Hybrid lightweight composite pyramidal truss sandwich panels with high damping and stiffness efficiency

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Abstract

Hybrid composite pyramidal truss sandwich panels combined with multiple damping configurations are fabricated in this work. Modal and quasi-static compressive tests are carried out to investigate the damping and stiffness efficiency of the candidate structures. Experimental results show that such structures combined with damping materials would significantly improve the damping loss efficiency but decrease simultaneously the stiffness efficiency in varying degrees compared with the bare hybrid sandwich panels. In order to evaluate the compatible effect of total damping and stiffness efficiency of the present sandwich structures, a synthetic evaluation criterion is developed, which shows that bare sandwich panels filled with hard polyurethane foam (B-II-HPF) and soft polyurethane foam (B-II-SPF) can yield the best performance up to 2-4 times higher than the base hybrid sandwich panels. It is also shown that multiple patch damping treatments based on the FE-MSE approach are suitable and

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effective to further improve the total damping efficiency.

Keywords: composite; sandwich panels; damping efficiency; stiffness efficiency; pyramidal truss cores

1. Introduction

Sandwich structures generally consist of two thin face sheets bonded to a thick and lightweight core with any topological configurations using adhesive interface layers. The insertion of a lightweight core increases the structural bending stiffness and strength substantially without adding much weight compared with single-layer homogenous structures [1-2]. For the high strength and stiffness to weight ratio, sandwich structures are widely used in many engineering applications including aircraft, automotive and construction industries. Various types of topological configurations of sandwich cores including metal alloys and composites have been developed [3-6] and at the same time mechanical properties such as compression, shearing, bending, impacting and vibration damping of sandwich structures have been extensively studied [7-13]. Unfortunately, lightweight and stiff materials and structures are usually associated with relatively low damping [14-17] which can cause early mechanical damage caused by resonant vibration. Owing to the outstanding designability of sandwich structures, an excellent combination of stiffness and damping can be obtained by choosing suitable materials and geometric configurations of the face sheets and cores. The method of constrained layer damping (CLD) that was first proposed by Kerwin [18] has been proven effective in vibration suppression

[19-20]. In addition, filling of the core voids with foam or viscoelastic material have been also investigated in order to improve the structural damping loss factors [21-22]. However, the insertion of the damping material inside the face sheets and core of the sandwich panel increases the extra mass which is undesired and always significantly changes the dynamic properties. Therefore it is also a main topic concerned by design engineers to efficiently use the CLD treatments. Previous works [23-24] have confirmed by theoretical analysis and experiments that the base structure partially covered with CLD was more mass efficient than with complete coverage. Based on that, varieties of comprehensive studies have been conducted to optimize CLD, location and dimensions in order to maximise the structural damping while minimising additional mass. To tackle this problem and its related filed, many optimization techniques such as Genetic Algorithm [25], Moving Asymptotes method [26], Topology Optimisation method [27], Modal Strain Energy method [28] and recently Double Shear Lap-Joint configuration [29-30] were successfully adopted. To date, most of the research about structural damping optimization focused on simple CLD beams, panels and shells using theory and numerical simulations, which usually lack of experimental verification. However, to the authors' knowledge, there are only few reports on vibration damping optimization of composite sandwich structures with honeycomb cores [22, 29-30], and much less for complicated lattice truss cores.

The purpose of the present work is to explore a way to meet the competing demands of vibration attenuation and minimizing the added mass of the hybrid

composite pyramidal truss sandwich panels. Inspired by the research mentioned above, a series of the hybrid composite pyramidal truss sandwich panels without and with combinations of high lossy materials is fabricated. Experimental modal and quasi-static compressive tests are carried out to investigate the damping and stiffness efficiency of the candidate structures. A synthetic evaluation criterion is developed to study the compatible effect of total damping and stiffness efficiency of the present sandwich structures. Furthermore, based on the modal strain energy approach, multiple patch damping treatments are implemented in the base structures using the validated Finite Element (FE) models that aim at obtaining the highest damping loss factor using the minimal mass without any stiffness penalty. Finally, the effects of the volume, configuration and thickness of the damping layer on natural frequencies and the strain energy proportion are also investigated.

2. Fabrication approaches

Hybrid composite pyramidal truss sandwich panels without and with combinations of high lossy materials are manufactured in the present study. For the former, the pyramidal truss cores are firstly assembled by interlocking 2-D truss patterns that are cut from aluminum alloy sheets (2A12-T4, Harbin Dongqing Metals Manufacturing Co., Ltd., China) using wire electrical discharge machining [8]. Then the top and bottom face sheets are made from orthogonal woven carbon fibre reinforce/epoxy resin (LS-3K, Shanghai Lishuo New Material Technology Co., Ltd., China) fabrics of thickness 0.2 mm through a hot press moulding method and cut into an overall size of

120mm×120mm with different thickness T_f . Finally, three parts are connected with each other by adhesive bonding (J-272, Heilongjiang Institute of Petrochemical, China) and held at 120°C for 2 h in the oven. The detailed fabrication processes are shown in Fig.1. For the latter, three main types of combinations of high lossy materials with the sandwich panels are selected for this study. For type I, the insertion of the viscoelastic damping sheet (VDS, Wuhan Great Wall Rubber Co., Ltd. China) with different thickness inside the middle layer of the top and bottom face sheets is adopted. For type II, the effective damping materials including hard polyurethane foam (HPF), soft polyurethane foam (SPF) and silicone rubber (SR) provided by Dongguan Huixin Industrial Co., Ltd, China are filled in the void spaces of the pyramidal truss cores, whilst type III can be designed as the integration of the two aforementioned types that combines high lossy materials on the middle layer of the face sheets and in the void spaces of the pyramidal truss cores, which are shown in Fig.2. The repeating unit cell (RUC) of such hybrid composite pyramidal truss sandwich panels is shown in Fig.2(b) and the following geometrical parameters are used $a = 25.28mm$, $h = 15mm$, $b = 1.5mm$, $c = 8mm$, $t = 1.5mm$, $l = 14.23mm$, $h_a = 3mm$, $h_b = 1.5mm$. The mechanical properties of the used materials are listed in Table 1. At least two specimens with the same size and configuration are tested to guarantee the reliability of the results.

3. Experiments

3.1 Modal testing of the hybrid sandwich panels

To understand the effect of the high lossy materials on the structural vibration damping, the specimens of hybrid composite sandwich panels illustrated in Table 2 are tested by modal analysis. The experimental apparatus of DEWETRON dynamic signal analyzers for the modal tests is shown in Fig.3 (a), where the impulse impact method is adopted via the single-input multi-output analysis method. In consideration of the clamped boundary that could induce extraneous energy dissipated, the specimen is suspended by thin wires to most closely simulate a completely free boundary condition. The force hammer (model SN30979, sensitivity 12.25mV/N) is used to tap the input points arranged on the specimen and the vibratory response is measured using an acceleration transducer (model SN46550, sensitivity 10.07 mV/m/s²). Then the input signal and output signal are simultaneously collected to the Fast Fourier Transform (FFT) analyzer. The typical Frequency Response Function (FRF) in the vibration tests is shown in Fig.3 (b), from which the damping loss factor of the specimen could be determined by means of the modal circle fit method [29] as $\eta = 2\zeta$ where ζ is the damping ratio of the specimen. In addition, the module of Frequency Response Function (FRF) Geometry is adopted to visualize various modal shapes, where the first four modes are considered in the current modal experiments. In order to detect the mode shapes, the force hammer is moved on 5×5 points arranged on the specimen along the length and width direction one by one. Taking the structural damping effects into consideration, we define the damping loss efficiency $E_\eta = \eta/m$ where m is the mass of the structure.

3.2 Quasi-static compression of the hybrid sandwich panels

After modal tests, all the specimens are subjected to quasi-static compression tests with a nominal displacement rate of 0.5 mm/min to determine their energy absorption characteristics according to the standardized test method, ASTM C365/C365M-05 [31]. Similarly, we also define the compressive stiffness efficiency $E_s = S/m$ where S is the total stiffness of the hybrid sandwich panel.

3.3 Evaluation criterion of the hybrid sandwich panels

In order to explore the compatible effect of total damping and compressive stiffness efficiency of the sandwich structures with damping inserts, an evaluation criterion $EC = S * \eta / m$ is defined.

4. Verification of FEM model and optimized patch damping allocation

4.1 Finite element-modal strain energy (FE-MSE) approach

It has been proved that the inherent damping capacity of fibre-reinforced composites is significantly higher than that of most common metallic structures [17]. To better estimate the total damping properties of the current hybrid carbon fibre composite sandwich panels, it is very desirable not only to consider the damping due to high lossy materials, but also the damping due to the composite material. Based on the FE-MSE approach [32], the total structural damping loss factor η_{total} can be expressed as:

$$\eta_{total} = \eta^c \frac{U^c}{U} + \eta^a \frac{U^a}{U} + \eta^v \frac{U^v}{U} \quad (1)$$

In which

$$\begin{aligned}\eta^c \frac{U^c}{U} &= \eta_{11}^c \frac{U_{11}^c}{U} + \eta_{22}^c \frac{U_{22}^c}{U} + \eta_{12}^c \frac{U_{12}^c}{U} = \eta_{11}^c SE_{11}^c + \eta_{22}^c SE_{22}^c + \eta_{12}^c SE_{12}^c, \\ \eta^a \frac{U^a}{U} &= \eta^a SE^a, \quad \eta^v \frac{U^v}{U} = \eta^v SE^v\end{aligned}\tag{2}$$

with

$$\begin{aligned}U_{11}^c &= \sum_{k=1}^n U_{11}^k, \quad U_{22}^c = \sum_{k=1}^n U_{22}^k, \quad U_{12}^c = \sum_{k=1}^n U_{12}^k \\ U^a &= \sum_{p=1}^m U^p, \quad U^v = \sum_{e=1}^l U^e\end{aligned}\tag{3}$$

where $\eta_{11}^c, \eta_{22}^c, \eta_{12}^c, \eta^a$ and η^v are the material damping loss factors, which are listed in Table 3. The superscript c, a and v represent the carbon fibre polymer composite material, aluminium material and viscoelastic material, respectively. The detailed identification of the damping properties in parent materials is shown in section 4.2. U is the total strain energy, $SE_{11}^c, SE_{22}^c, SE_{12}^c, SE^a$ and SE^v denote the corresponding strain energy proportion. $U_{11}^k, U_{22}^k, U_{12}^k, U^p$ and U^e are the strain energy component for element k, p and e respectively. n, m and l are the total number of elements.

In this section, a commercial finite element code ABAQUS 6.13 is used to model such hybrid composite sandwich panels. Firstly, 3D solid elements are adopted to establish the FFM model of hybrid composite sandwich panels, then, a frequency extraction procedure using the Lanczos eigensolver is implemented and the natural frequencies, mode shapes and the mechanical properties such as modal strain energy magnitude, stress components, strain components and volume of each element can be

obtained by the data post-processing.

4.2 Identification of the damping properties in parent materials

In order to effectively predict the total structural damping loss factors of the hybrid sandwich panels, the damping properties of the basic materials including the carbon fibre polymer composite materials, aluminium alloy pyramidal truss cores and three types of high lossy materials are primarily determined using mixed numerical-experimental modal method [33-35], which is a powerful tool for estimating unknown constitutive dynamic coefficients in composite structures, and for the details of the solving processes we refer to our previous works [36]. It's worth mentioning that the damping property of orthogonal woven carbon fibre reinforce/epoxy resin LS-3K has been previously obtained in our previous works [37]. Based on that, the other damping properties of aluminium material and viscoelastic materials can be finally obtained through several specific sandwich structures such as bare composite pyramidal truss sandwich panels, composite HPF sandwich panels and composite SPF sandwich panels through Eqs.(1), which are listed in Table 3.

4.3 Multiple patch damping allocation

Based on the experimental results, it can be found that the specimens B-II-HPF and B-II-SPF are the most efficient configurations. To further maximise the structural damping while minimising additional mass, multiple patch damping treatment is adopted and it is reasonable to partially embed high damping materials into the base composite pyramidal truss sandwich panels at areas of high strain energy. According

to the FEM results, the energy distributed within the total structural areas can be clearly visualized, which makes it simple and convenient to determine the position of maximum strain energy on the specimen for different modes. Finally, the volume, configuration and thickness D_t of the damping layer are investigated systematically.

5. Results and discussions

5.1 Modal characteristics and compressive response

Fig.4(a) gives the frequency responses of bare composite pyramidal truss sandwich panels (specimen B) by experimental modal testing in a range of first several predominant frequencies for the sake of brevity. It can be found that, the natural frequencies increase with the increase of face sheet thickness. The reason is mainly that increasing the thickness would greatly enhance the structural total stiffness. It also can be observed that the amplitudes of the peaks slightly decline with the increase of face sheet thickness. It seems that appropriately increasing the thickness of the face sheets can effectively improve the structural damping. The comparisons of frequency responses of specimen B with combinations of high lossy materials are shown in Fig.4(b). The amplitudes of the peaks decline significantly after adding high damping materials, even some of the response amplitudes significantly diminish which leads to the disappearance of the peak values. Fig.6(a) shows the damping loss efficiency of such hybrid sandwich panels with different combination of high lossy materials. Compared to the bare specimen B, it is revealed that such hybrid sandwich

panels with different damping materials always can improve the damping loss efficiency to a certain degree, especially for the specimens B-II-SPF and B-III-SPF that can increase nearly 5.5 times higher than the base specimen B, which achieve maximum damping simultaneously with minimum mass among all the candidate specimens. Similarly, we also investigate the compressive responses of the present sandwich structures shown in Fig.5(a)-(c). All the stress-strain curves show the similar phenomenon from linear elasticity and plastic deformation, until densification that has also been confirmed by our previous work [8]. The experimental results indicated that increasing the face sheet thickness and filling high damping materials in the void spaces of the truss cores has little effect on the total compressive stiffness but would relatively affect the strength compared to the unfilled structures. However, inserting the VDS inside the middle layer of the upper and lower face sheets obviously decreases total compressive stiffness. The reason is that the VDS layer is more easily to be deformed than filled structures combined with truss members, which play the role of strengthening the structures. To further explore the additional mass on the influence of the total stiffness, the compressive stiffness efficiency E_s of such hybrid sandwich panels with different combination of high lossy materials is shown in Fig.6(b). It is easy to understand that the bare specimen B possesses the highest stiffness efficiency, followed by the specimen B-II-HPF and B-II-SPF, until the B-III-SPF because of their lower specific modulus. In conclusion, Fig.6(c) gives the comprehensive evaluation criteria of specimen B with different combinations of

high lossy materials. It is clearly revealed that the specimen B-II-HPF and B-II-SPF occupy the highest values with the average error. It means that such two structural configurations can significantly improve modal damping using least redundant mass without any stiffness loss.

5.2 Optimized patch damping allocation

The first four mode shapes and natural frequencies of specimens B deduced from experiment and finite element calculation are shown in Fig.7 and Fig.8, respectively. As it can be seen, all measured vibration modes are very coincident with the numerical modes. A good agreement can also be observed for the corresponding natural frequencies such that the error of the numerical results is acceptable for engineering application, especially for the specimen B with face sheet thickness $T_f=0.8\text{mm}$ within 1.65% error. So FE models are considered to be valid and further applied to investigate the patch damping allocation. Through the modal analysis using the FFM models mentioned in section 4.3, the magnitude and distribution of the first four modal strain energies of specimen B are displayed in Fig.9. It is noted that most of the modal strain energy is concentrated in the upper face sheet and distributes at the edges with varying degrees for the first four modes, which can account for about 80% of the total strain energy. Fig.10 gives the modal strain energy proportions of components of specimens B. The reason is probably that larger deformation can be induced in the upper face sheet by suffering from less restriction from the truss cores compared to the lower face sheet. Based on the above results, three configurations

including square, frame and triangle damping patches are developed to further maximise the structural damping while minimising additional mass. As it is shown in Fig.11, on the premise of the same volume, the three kinds of damping patches indicated by red colour are filled into the void of the truss cores. For convenience of avoiding confusion, we also define the thickness D_t of the damping layer. According to Eqs.(1)-(3), the total structural damping loss factor not only depends on the material damping loss factor that is a constant value, but also relies on the corresponding strain energy proportion. Therefore strain energy proportion of the additional damping materials SE^v is adopted to evaluate the total damping effect. Fig.12 and Fig.13 shows the effect of damping volume proportion on the first two order modal strain energy proportions and natural frequencies. It is shown that a fast convergence can be observed that implies more damping material is not always better and it is suitable and practical to use the present damping patches. It should be noted that all the damping patches are filled through the thickness direction. For the specimen B-II-HPF, as it can be seen, for the same damping volume, the frame damping patch always can obtain over 2-4 times much larger strain energy proportion compared to the square and triangle damping patches. Simultaneously, the frame damping patch also can achieve higher natural frequencies for the same damping volume. It means that application of the frame damping patch in specimen B-II-HPF can realize the highest damping loss factor using the minimal mass without any stiffness penalty. However, for the specimen B-II-SPF, it is found that three kinds of

damping patches almost possess the same excellent performance, which quickly converges to tend a stable value when the damping volume proportion is around 12.5%. The specimen B-II-SPF can obtain higher strain energy proportion around 30.4-58.5% than specimen B-II-HPF around 12.5-26.7% in the first modes. The results reveal that inserting a damping patch with lower specific modulus can gain higher damping capacity that is accompanied with a certain degree of stiffness loss. Furthermore, the effect of damping thickness on the first two order modal strain energy proportions and natural frequencies for specimen B-II-HPF with frame damping patch is plotted in Fig.14. Similar trends are observed concerning that the natural frequencies' increase with the increase of damping thickness due to the enhancement of overall stiffness. Yet the corresponding strain energy proportion regularly increases to a maximum value with the increase of damping thickness, and then decreases until the damping material completely fills through the thickness direction with a damping thickness D_t of 7.5mm. The tendency also illustrates that the total damping effect of the present structure does not depend on the thickness of damping material at any time. It seems that excessive damping thickness improves the restriction from the upper and lower face sheet and may eventually lead to a decrease of the strain energy proportion.

6. Conclusions

In this study, modal and compression tests are carried out to investigate the vibration damping and stiffness efficiency of hybrid composite pyramidal truss

sandwich panels combined with multiple damping configurations, respectively. Experimental results show that increasing of the face sheet thickness would effectively increase the natural frequencies and appropriately improve the structural damping. Compared with the bare hybrid sandwich panels, such structures combined with damping materials would significantly improve the damping loss efficiency but decrease the stiffness efficiency in varying degrees simultaneously. According to the comprehensive evaluation, specimen B-II-HPF and B-II-SPF can yield the best performance among all the candidate specimens. Based on the FE-MSE approach, a set of verified FE models is developed to seek the best solution for patch damping allocation. Then three configurations including square, frame and triangle damping patches are reasonably adopted. A fast convergence reveals that it is suitable and practical to use the present damping patches. The numerical results imply that for the specimen B-II-HPF the frame damping patch always can obtain larger strain energy proportion and higher natural frequencies compared to the square and triangle damping patches for the same damping volume. However, almost the same excellent performance of the three kinds of damping patches can be found for the specimen B-II-SPF. The natural frequencies and the damping loss factors are very sensitive to the damping thickness. In general, the natural frequencies are proportional to adding damping thickness, which is not the case for the total damping effects. Authors are continuing to search and investigate some other superior damping materials combined with the present hybrid lightweight composite pyramidal truss sandwich panels.

Acknowledgements

This present work was supported by the National Science Foundation of China under Grant Nos.11172080 and 11222216, the Fundamental Research Funds for the Central Universities under Grant No.HIT.BRETIV.201301, and the Open-ended fund of Science and Technology on Advanced Composites in Special Environments Laboratory. Jin-Shui Yang would also gratefully acknowledge the financial support from the China Scholarship Council (CSC) during the visit at RWTH Aachen University.

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Table 1 The mechanical properties of the used materials

Property	Symbol	LS-3K [37]	2A12-T4	VDS	HPF	SPF	SR
Young's modulus (Mpa)	E_1, E_2	46700	68700	20.69	61.50	1.25	1200
Shear modulus (Mpa)	G_{12}	3600	25400	—	—	—	—
Poisson's ratio	ν_{12}	0.30	0.32	0.47	0.32	0.27	0.48
Density (kg/m ³)	ρ	1523.3	2687	1650	73.22	114.9	789.1

Table 2 Specifications of the hybrid sandwich structures tested

<i>Specimen</i>	<i>symbol</i>	<i>composition</i>
Bare composite pyramidal truss sandwich panels	B	Two CFRP face sheets, 4×4 Pyramidal truss core
Composite pyramidal truss sandwich panels of type I	B-I	Two CFRP face sheets embedded with VDS, 4×4 Pyramidal truss cells
Composite pyramidal truss sandwich panels of type II	B-II-HPF, SPF, SR	Two CFRP face sheets, 4×4 Pyramidal truss cells filled with HPF, SPF, SR
Composite pyramidal truss sandwich panels of type III	B-III-HPF, SPF	Two CFRP face sheets embedded with VDS, 4×4 Pyramidal truss cells filled with HPF, SPF

In the present testing, CFRP face sheets with different thickness 0.4mm-1.2mm and VDS with

different thickness 1.0mm-2.0mm are designed, respectively.

Table 3 The material damping loss factors used in the FEM*

Property	LS-3K [37]	2A12-T4	VDS	HPF	SPF	SR
Damping loss factors η (%)	$\eta_{11} = \eta_{22} = 1.84$ $\eta_{12} = 2.26$	0.20	18.59	7.61	16.91	26.61

* The damping loss factors of composite and the high damping materials are the average values in first several predominant frequencies.

Fig.1 Fabrication processes of hybrid composite pyramidal truss sandwich panels

Fig.2 (a) The bare hybrid composite pyramidal truss sandwich panel, (b) the repeating unit cell (RUC), (c) hybrid sandwich panel filled with polyurethane foam, (d) hybrid sandwich panel filled with silicone rubber, (e) hybrid sandwich panel inserted with viscoelastic damping sheets and filled with polyurethane foam.

Fig.3 (a) The experimental apparatus of modal tests and (b) the typical frequency response functions of a bare hybrid sandwich panel.

Fig.4 Comparison of frequency responses. (a) Specimens B with different face sheet thickness, (b) Specimens B with different combination of high lossy materials.

Fig.5 Comparison of compressive responses. (a) Specimens B-II-HPF with different face sheet thickness, (b) and (c) Specimens B with different combination of high lossy materials ($T_f=0.8\text{mm}$).

Fig.6 Comparison of (a) Damping loss efficiency, (b) Stiffness efficiency and (c) Evaluation criteria of specimen B with different combination of high lossy materials ($T_f=0.8\text{mm}$).

Fig.7. The first four mode shapes of specimens B deduced from experiment (a), (b), (c), (d) , and finite element calculation (e) ,(f) (g), (h).

Fig.8 Natural frequencies of specimens B with different thickness of face sheets obtained by FEM and experimental methods.

Fig.9 The first four modal strain energy magnitudes of specimens B deduced from finite element calculation (a), (b), (c), (d).

Fig.10 Modal strain energy proportions of components of specimens B.

Fig.11 Diagram of the configuration and thickness D_t of the damping material.

Fig.12 Effect of damping volume proportion on the first two order modal strain energy proportions (a), (b) and natural frequencies (c), (d) for specimen B-II-HPF.

Fig.13 Effect of damping volume proportion on the first two order modal strain energy proportions (a), (b) and natural frequencies (c), (d) for specimen B-II-SPF.

Fig.14 (a) Effect of damping thickness on the first two order modal strain energy proportions and (b) Natural frequencies for specimen B-II-HPF with frame damping patches.

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response functions of a bare hybrid sandwich panel.

Fig.4 Comparison of frequency responses. (a) Specimens B with different face sheet thickness, (b) Specimen B with different combination of high lossy materials.

Fig.5 Comparison of compressive responses. (a) Specimens B-II-HPF with different face sheet thickness, (b) and (c) Specimens B with different combination of high lossy

materials ($T_f=0.8\text{mm}$).

Fig.6 Comparison of (a) Damping loss efficiency, (b) Stiffness efficiency and (c)

Evaluation criteria of specimen B with different combination of high lossy materials
($T_f=0.8\text{mm}$).

Fig.7. The first four mode shapes of specimens B deduced from experiment (a), (b), (c), (d) , and finite element calculation (e) ,(f) (g), (h).

Fig.8 Natural frequencies of specimens B with different face sheet thickness obtained by FEM and experimental methods.

Fig.9 The first four modal strain energy magnitudes of specimens B deduced from finite element calculation (a), (b), (c), (d).

Fig.10 Modal strain energy proportions of components of specimens B.

Square

Frame

Triangle

Fig.11 Diagram of the configuration and thickness D_t of the damping material.

Fig.12 Effect of damping volume proportion on the first two order modal strain energy proportions (a), (b) and natural frequencies (c), (d) for specimen B-II-HPF.

Fig.13 Effect of damping volume proportion on the first two order modal strain energy proportions (a), (b) and natural frequencies (c), (d) for specimen B-II-SPF.

(a)

(b)

Fig.14 (a) Effect of damping thickness on the first two order modal strain energy proportions and (b) Natural frequencies for specimen B-II-HPF with frame damping patches.