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EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF STAND-OFF LAYER DAMPING TREATMENTS FOR BEAMS

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ABSTRACT

Passive stand-off layer (PSOL) and slotted stand-off layer (SSOL) damping treatments are presently being implemented in many commercial and defense designs. In a PSOL damping treatment, a stand-off or spacer layer is added to a conventional passive constrained layer damping treatment. In an SSOL damping treatment, slots are included in the stand-off layer. A set of experiments using PSOL and SSOL beams in which the geometric properties of the stand-off layer were varied was conducted to analyze the contribution of the stand-off layer to the overall system damping. This set of experiments measured the frequency response functions for a series of beams in which the total slotted area of the stand-off layer was held constant while the number of slots in the stand-off layer was increased for a constant stand-off layer material.

Finite element analysis models were developed in ANSYS to compare the predicted frequency response functions with the experimentally measured frequency response functions for the beams treated with PSOL and SSOL damping treatments. In these beams, the bonding layers used to fabricate these treatments were found to have a measurable and significant effect on the frequency response of the structure. The finite element model presented here thus included an epoxy layer between the base beam and the stand-off layer, a contact cement layer between the stand-off layer and the viscoelastic layer, and a method for modeling delamination.

INTRODUCTION

Stand-off layer (SOL) damping treatments have been widely implemented to reduce vibration in commercial and defense aerospace applications. These thin and lightweight damping treatments have proven to be inexpensive, durable, robust, reliable, and effective in a variety of environments. Some aerospace applications for these damping treatments include reducing acoustic noise in commercial airplane cabins, and damping vibration in wing skins and satellite instrumentation platforms. Stand-off layer damping treatments are a multi-layer variation of a constrained layer damping treatment and consist of a stand-off or spacer layer, topped with a viscoelastic damping layer protected by a stiff cover sheet, or constraining layer. These damping treatments have been termed passive stand-off layer (PSOL) damping treatments (Fig. 1) and slotted stand-off layer (SSOL) damping treatments (Fig. 2).

Stand-off layer damping treatments were originally proposed by Whittier [1]. Subsequent studies of stand-off layer damping treatments include experimental work and theoretical predictions for SSOL treatments by Falugi [2-3], and experimental studies by Parin *et al.* [4] on plates and airplane wings partially treated with slotted stand-off layer damping treatments. Using commercially available SSOL damping treatments, Rogers and Parin [5] demonstrated experimentally that these

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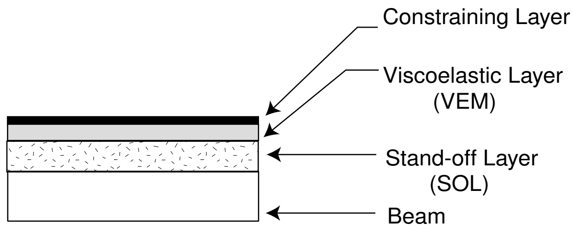

Figure 1. BEAM TREATED WITH PSOL.

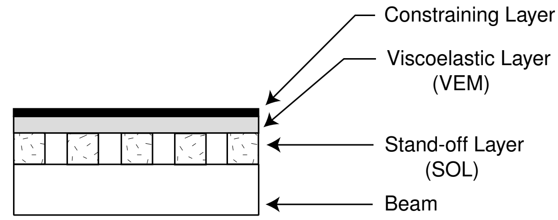

Figure 2. BEAM TREATED WITH SSOL.

treatments provided significant damping in aerospace structures such as fuselages and wing skins. Experimental and finite element studies by Tao *et al.* [6] confirmed that these commercially available SSOL damping treatments were effective in reducing low frequency vibration in aerospace structures.

Garrison and Miles [7] also presented an analytical model for the random response of a plate partially treated with PSOL. An analytical study of passive stand-off layer damping treatments by Mead [8] considered finite shear stiffness and internal loss factor in the stand-off layer by assuming that the viscoelastic and stand-off layers act as dampers in parallel deforming in pure shear. These initial analytical models assumed that axial deformation of the beam and constraining layers was negligible, that the stand-off layer did not deform in shear, and that the stand-off layer had no internal damping properties. Further studies by Yellin *et al.* [9-10] developed analytical models for PSOL and SSOL beams that included internal damping properties in all layers, but assumed that the bonding layers were negligible.

This paper describes a set of experiments for PSOL and SSOL beams treated with polyurethane rigid foam stand-off layers that was conducted in order to analyze the contribution of the number of slots in the stand-off layer to the overall system damping. In these experiments, the frequency response functions for four treated beams were measured. Three of the beams were treated with SSOL damping in which the total slotted area of the stand-off layer was held constant while the number of slots in the stand-off layer was varied. These three SSOL beams were compared with a corresponding PSOL beam which was identical to the SSOL beams except that the stand-off layer was solid instead of slotted.

The experimentally measured modal frequencies for the SSOL beams were first compared with the modal frequency results from a four-layer finite element model that assumed that the contribution of the bonding layers was negligible. The agreement between this finite element model and experimental results was poor. The finite element model was then revised to include the layer of epoxy bonding the stand-off layer to the beam layer. The experimentally measured results were compared again with the finite element results; the agreement was closer, but the five-layer finite element model was still unable to predict the trend of the experiments. Finally, a second bonding layer representing the primer layer was added the finite element model, and a method for modeling delamination between the stand-off and viscoelastic layers was developed. The resulting six-layer finite element model was able to predict the trend of the experiments. This six-layer finite element model was then used to generate frequency response functions that could be compared with the experimentally measured frequency response functions for the all of the PSOL and SSOL beam specimens.

DESCRIPTION OF TEST SPECIMENS

The test beams used in this experiment were fabricated by General Plastics Manufacturing Company. These test beams were machined to very high tolerances and the weights and as-built dimensions of each of the test specimen layers were recorded with great thoroughness and accuracy. The total treated length L and width b of all test beams were 182.9 mm (7.200 in) and 12.7 mm (0.500 in), respectively. All test beams were made from Al 6061, with tensile modulus $E_b = 68.9$ GPa. The aluminum constraining layer was assumed to have a tensile modulus $E_b = 70$ GPa, with the density for both aluminum layers $\rho_b = \rho_c = 2700$ kg/m^3. The viscoelastic and constraining layers were made from Scotchdamp^{TM} Vibration Damping Tape 435, which consisted of an 0.14 mm (5.5 mils) viscoelastic layer made from ISD 830 bonded to a 0.20 mm (8 mils) aluminum constraining layer. Table 1 summarizes the geometric and material properties of the test beams.

The number of slots in the stand-off layer was varied while keeping the slot area constant at 31 %. The purpose of this test was to determine the effect of changing the number of slots on the damping of the beam. For this set of beams, the slot area was fixed at 1939.5 mm^2, and the stand-off layer for all beams was made from Last-a-Foam^{TM} FR-3720 rigid polyurethane foam with a nominal density of 20 lb/ft^3, or 320 kg/m^3. The density of the foam as tested was 22.06 lb/ft^3, or 353 kg/m^3.

In order to determine the effect of increasing the number of slots in the stand-off layer, beam 1a/1 had 19 narrow slots in the stand-off layer, beam 1b/2 had 9 slots that were approximately twice as wide as the slots in beam 1a/1, and beam 1c/3 had 5

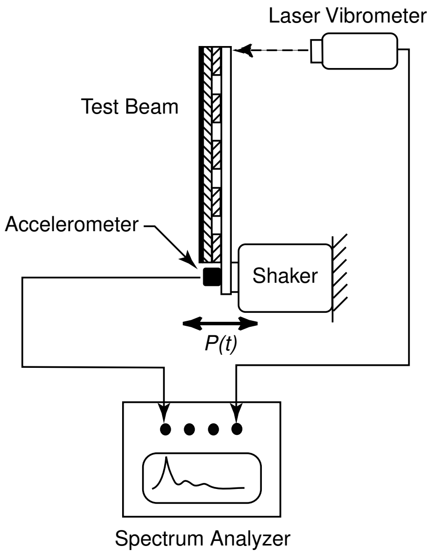

Figure 3. SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SETUP.

slots that were approximately four times as wide as those in beam 1a/1. Because the total slotted area was the same, the mass of the treatment for all of the SSOL beams was approximately the same. Beam 3b/4 was the corresponding PSOL beam with a solid stand-off layer, and was included in this set for comparison.

EXPERIMENTAL SETUP

Figure 3 shows a schematic drawing of the experimental setup. The treated test beam was cantilevered at its base to a shaker with the constraining layer remaining free at both ends. In order to study the frequency response of the beam, a prescribed input excitation $P(t)$ was used to excite the beam at the cantilevered end. A Hewlett Packard HP35665A Dynamic Signal Analyzer generated this input displacement $P(t)$ in the form of a swept sine from 10 Hz to 2 kHz that was amplified and used to drive a Ling-Altec 25-lb shaker. An accelerometer attached with wax to the fixed end of the beam measured this input excitation, and a laser vibrometer measured the response of the beam at its tip. The accelerometer was a PCB piezotronics PCB accelerometer that had a voltage sensitivity of 9.79 mV/g. This accelerometer was connected to a PCB charge amplifier. The laser vibrometer was a Polytec OFC511 connected to a Polytec OFV 3001 vibrometer controller, with voltage sensitivity set to 125 $\frac{mm}{s \cdot V}$.

These measurements were returned to the spectrum analyzer, which computed the raw and uncalibrated frequency response functions for the lateral velocity of the beam tip relative to acceleration of the beam base $\frac{dw'(L,i\omega')}{dw''(0,i\omega')}$. The normalized variance of the input and output channels and the frequency response functions were also measured in order to check the quality of the input and output signals. The experimentally measured frequency response functions were calibrated, integrated, and normalized using Matlab to give the lateral displacement of beam tip vs. the lateral displacement of beam base, $\frac{w(1,i\omega')}{w(0,i\omega')}$.

FOUR-LAYER FEA MODEL

The first finite element analysis model was a four-layer model developed in ANSYS using PLANE42 two-dimensional solid elements. This four-layer model assumed that the bonding layers used to fabricate the PSOL and SSOL damping treatments were negligible. The stand-off layer for all the beams was modelled as an orthotropic solid. The PLANE42 elements used for all layers supported orthotropic material property data. This preliminary comparison did not include damping; the modal frequencies and mode shapes were calculated from the eigenvalues and eigenvectors using modal analysis. However, the storage modulus $G_v(i\omega)$ for the viscoelastic layer was highly frequency dependent at the ambient laboratory temperature of 20°C, so the storage modulus in the regions of the first four lateral vibration modes were taken from the reduced frequency nomogram for ISD 830 provided by 3M and incorporated into the ANSYS model. The viscoelastic layer was modelled as an isotropic solid with an assumed Poisson's ratio ν_v of 0.45. The corresponding frequency dependent tensile moduli for the first four modes were then calculated and entered into the ANSYS material properties batch file. For the first and second modes, a value of E_v = 1 MPa was used, and for the third and fourth modes E_v = 3 MPa and E_v = 5 MPa, respectively. Table 2 shows the predicted modal frequencies from ANSYS compared with the experimentally measured modal frequencies for beams 1a/2 through 3b/4.

The ANSYS model did not follow the trend of the experiments for this first comparison. In the experiments, changing the number of slots while keeping the total slotted area constant had a noticeable and significant effect on the modal frequencies. In the experiments, as the number of slots increased, the modal frequencies lowered. Therefore, the modal frequencies for the four slot beam beam 1c/3 shifted to the right, approaching the modal frequencies of PSOL beam 3b/4. The predicted modal frequencies from the finite element model changed minimally as the number of slots was varied for the second mode, and followed an opposite trend from the experimental result for the third mode, with the predicted modal frequencies increasing as the number of slots decreased. The ANSYS model also did not predict the trend of the modal frequencies for the PSOL beams compared with the SSOL beams. In the experiments, the modal frequencies for the PSOL beams were higher than those of the SSOL beams for all but the first mode. In addition to this, the modal frequencies for the second, third, and fourth modes predicted by ANSYS were significantly higher than the experimentally measured modal frequencies.

Table 1. SPECIFICATIONS FOR PSOL AND SSOL BEAMS 1a/1, 1b/2, AND 1c/3. THE NUMBER OF SLOTS IN THE STAND-OFF LAYER FOR THE SSOL BEAMS WAS VARIED WHILE KEEPING THE TOTAL SLOT AREA CONSTANT. THE CORRESPONDING PSOL BEAM IS 3b/4. FOR THE STAND-OFF LAYER MATERIAL PROPERTY DATA, x , y, AND z ARE THE LENGTH, THICKNESS, AND WIDTH DIRECTIONS, RESPECTIVELY.

Series/Beam No.	**1a/1**	**1b/2**	**1c/3**	**3b/4**
No. slots	19	9	4	solid
riser, mm	7.64	15.27	30.54	N/A
slot, mm	1.59	3.35	7.54	N/A
beam thickness h_b, mm	2.24	2.22	2.24	2.24
SOL thickness h_s, mm	2.56	2.55	2.55	2.54
SOL total contact area, mm^2	1940.56	1939.29	1939.29	2322.83
US Anchor epoxy, g	0.133	0.168	0.198	0.23
Epoxy thickness h_{ep}, mm	0.0548	0.0693	0.0817	0.0792
3M Fastbond primer, g	0.0430	0.0380	0.0310	0.0440
Primer thickness h_{pr}, mm	0.0205	0.0182	0.0148	0.0176
SOL Tensile modulus E_x, E_z, MPa	244.5	244.5	244.5	244.5
SOL Tensile modulus E_y, MPa	247.3	247.3	247.3	247.3
SOL Shear modulus G_{xy}, G_{yz}, MPa	50.16	50.16	50.16	50.16
SOL Shear modulus G_{xz}, MPa	43.64	43.64	43.64	43.64
SOL Total treatment mass, g	3.486	3.511	3.482	3.900

However, the overprediction of the modal frequencies was less important than the ability of the ANSYS model to predict the trend of the experiments. In the next section, a revised finite element model that included an additional layer representing the epoxy between the beam and stand-off layers is presented.

FIVE LAYER FEA MODEL

It was decided to revise the ANSYS model by adding a layer to represent the epoxy. Although the epoxy layer was relatively thin, it was extremely stiff relative to other layers in the treatment. From company property data, the US Anchor epoxy had a tensile modulus of approximately 2.22 GPa. Therefore, it was decided to include this layer in the finite element model because the epoxy layer might be too stiff to be considered negligible.

In this second comparison, it was decided not to include the contact cement primer layer. From company data, the tensile modulus of the 3M Fastbond 30 NF contact cement primer used to bond the viscoelastic layer to the stand-off layer was given as 0.904 MPa. This primer layer was relatively thin; approximately one order of magnitude thinner than the viscoelastic layer, and the tensile modulus of the primer was similar to that of the viscoelastic layer.

During the fabrication, US Anchor epoxy was used to bond the stand-off layer to the beam layer, and a 3M contact cement was used to improve the bonding between the self-adhesive ISD 830 viscoelastic layer and the top of the stand-off layer. In the as-built specifications for each test beam, the specimens were weighed after each layer was added. Therefore, the mass of each layer was known. The material properties of the epoxy used to bond the stand-off layer to the beam layer and the primer used to bond the viscoelastic layer to the stand-off layer were available through company data. The surface area of the bonding area was also known. In order to estimate the thickness of the bonding layers, the mass of the bonding layer was divided by the density of the layer material.

The thickness of the epoxy layer was calculated to be approximately 0.05 – 0.10 mm (2 – 4 mils) for most of the specimens. Batch files for meshing the epoxy layer for the slotted and solid configurations were created and incorporated into the ANSYS model. The epoxy layer was meshed using the PLANE42 elements that comprised all of the layers, with three elements across the thickness dimension of the epoxy.

Table 2. COMPARISON OF MODAL DATA FROM THE FOUR-LAYER ANSYS MODEL AND THE EXPERIMENTS FOR BEAMS 1a/1, 1b/2, 1c/3, AND 3b/4. THE FOUR-LAYER MODEL DOES NOT CONSIDER THE EPOXY AND PRIMER BONDING LAYERS.

MODE	**ANSYS**				**EXPERIMENTS**			
(Hz)	**1a/1 (19)**	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**	**1a/1 (19)**	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**
1	58.9	58.7	59.5	57.1	49.8	54.8	54.8	54.8
2	399.6	397.8	400.6	393.2	348.3	348.3	373.2	383.1
3	1138.2	1087.7	1095.6	1078.9	895.6	930.4	955.3	970.2
4	1935.6	2035.1	2055.2	2013.7	1716.0	1746.0	1796.0	1821.0

Table 3. COMPARISION OF MODAL DATA FROM THE FIVE-LAYER ANSYS MODEL AND THE EXPERIMENTS FOR BEAMS 1a/1, 1b/2, 1c/3, AND 3b/4. THE FIVE-LAYER MODEL CONSIDERS THE EPOXY THAT BONDS THE STAND-OFF LAYER TO THE BEAM AS A SEPARATE LAYER, BUT DOES NOT CONSIDER THE PRIMER LAYER.

MODE	**ANSYS**				**EXPERIMENTS**			
(Hz)	**1a/1 (19)**	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**	**1a/1 (19)**	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**
1	55.8	55.6	56.4	53.6	49.8	54.8	54.8	54.8
2	379.4	377.7	380.5	370.2	348.3	348.3	373.2	383.1
3	1035.7	1032.2	1040.6	1015.4	895.6	930.4	955.3	970.2
4	1985.6	1929.4	1951.8	1893.2	1716.0	1746.0	1796.0	1821.0

Table 3 shows the comparison between the ANSYS model that included the epoxy layer and the experimentally measured results for beams 1a/1, 1b/2, 1c/3, and 3b/4. Although the frequencies predicted by the ANSYS model were lower and therefore closer to the experimentally measured modal frequencies than the first comparison, the revised ANSYS model was still unable to predict the trend of the experiments completely. However, the modal frequencies predicted by ANSYS changed noticeably and significantly with the addition of the epoxy layer. Therefore, the assumption that the epoxy bonding layers were negligible was not accurate for these test specimens.

With an epoxy layer, the predicted modal frequencies now increased as the number of slots decreased for all but the third modes. However, the magnitude of the change in modal frequency for the ANSYS model as the number of slots increased was proportionally less than the experimentally measured results. This five-layer ANSYS model was still not able to predict the trend of the modal frequencies for the PSOL beams compared with the SSOL beams, although including an epoxy layer in the model did improve the agreement compared with the four-layer model. The modal frequencies predicted by ANSYS were still lower for the PSOL beams than the corresponding SSOL beams, which was opposite the trend of the experiments. Because the inclusion of the epoxy bonding layer made a significant difference in the modal frequencies, it was decided to include the primer layer in the next revision of the ANSYS model.

SIX LAYER FEA MODEL

A six-layer ANSYS model was created in which the 3M Fastbond 30 NF contact cement primer layer bonding the ISD 830 viscoelastic layer to the stand-off layer was included. The thickness of this primer layer varied from approximately 0.01 mm to 0.022 mm (0.4 – 0.9 mils). The tensile modulus of the primer was actually slightly less than the frequency dependent tensile modulus for the viscoelastic layer in the frequency range tested; 3M reported that the primer had a tensile modulus of 0.903 MPa, while the 3M ISD 830 viscoelastic adhesive had a tensile modulus of 1 MPa for the first two modes, 3 MPa for the third mode, and 5 MPa for the fourth mode. The primer layer was modelled in ANSYS using PLANE42 elements, with three elements spanning the thickness dimension of the layer.

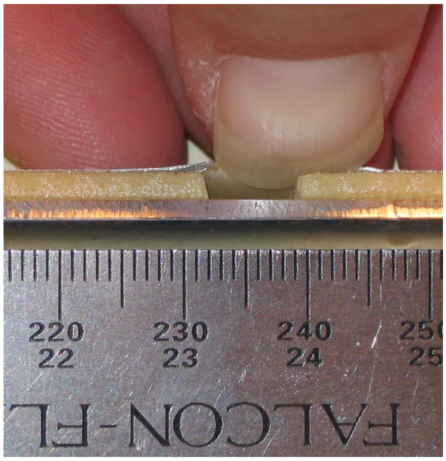

Figure 4. PHOTOGRAPH OF THE FIRST AUTHOR DEMONSTRATING AREAS OF DELAMINATION ALONG THE BOUNDARIES OF THE SLOTTED SEGMENTS IN BEAM 1c/3. THE 15 % DELAMINATION FACTOR RESULTED IN DELAMINATION SLITS OF 4.58 mm; THE RULER IN THE PHOTOGRAPH SHOWS THAT THIS WAS APPROXIMATELY THE LENGTH OF THE DELAMINATED AREA.

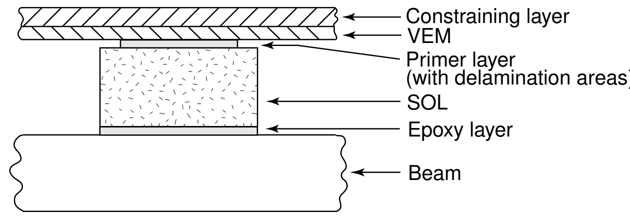

Figure 5. SCHEMATIC DIAGRAM OF A SLOTTED SEGMENT IN AN SSOL BEAM THAT INCLUDES AN EPOXY LAYER BONDING THE STAND-OFF LAYER TO THE BEAM AND A PRIMER LAYER WITH DELAMINATION AREAS AT THE EDGES OF THE SLOTS.

Table 4 shows the comparison between the predicted modal frequencies from the six-layer ANSYS model with the experimentally measured modal frequencies. The six-layer model still did not predict the trend of the experiments completely; the predicted modal frequencies for the PSOL beam were still lower than those of the SSOL beams, which was opposite the trend of the experiments. With the exception of the predicted modal frequencies for the fourth modes, the modal frequencies increased less strongly as the number of slots decreased than the experimentally measured modal frequencies. The addition of the primer layer did have a noticeable change in the modal frequencies compared with the second iteration; however, these changes were less statistically significant than the changes in the modal frequencies that resulted from adding an epoxy layer. The addition of the softer primer layer reduced the predicted modal frequencies between 5-80 Hz for each mode compared with the five-layer model that considered the epoxy layer only. Therefore, the assumption that the primer layer was negligible was not accurate, although its contribution to the frequency response was smaller than those of the epoxy layer.

The epoxy and primer bonding layers in the six-layer model moved the predicted modal frequencies closer to the experimentally measured values, but the six-layer model still did not predict the trend of the experiments accurately. The test beams were then visually inspected very closely to see if there were other characteristics that the finite element model needed to consider. The next section discusses these observations about the test specimens and shows the modal analysis results after these empirical observations were incorporated into the ANSYS model.

MODELING DELAMINATION IN PRIMER LAYER

After a visual and physical inspection of the solid and slotted test specimens, the following empirical observations about the PSOL and SSOL beams were made:

1. The primer bond between the stand-off and viscoelastic layers appeared to be weaker overall in the SSOL specimens than in the PSOL specimens.
2. The viscoelastic layer showed signs of delamination along the edges of the slotted segments in the SSOL beams.

In all of the PSOL beams, the bond between the viscoelastic and stand-off layers appeared to be very tight, and a thin object such as a fingernail or knife blade could not be inserted easily between these layers. Figure 4 shows a photograph of the author demonstrating delamination in beam 1c/3, the four slot beam. The photograph shows that it was possible to insert a fingernail to approximately 4 mm on the solid segments; this was difficult to do on the corresponding PSOL beams, and very easy to do on all of the SSOL beams.

Without completely taking the test specimens apart, it was very difficult to quantify the size of these areas of delamination around the borders of the solid blocks. It was also difficult to quantify the degree of degradation in the bonding in the regions which had not delaminated. The areas of delamination were modelled as slits in the primer layer, and the weaker bond was modelled by decreasing the tensile strength of the primer to 0.5 MPa from 0.903 MPa. Figure 5 shows a schematic drawing of a SSOL beam with an epoxy layer and with a primer layer that has delamination slits at the edges of the slots. A delamination percentage of 15 % was used for all of the SSOL beams which

Table 4. COMPARISON OF MODAL DATA FROM THE SIX-LAYER ANSYS MODEL AND THE EXPERIMENTS FOR BEAMS 1a/1, 1b/2, 1c/3, AND 3b/4. THE SIX-LAYER MODEL CONSIDERS THE EPOXY THAT BONDS THE STAND-OFF LAYER TO THE BEAM AND THE PRIMER THAT BONDS THE STAND-OFF LAYER TO THE VISCOELASTIC LAYER AS TWO SEPARATE LAYERS, BUT DOES NOT CONSIDER DELAMINATION IN THE PRIMER LAYER.

MODE	**ANSYS**				**EXPERIMENTS**			
(Hz)	**1a/1 (19)**	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**	**1a/1 (19)**	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**
1	55.2	55.2	55.9	53.1	49.8	54.8	54.8	54.8
2	373.5	372.6	376.4	365.6	348.3	348.3	373.2	383.1
3	1001.3	1001.5	1015.6	985.0	895.6	930.4	955.3	970.2
4	1863.3	1864.2	1897.3	1824.7	1716.0	1746.0	1796.0	1821.0

resulted in delamination slits in the primer layer of 4.58 mm. Because the corresponding PSOL beam 3b/4 did not show any empirically observable evidence of delamination, no slits were included in the ANSYS model for this beam. The tensile modulus for the primer layer in PSOL beam 3b/4 was the original value of 0.903 MPa from the company material property data.

The viscous damping factors listed in this table were calculated from the ANSYS data file for each mode using the same Matlab m-file that calculated the viscous damping factors from the experimentally measured frequency response functions. The viscous damping factors recovered from the ANSYS generated frequency response functions were virtually identical to the experimentally measured values, which indicated that ANSYS was able to incorporate this damping data successfully into the model. The modal magnitudes from the frequency response functions in ANSYS were very similar to the experimentally measured modal magnitudes with the exception of the first modes. However, the first modes in the experiments were very lightly damped with extremely narrow peaks. These first modes were clipped due to the resolution setting of the spectrum analyzer; the magnitude and viscous damping factors for the experimentally measured first modes were not as accurately measured as the higher modes. Therefore, the ANSYS results for the first modes were reasonable. The delamination of the SSOL beams implied that fabricating slotted stand-off layer damping treatments may require different manufacturing steps than PSOL beams. The viscoelastic and constraining layers for all of the PSOL and SSOL beams were manufactured in the same way. The contact cement was applied to the surface of the stand-off layer, the damping tape was pinned to the table, and then the primed stand-off layer and beam layer were lowered onto the damping tape. Pressure was applied to the bottom of the beam layer using flat-bottomed iron weights, and the specimens were allowed to set for 24 hours before the weights were removed.

Although the slotted stand-off layers were very carefully machined to high tolerances ($\pm$0.125 mm/ $\pm$5 mils), the epoxy and primer bonding layers may have absorbed unevenly into the rigid foam stand-off layers, causing variations in the combined thickness of the beam, epoxy, stand-off, and primer layers. Small variations in the combined thickness of these layers in the solid segments may have caused the pressure from the weights to be applied unevenly, leading to decreased bonding in the primer layer. Because the solidly treated PSOL beams did not have discontinuities, the application of the epoxy and primer layers using a roller may have been a simpler and faster process, allowing less time for the epoxy and primer to absorb unevenly during fabrication.

CONCLUSIONS

Developing the finite element model in ANSYS to match the trend of the experimental results showed that assuming that the bonding layers were negligible was not accurate. The following conclusions were based on the ANSYS models developed to explain and verify the experimental data:

1. The contribution to the frequency response of the bonding layers (epoxy, contact cement primer) was not negligible.
2. Conditions resulting from imperfect bonding between the layers (delamination, improper fusing) affected the frequency responses of the experimental test beams.
3. The SSOL beams were more prone to delamination and weaker bonding in the primer layer than the PSOL beams.
4. Modeling delamination and weaker bonds was difficult to quantify and required incorporating multiple assumptions about the quality of the bonds into the finite element model.
5. These assumptions (addition of delamination slits, reducing the tensile modulus of the primer layer) allowed the ANSYS results to agree with the trend of the experiments and provided a plausible explanation for the frequency responses

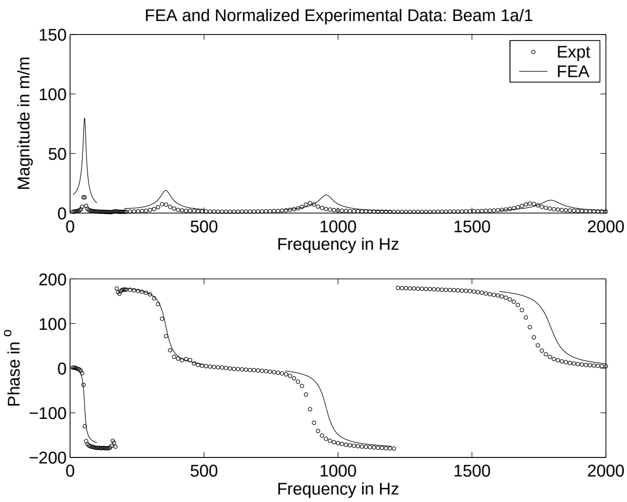

Figure 6. COMPARISON OF FREQUENCY RESPONSE FUNCTIONS FROM ANSYS WITH EXPERIMENTAL DATA FOR BEAM 1a/1.

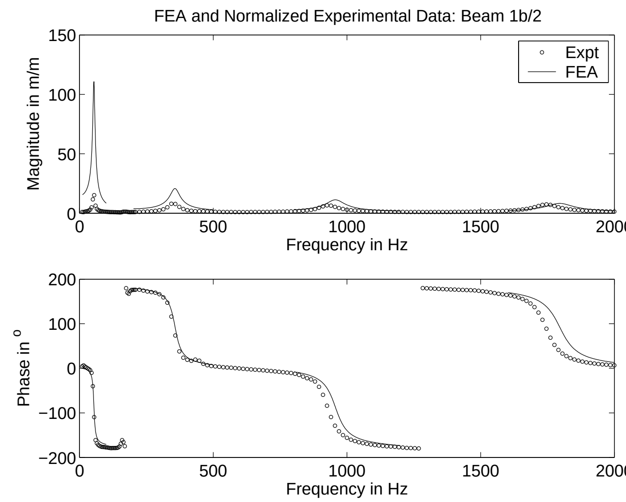

Figure 7. COMPARISON OF FREQUENCY RESPONSE FUNCTIONS FROM ANSYS WITH EXPERIMENTAL DATA FOR BEAM 1b/2.

measured experimentally, but were based on empirical observations and were therefore not as rigorous as other properties used in the finite element models.

When the epoxy and contact cement primer layers were included in the ANSYS model, and a method for modeling delamination in the primer layer for the SSOL beams was also incorporated into the model, the results from the ANSYS model followed the trend of the experimental results. However, these empirical observations about the bonding layers required adding multiple assumptions to the finite element model.

The epoxy and primer bonding layers used to fabricate this series of test beams were not negligible. The finite element model did not match the trend of the experimental results unless it included the epoxy and primer bonding layers and considered the effects of delamination in the primer layer. Therefore, the bonding layers in other SSOL and PSOL damping treatments in commercial use may also not be negligible. The effect of these and other bonding layers should be considered when using these damping treatments in design applications.

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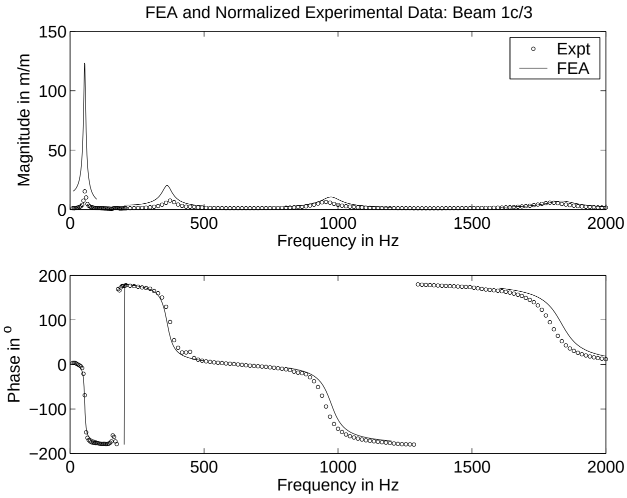

Figure 8. COMPARISON OF FREQUENCY RESPONSE FUNCTIONS FROM ANSYS WITH EXPERIMENTAL DATA FOR BEAM 1c/3.

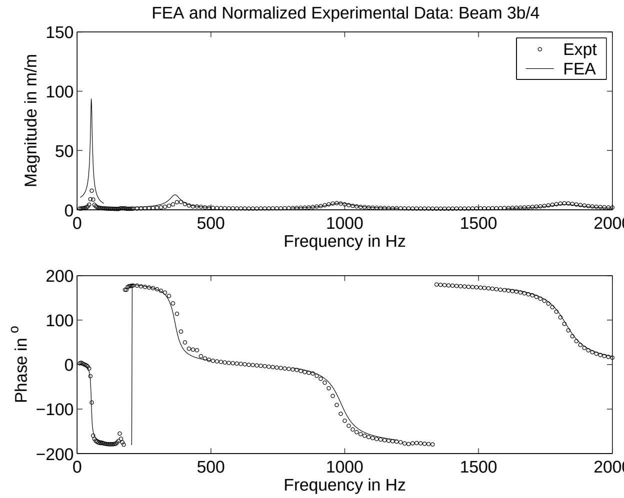

Figure 9. COMPARISON OF FREQUENCY RESPONSE FUNCTIONS FROM ANSYS WITH EXPERIMENTAL DATA FOR BEAM 3b/4.

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Table 5. COMPARISON OF THE MODAL DATA FROM FREQUENCY RESPONSE FUNCTIONS GENERATED FROM THE SIX-LAYER ANSYS MODEL WITH DELAMINATION USING HARMONIC ANALYSIS WITH THE EXPERIMENTAL RESULTS FOR BEAMS 1a/1, 1b/2, 1c/3, AND 3b/4. THE DELAMINATION FACTOR WAS 0.15 FOR ALL SSOL BEAMS. THE FIRST MODES MEASURED IN THE EXPERIMENTS WERE SUBJECT TO SOME CLIPPING DUE TO LOW RESOLUTION.

MODE	**ANSYS**				**EXPERIMENTS**			
	Frequency in Hz				**Frequency in Hz**			
	1a/1 (19)	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**	**1a/1 (19)**	**1b/2 (9)**	**1c/3 (4)**	**3b/4 (solid)**
1	53.9	54.0	54.0	53.0	49.8	54.8	54.8	54.8
2	358.0	356.0	362.0	366.0	348.3	348.3	373.2	383.1
3	956.0	956.0	974.0	986.0	895.6	930.4	955.3	970.2
4	1794.0	1796.0	1834.0	1826.0	1716.0	1746.0	1796.0	1821.0
	Magnitude m/m				**Magnitude m/m**			
1	79.7	110.7	123.3	93.5	13.2	15.1	15.2	16.1
2	18.9	20.8	20.2	12.7	7.6	8.4	7.6	6.9
3	15.2	11.3	10.6	5.7	8.2	6.7	6.4	5.6
4	10.7	8.3	7.1	4.4	7.9	7.5	5.8	5.5
	Viscous Damping Factor ζ				**Viscous Damping Factor ζ**			
1	0.104	0.075	0.067	0.060	0.010	0.075	0.066	0.059
2	0.057	0.053	0.052	0.053	0.057	0.052	0.052	0.053
3	0.027	0.036	0.037	0.045	0.027	0.036	0.037	0.044
4	0.021	0.027	0.030	0.032	0.021	0.027	0.030	0.032