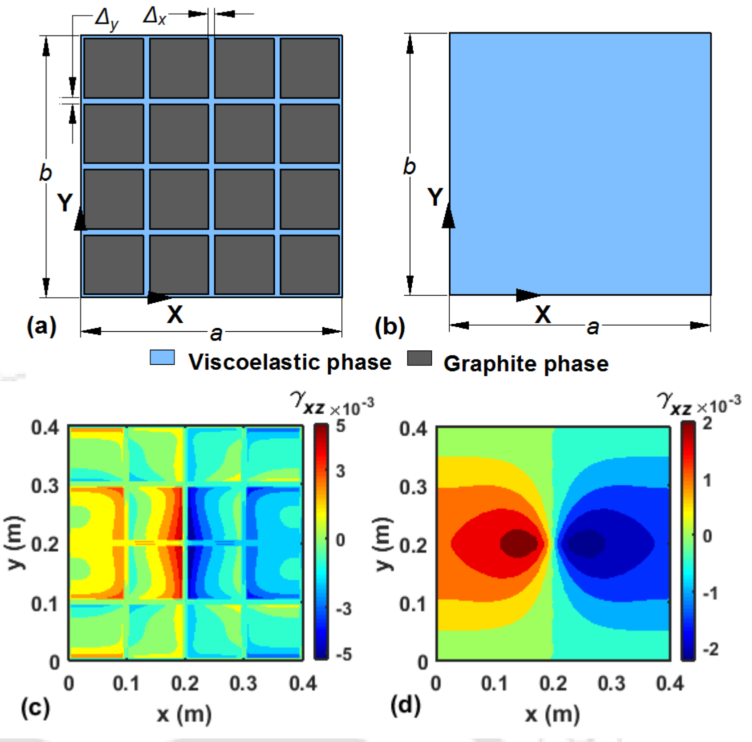

Fig. 15. Distributions of materials over the middle plane of the constrained (a) 0-3 VEC or (b) monolithic VEM layer; distributions of shear strain (γ_{xz}) over a horizontal plane through the viscoelastic phase of the constrained layer made of (c) 0-3 VEC or (d) monolithic VEM.

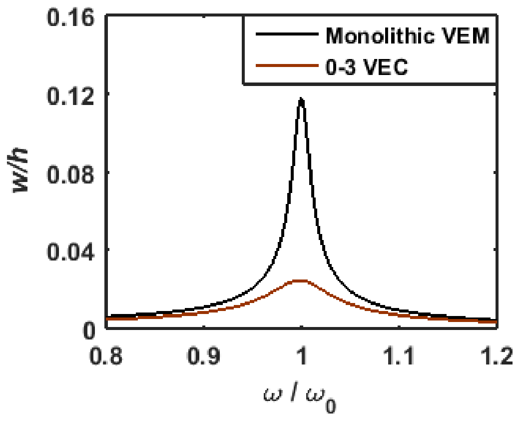

Fig. 16. Frequency responses of the overall plate around its fundamental natural frequency (ω_0).

of the new 0-3 VEC layer for PCLD treatment of vibration of plates.

2.6 Performance of a graphite wafer-reinforced viscoelastic composite layer for active-passive damping of plate vibration

An indicative improvement of passive damping in the CLD treatment of plates is observed when the monolithic VEM layer is replaced by the present 0-3 VEC layer, and thus this study is extended to investigate the performance of the same VEC layer as a constrained layer for the ACLD treatment of plates.

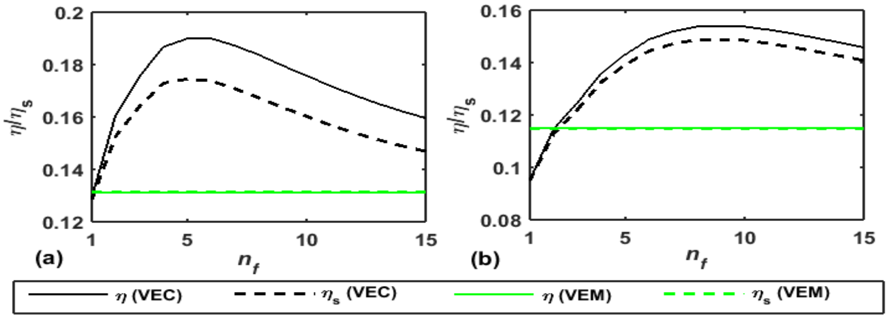

Fig. 17. Variations of the modal loss factors (η, η_s) with the number of graphite-wafers ($n_x = n_y = n_f$) within the constrained damping layer, (a) $h_d = 1$ mm and (b) $h_d = 0.5$ mm (h_d is the thickness of the constrained layer).

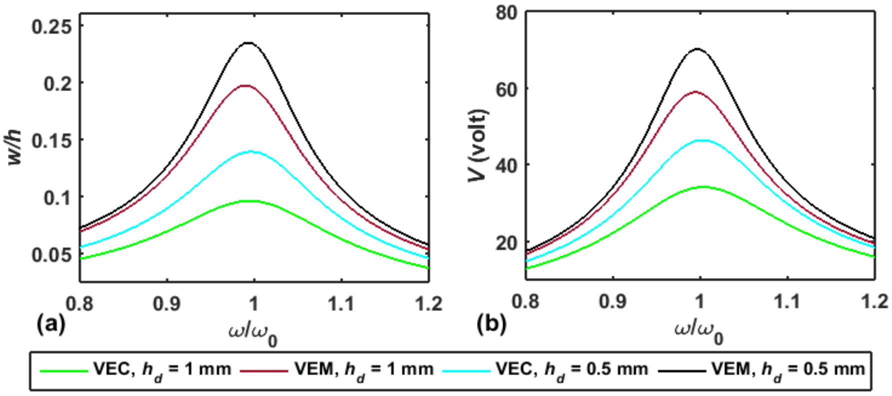

Fig. 18. Variations of (a) the transverse displacement-amplitude and (b) the corresponding required control-voltage within a range of the operating frequency around the fundamental natural frequency (ω_0) of the overall plate (k_d =100).

For this ACLD treatment, the constraining layer of the overall plate (Fig. 14(b)) is considered to be made of a monolithic piezoelectric material (PZT5H). This piezoelectric layer is activated by supplying the external voltage across its thickness according to the velocity feedback control strategy. For the analysis of active-passive damping in the overall plate, an FE model is developed based on the layer-wise first-order shear deformation theory. Using this FE model, first, a bending analysis of the overall plate is performed where the strains in the viscoelastic phase of the actively constrained 0-3 VEC layer are evaluated in the absence and the presence of the graphite-wafers. All these results are furnished in the dissertation. Qualitatively, these static results exhibit similar characteristics of the strains as those are obtained for the PCLD treatment of plates using the 0-3 VEC layer. Thus, the expected augmentation of damping in the ACLD treatment is corroborated by evaluating the total modal loss factor (η) and the modal loss factor due to the transverse shear strain (η_s) only in the viscoelastic phase. A corresponding result is shown in Fig. 17 for the variations of the modal loss factors (η, η_s) with the number (n_f) of graphite-wafers within the 0-3 VEC layer. The difference between the curves of η and η_s for any material (VEM or VEC) indicates the contribution of the in-plane strains to the total active-passive damping in the overall plate. So, this result (Fig. 17) shows that the augmented active-passive damping in the plate appears through all the strains of the viscoelastic phase for the use of 0-3 VEC layer instead of the monolithic VEM layer. Similar results for the effects of other geometric parameters of the 0-3 VEC layer on the active-passive (ACLD) damping in the overall plate are also furnished in the dissertation, and an optimal geometric configuration of the 0-3 VEC layer for the maximum damping capacity of the ACLD treatment is evaluated. The corresponding controlled frequency responses of the overall plate and the required control voltage (V) for the ACLD treatment are illustrated in Fig. 18 for different values of the thickness of the constrained 0-3 VEC layer. This result shows an indicative improvement of active-passive damping in the overall plate for the use of 0-3 VEC layer instead of the monolithic VEM layer. At the same time, the required control voltage also decreases. Other important results are also presented in the dissertation for illustrating the characteristics of ACLD treatment of plates using the new 0-3 VEC layer.

3. Summary and conclusions

This dissertation deals with the design of viscoelastic composite (VEC) layers for improved passive and active-passive damping of vibration of basic structural elements (beams, plates, shells). First, a beam integrated with the conventional UCLD/PCLD treatment is considered, and the graphite-wafers are inserted through the middle surface of the viscoelastic layer within the arrangement of the UCLD/PCLD treatment. These inclusions of graphite-wafers within the viscoelastic layer yield a 1-3 VEC layer, and the corresponding changes in the passive damping characteristics of the overall beam are studied through its static and dynamic bending analyses using FE procedure. The static analysis reveals the improved magnitudes of the transverse shear strain in the viscoelastic phase along with a reasonable magnitude of the extensional strain in the same phase due to the graphite-inclusions. So, these static results infer the augmented passive damping in the plate due to the graphite-inclusions, and it is subsequently corroborated through the quantification of modal loss factor of the overall beam in the presence and the absence of the graphite-inclusions in the viscoelastic layer. It is found that the passive damping in the overall beam increases significantly due to the graphite-inclusions in the form of a 1-3 VEC layer. This observation motivates to utilize this 1-3 VEC layer as the damping layer in the ACLD treatment of beams, and thus a monolithic piezoelectric layer is taken to constrain the 1-3 VEC layer against the top surface of a host beam, while this active constraining layer is considered to be activated by supplying the external voltage across its thickness according to the velocity feedback control strategy. For the bending deformation of the overall beam under the active piezoelectric constraining layer, the characteristics of the strains in the constrained viscoelastic layer are studied in the presence and the absence of the graphite-inclusions, and the same observations are obtained as those appear in the previous PCLD treatment. So, the active-passive (ACLD) damping in the overall beam is quantified, and this result reveals indicatively improved ACLD treatment of beam due to the graphite-inclusions in the constrained viscoelastic layer.

Next, this concept of 1-3 VEC layer is implemented for CLD treatment of circular cylindrical shell structures. The cylindrical shell is constructed in the form of a sandwich shell with the viscoelastic core, and the graphite-strips are longitudinally inserted through the middle surface of the viscoelastic core so that the 1-3 VEC core appears. The distributions of strains in this 1-3 VEC core for the bending modes of deformation of the sandwich shell infer the similar damping mechanisms as those are obtained for the previous PCLD treatment of beams. Through these damping mechanisms, augmented passive damping in the sandwich shell is observed due to the graphite-inclusions. This augmentation of passive damping is found to be dependent indicatively on the geometrical parameters in the arrangement of the graphite-strips. So, the geometrical configuration of the 1-3 VEC core is optimized with an objective of the maximum weighted average modal loss factor where the weights for different modes of vibration are taken in proportion to the corresponding resonant displacement-amplitudes in the absence of inclusions. In the results for corresponding frequency responses of the sandwich shell, indicatively augmented attenuation of vibration-amplitudes is observed, and also this augmented attenuation appears following the assigned weights. So, it is possible to attenuate all the modes of vibration of a sandwich shell within an operation frequency-range using an optimally configured 1-3 VEC core. Following these fruitful results in the use of 1-3 VEC core, it (1-3 VEC layer) is further utilized as the constrained layer in an ACLD treatment of circular cylindrical shell structures. The material for the corresponding piezoelectric constraining layer is taken as the vertically reinforced 1-3 PFC for the requirement of its (constraining layer) conformability with the curved surface of the host cylinder. The ACLD is considered to be distributed throughout the outer surface of the shell, while the effective active-passive damping of several modes of vibration is achieved through the arrangement of the patches of surface-electrodes over the surfaces of the 1-3 PFC layer in an appropriate manner. The overall shell is analysed by developing an FE model, and it is observed that the active-passive damping in the overall shell indicatively increases due to the graphite-inclusions. Also, the displacement-amplitudes at all the resonances within an operating frequency-range are attenuated effectively for the present arrangement of the patches of surface-electrodes.

For the inclusions of graphite-strips or graphite-wafers in the form of 1-3 VEC, the magnitudes of certain strain components in the viscoelastic phase improve, and these strain components lie in the transverse plane over which the inclusions are discontinuously distributed. However, for the enhancement of all the strains in the viscoelastic phase of damping layer, a new 0-3 VEC layer is proposed by means of inserting a rectangular array of thin rectangular graphite-wafers through the middle surface of a viscoelastic layer. The performance of this 0-3 VEC layer in the PCLD arrangement over a plate is investigated by analysing the bending deformation/vibration of the overall plate. The bending analysis of the overall plate reveals the appearance of in-plane strains with reasonable magnitudes while the magnitudes of all the transverse shear strains increase indicatively. This observation signifies improved damping in the plate due to the inclusions of graphite-wafers, and it is substantiated by evaluating the modal loss factors for different sets of values of geometrical parameters in the arrangement of graphite-wafers. It is observed that some geometric parameters of the 0-3 VEC layer have indicative influences on the damping in the overall plate. So, the geometry of the 0-3 VEC layer is optimized for maximum damping, and the frequency responses of the overall plate are evaluated with and without considerations of the inclusions. These responses reveal significantly improved attenuation of vibration-amplitudes of the overall plate due to the presence of an array of graphite-wafers in an optimal manner. This study is subsequently extended for the ACLD treatment of the plates, and it is observed that the damping mechanisms in the use of the 0-3 VEC layer do not alter for the consideration of active constraining layer instead of the passive one. Also, the active-passive (ACLD) damping increases indicatively for the inclusion of an array of graphite-wafers within the actively constrained viscoelastic layer.

4. Contributions

The following contributions in the field of viscoelastic damping of structural vibration have been made towards the preparation of the dissertation.

1. A novel concept of 1-3 VEC layer is proposed for improved UCLD, PCLD and ACLD treatments of thin-walled flexible structures.
2. A novel concept of 0-3 VEC layer is proposed for improved PCLD and ACLD treatments of plates.
3. An optimal design of 1-3 VEC at the core of a circular cylindrical sandwich shell is presented for augmented passive damping of all the modes of vibration of the shell within an operating frequency range. This augmented damping over different modes of vibration can also be achieved as per the assigned weights over the modes.
4. A new design of ACLD treated circular cylindrical shell structure is presented using the 1-3 VEC layer, electrode-patches and velocity sensors. Through this design, it is possible to achieve augmented active-passive control of all the modes of vibration of the shell within the operating frequency-range of interest.
5. A strategy for the arrangement of electrode-patches over the surface of the piezoelectric constraining layer of the ACLD arrangement is proposed for active-passive control of all the modes of structural vibration effectively.
6. The performance of vertically reinforced 1-3 PFC actuator layer for active or active-passive control of circular cylindrical shells is presented using the electrode-patches over its (1-3 PFC) surfaces.
7. A geometrically nonlinear incremental thermo-visco-electro-elastic FE model of a circular cylindrical shell integrated with the actively constrained 1-3 VEC layer is developed for the analysis of its vibration characteristics under the thermal environment.

The contributions as mentioned above are recognized by the following **research papers published and being under review** in peer reviewed international journals.

1. Kumar A, Panda S. Design of a 1-3 viscoelastic composite layer for improved free/constrained layer passive damping treatment of structural vibration. Composites Part B: Engineering 2016; 96:204-214.
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4. Kumar A, Panda S, Narsaria V, Kumar As. Augmented constrained layer damping in plates through the optimal design of a 0-3 viscoelastic composite layer. 2017 (First review report obtained and the revised manuscript has been submitted to Journal of Vibration and Control).
5. Kumar A, Panda S, Kumar As, Narsaria V. Performance of a graphite wafer-reinforced viscoelastic composite layer for active-passive damping of plate vibration. 2017 (First review report obtained and the revised manuscript has been submitted to Composite Structures).

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