Using Photo Modeling to Obtain the Modes of a Structure

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Photo modeling technology has progressed to the point where a dimensionally accurate 3D model can be economically constructed from a series of digital photographs of a structure. We show in this article how a photo model of a structure can be used to create an FEA model from which the modes of the structure can be calculated. The FEA mode shapes obtained from the photo models are then compared with the experimentally derived mode shapes of each structure to demonstrate the validity of this approach to FEA modeling.

Experimental modal analysis (EMA), also called modal testing or a modal survey, is performed on real structures to characterize their dynamic behavior in terms of their modes of vibration. Each mode is defined by its modal frequency, modal damping and mode shape.

Finite-element analysis (FEA) is also done to characterize structural dynamics by constructing a computer model using the geometry and physical properties of the structure. The analytical mode shapes and frequencies are then calculated by solving the dynamic equations of motion for the structure. FEA is analytical, EMA is experimental and modes are the common ground between the two by which they can be compared for accuracy.

If both an EMA and FEA are done correctly, then both should provide the same modes of vibration. We show here that relatively simple FEA models derived from digital photographs can yield mode shapes that match experimental mode shapes very well. The advantage of this approach is that a CAD or solid model, which can be time consuming and expensive to produce, is not required. A few photographs of the real structure, which can be taken with a very inexpensive digital camera, provide the necessary accuracy for constructing useful FEA models.

EMA and FEA are Complementary

EMA and FEA are complementary, and each has advantages over the other. EMA can accurately measure the modal frequency and damping of the modes of a real structure, but it cannot be used to measure mode shapes with nearly the number of degrees of freedom (DOFs) that are typically calculated from an FEA model.

On the other hand, even though an FEA model can yield mode shapes with many thousands of DOFs, analytical modal frequencies are usually less accurate than experimental frequencies and damping is typically ignored in an FEA model. To yield accurate mode shapes, an FEA model must start with a dimensionally correct 3D model. Also, the physical properties of the structural materials must be correct.

Today, most organizations involved in product development have built FEA models even before any prototype hardware is available for testing. FEA models are traditionally built directly from CAD drawings or solid models of the structure. In this article, we show with several examples how digital photographs are used to construct dimensionally correct FEA models that yield FEA mode shapes that compare very well with the EMA mode shapes obtained by testing the real structure.

Example 1 – FEA Model with Plate Elements

In this example, the FEA modes of the beam structure shown in Figure 1 are compared with its EMA modes. The actual beam structure was constructed using three 3/8-in. nominally thick aluminum plates fastened together with cap screws. The overall dimensions of the structure are $12 \times 6 \times 4.75$ in.

The photo model was built from the photos shown in Figure 2. Typically, a minimum set of eight photographs (taken from all sides of the structure) is required to build a model. In this case, the eight photos from Figure 2 were used.

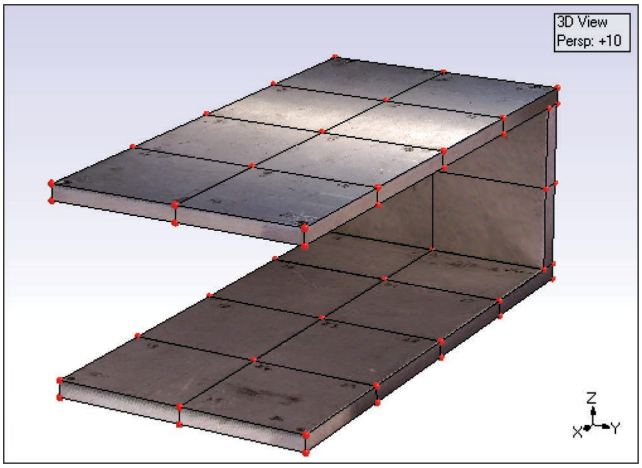

Figure 1. Photo model of three-plate beam.

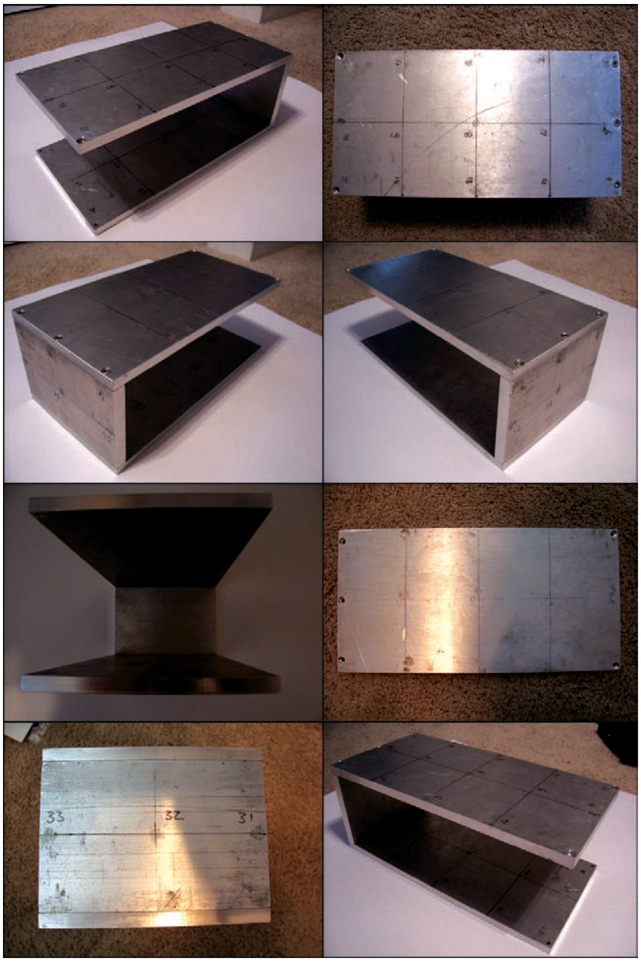

Figure 2. Photos used to build photo model.

Extruded Cross Section. The FEA model was built by extruding a cross section of the photo model of the three-plate beam. The cross section was constructed using several points and lines from one edge of the photo model. The extruded plate model is shown in

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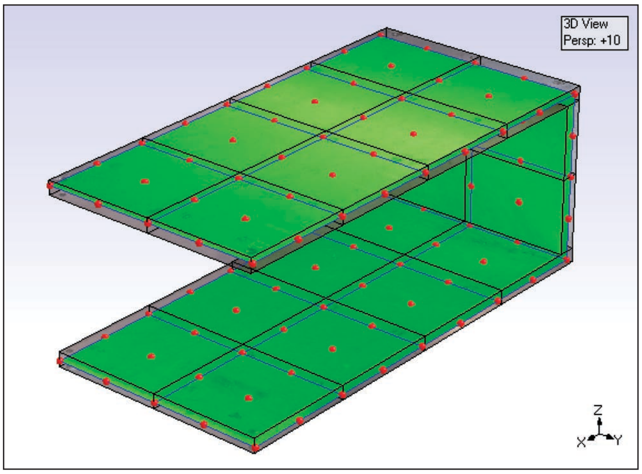

Figure 3. Extruded cross section of photo model.

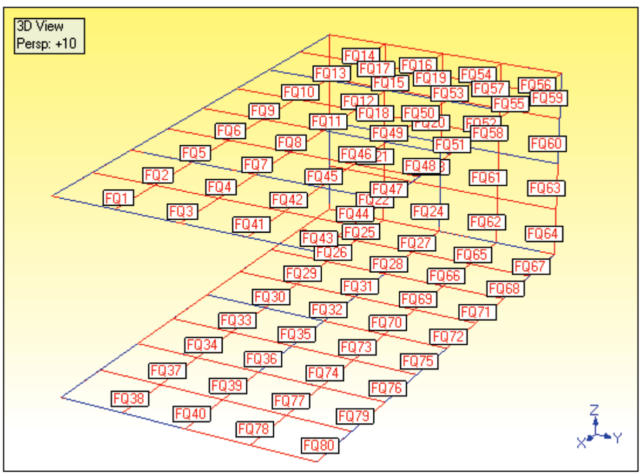

Figure 4. FEA model with 80 pate elements.

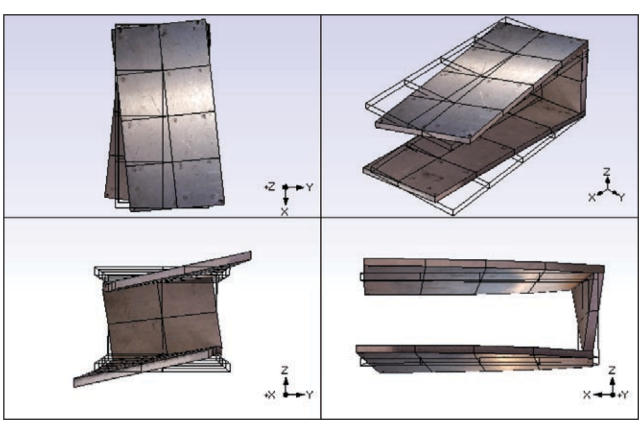

Figure 5a. 150-Hz FEA mode shape.

Figure 3. To improve its accuracy, the FEA model was also meshed (subdivided) to give it more plate elements.

FEA Model. An FEA model of the three-plate beam was built using 80-quad plate elements, as shown in Figure 4. The plate elements have the following properties.

Thickness = 0.375 in.

Elasticity (aluminum) = 1×10^7 lbf/in.^{2}

Poissons ratio (aluminum) = 0.33

Density (aluminum) = 0.101 lbm/in.^{3}

The FEA model was solved for its first 20 (lowest frequency) modes. The FEA mode shapes had three translational and three rotational DOFs at 105 points, for a total on 640 DOFs each. Figure 5 shows five of the FEA mode shapes.

EMA Mode Shapes. The experimental modes were obtained from a set of 99 frequency response functions (FRFs), which were acquired during an impact test of the beam. During the test, the structure was impacted at the same DOF (a corner of the top plate), and a roving tri-axial accelerometer was used to measure the beam's

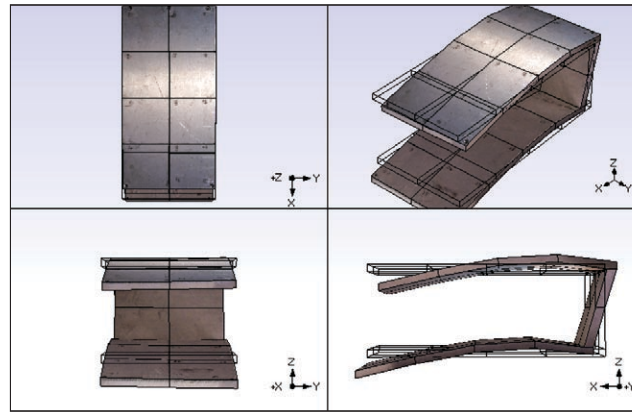

Figure 5b. 216-Hz FEA mode shape.

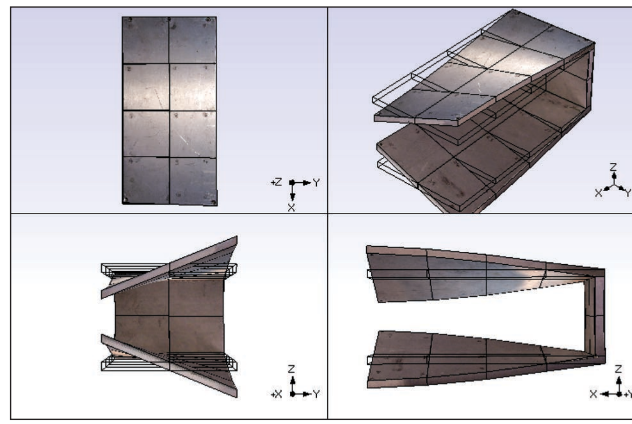

Figure 5c. 311-Hz FEA mode shape.

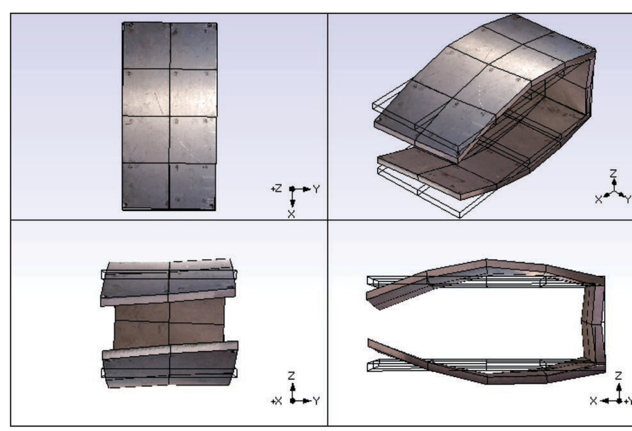

Figure 5d. 428-Hz FEA mode shape.

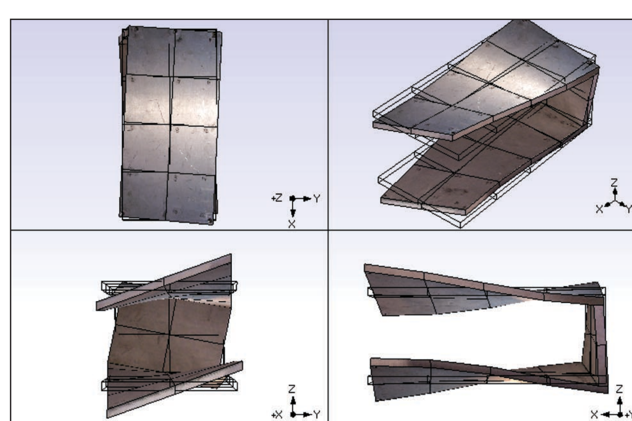

Figure 5e. 451-Hz FEA mode shape.

3D response at 33 points. The test points are shown on the photo model in Figure 1. The resulting experimental mode shapes had three DOFs per point, for a total of 99 DOFs each.

FEA versus EMA Mode Shapes. Ten consecutive FEA mode shapes matched well with 10 consecutive EMA mode shapes, as verified by their modal assurance criterion (MAC) values in Table 1. Only the translational DOFs of the FEA shapes that *matched the same 99 DOFs* as the EMA shapes were used for the MAC calculations.

MAC values range between 0 and 1. *MAC values greater than 0.90 indicate a strong correlation between two mode shapes.* Table 1 lists the 3D MAC as well as the X direction only, Y direction only, and Z direction only MAC values. All values equal to or greater than 0.90 are in bolface type.

The Z direction MAC values gave the best correlation between all of the shapes, because the *predominant motion* of most of these mode shapes is in the vertical (Z axis) direction. The first mode correlated well in all three directions, because it has significant motion in these directions.

The second mode correlated well in the X direction, because it also has significant motion in that direction. The rest of the mode shapes had smaller values in the X and Y directions; consequently, the experimental error of the EMA mode shapes caused lower MAC values in those directions than it did in the Z direction.

Example 2 – FEA Model of an I Beam

The photo model in Figure 6 was built from the photos shown in Figure 7. The overall dimensions of the I beam are: 10 × 4 × 3 in. A cross section of the I beam was used to extrude the 3D structure model shown in Figure 8.

FEA Model. An FEA model of the I beam structure was built using 120 solid elements; 100 brick and 20 prism elements. Since the real I beam is made out of aluminum, the same elasticity, Poissons ratio, and density properties used in the previous example were used again in this example.

FEA Mode Shapes. The extruded model shown in Figure 8 contains 264 points (or nodes). Therefore, its FEA mode shapes have 792 translational DOFs. (Solid elements only yield mode shapes with translational DOFs.) Five of the FEA mode shapes are shown in Figure 9. These mode shapes were compared with the EMA mode shapes obtained from testing the I Beam.

EMA Mode Shapes. The I Beam was tested using an impact hammer (impacting at a fixed DOF on a corner of the top flange), and

Table 1. FEA versus EMA MAC values (three-plate beam).

Mode	FEA Freq, Hz	EMA Freq, Hz	3D MAC	X Dir MAC	Y Dir MAC	Z Dir MAC
1	150	165	**0.96**	**0.98**	**0.94**	**0.97**
2	216	225	**0.96**	**0.98**	0.00	**0.96**
3	311	348	**0.95**	0.19	0.16	**0.98**
4	428	460	**0.90**	0.13	0.88	**0.94**
5	451	494	**0.93**	0.87	0.00	**0.95**
6	607	635	**0.93**	0.63	0.05	**0.97**
7	1013	1108	0.89	0.25	0.26	**0.95**
8	1109	1211	0.88	0.23	0.65	**0.94**
9	1212	1323	0.85	0.44	0.02	**0.92**
10	1440	1557	0.83	0.05	0.00	**0.93**

Table 2. FEA versus EMA MAC values (I beam).

Mode	FEA Freq, Hz	EMA Freq, Hz	3D MAC	X Dir MAC	Y Dir MAC	Z Dir MAC
1	461	436	0.77	0.58	**0.94**	0.82
2	574	636	**0.98**	0.84	0.89	**1.00**
3	1293	1335	**0.96**	0.71	0.89	**0.99**
4	1399	1407	**0.98**	0.85	**0.92**	**0.99**
5	1805	1846	**0.95**	0.52	0.82	**0.98**
6	2417	2380	**0.90**	0.82	**0.91**	**0.98**
7	2830	2927	0.88	0.18	0.47	**0.93**
8	3764	3554	0.66	0.43	0.86	**0.94**
9	3901	3770	0.49	0.23	0.66	**0.96**

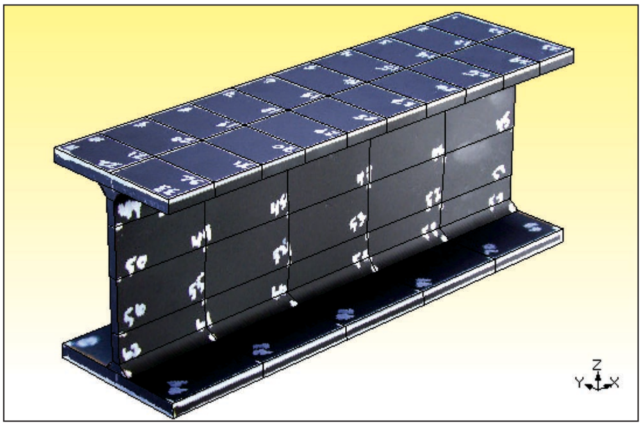

Figure 6. Photo model of I beam.

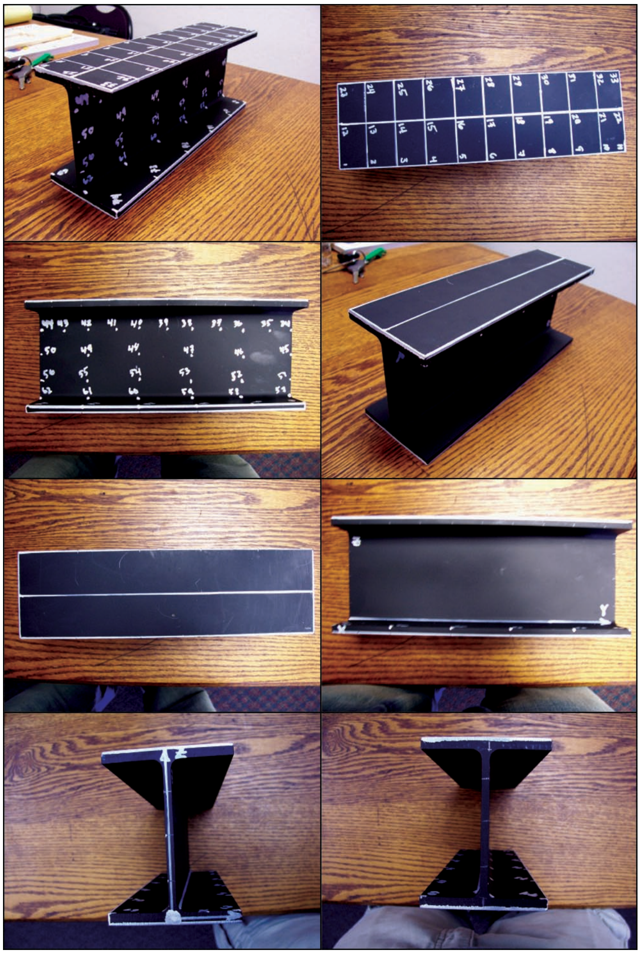

Figure 7. Photos used to build I beam model.

a roving triaxial accelerometer attached to 74 different points on the structure. (Some of the numbered points are shown in Figure 6.) A set of 222 FRF measurements was acquired over a frequency span of 0 to 4000 Hz. EMA mode shapes were extracted from the FRFs by curve fitting them, as shown in Figure 10. Nine modes were extracted from 436 Hz to 3770 Hz.

FEA versus EMA Mode Shapes. Nine consecutive FEA mode shapes matched well with nine consecutive EMA mode shapes, as verified by their modal assurance criterion (MAC) values in Table 2. Only the FEA mode shape DOFs that *matched the same DOFs* of the EMA shapes were used for the MAC calculations. Table 2 lists the 3D MAC as well as the X direction only, Y direction only, and Z direction only MAC values. All MAC values equal to or greater than 0.90 are in boldface type.

Again, the Z direction MAC values are better (more are above 0.90) because the *predominant motion* of most of these mode shapes is in the vertical (Z axis) direction. As in the previous

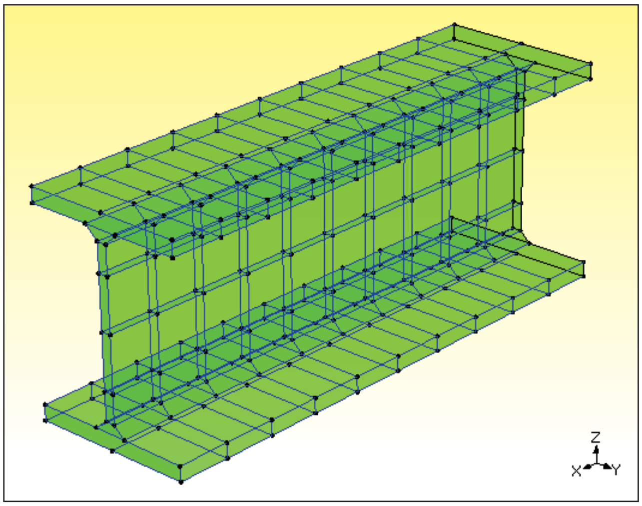

Figure 8. I beam extruded from cross section of photo model.

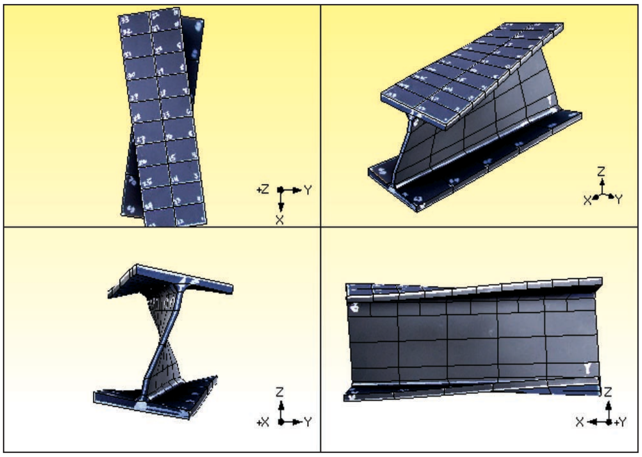

Figure 9a. 461-Hz FEA mode shape.

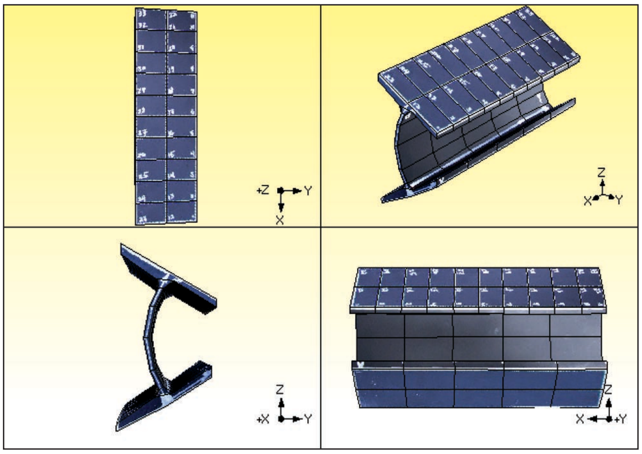

Figure 9b. 574-Hz FEA mode Shape.

example, because most of the mode shapes had smaller values in the X and Y directions, the experimental error of the EMA mode shapes caused lower MAC values in those directions than it did in the Z direction. The first mode correlated best in the Y direction, because its predominant motion is in that direction.

Conclusions

Two different examples were presented showing how photo models of structures can be used to construct simple FEA models. These models yielded analytical mode shapes that compared quite accurately with experimentally derived mode shapes. The relative dimensions of any object are preserved in a set of digital photographs, thus making it straightforward to construct geometrically accurate 3D photo models required for FEA modeling.

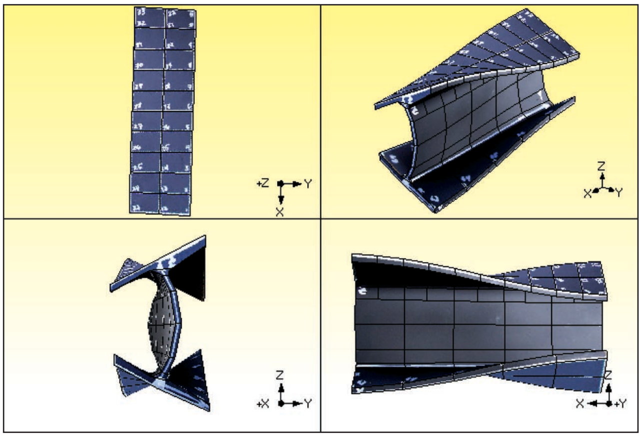

Figure 9c. 1293-Hz FEA mode Shape.

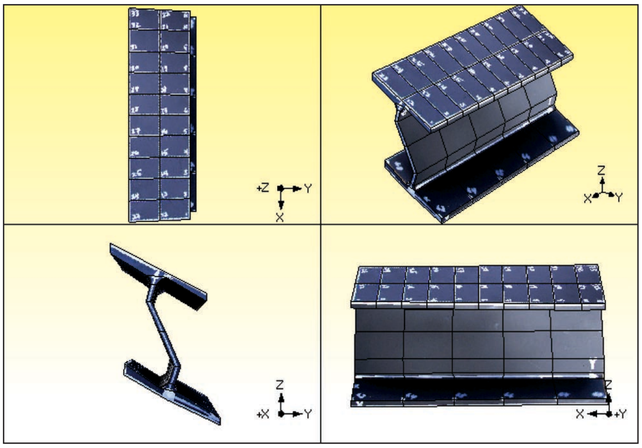

Figure 9d. 1399-Hz FEA mode Shape.

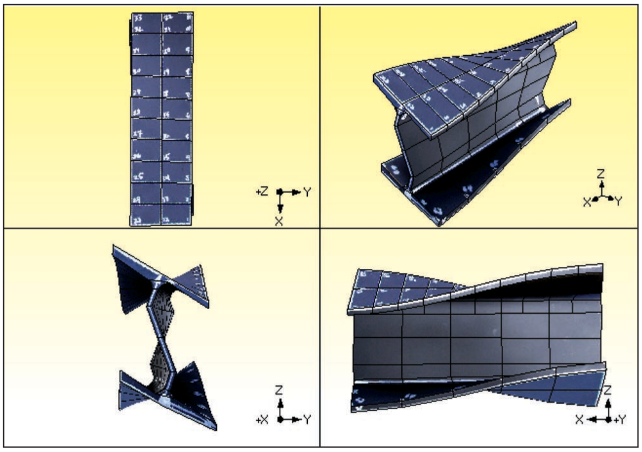

Figure 9e. 1805-Hz FEA mode Shape.

The Photo Modeler program developed by EOS Systems (www.eossystems.com) was used to construct the photo models. These models were then imported in ME'scopeVES, developed by Vibrant Technology, Inc., (www.vibetech.com) where the FEA mode shapes were calculated and compared with EMA mode shapes.

In the first example, all of the FEA mode shapes had frequencies lower than the EMA modes. This can be caused by differences in joint stiffnesses, inaccurate material property's, or because the actual plate thicknesses were different than those used in the FEA model. In the second example, most of the FEA modes have higher frequencies than the EMA modes. Closer correlation of modal frequencies could possibly be achieved by using more FEA elements to model the beam cross section.

Nevertheless, in both cases strong correlations between the FEA and EMA mode shapes were obtained, confirming that FEA models built from photo models are accurate and their mode shapes correlate well with real-world measurements.

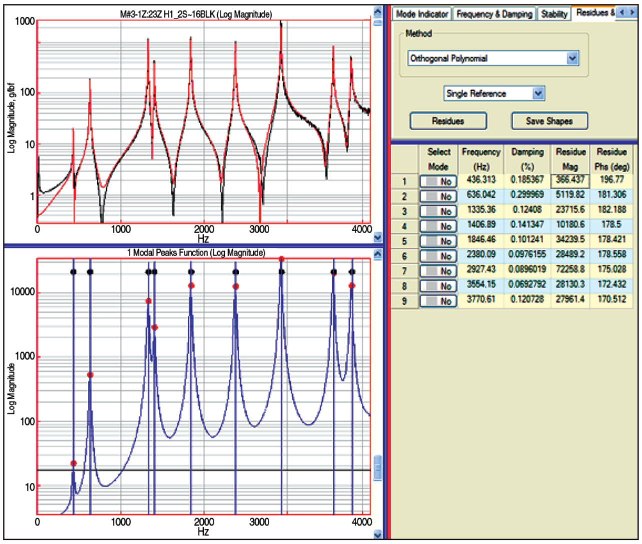

Figure 10. FRF curve fit to extract EMA modes.

Obtaining structural dimensions directly from digital photos is called photogammetry. The dimensions obtained directly from the digital photos in these two cases were: three-plate beam – 11.998 × 4.753 × 6.013 in.; I beam – 10 × 3.983 × 2.978 in.

Point Matching. Normally, the number of test points in an EMA are far less than the number of points (or nodes) in an FEA model. Many nodes are typically required to obtain accuracy with an FEA model, while relatively few points are measured in an EMA. In an EMA, accuracy depends on the accuracy of each measurement and not on the number of points tested.

Nevertheless, to compare mode shapes between FEA and EMA mode shape pairs, a point-matching capability is required. Point matching finds the nearest node on a FEA model to each point on an EMA geometric model. For each EMA point that matches an FEA node, the DOFs in the FEA shapes must be transformed to match the DOFs of the EMA shapes and the EMA DOFs must be renumbered to match the FEA node numbers. Once point matching has been done, the EMA shapes can be used together with FEA shapes for MAC calculations. Point matching is provided in the ME'scopeVES software which is available from Vibrant Technology, Inc., Scotts Valley, CA.

References

1. Allemang, R. J., Brown, D. L., "A Correlation Coefficient for Modal Vector Analysis," Proceedings of the International Modal Analysis Conference, pp.110-116, 1982.
2. Richardson, M. H., "Modal Analysis versus Finite Element Analysis," *Sound and Vibration*, September 2005.

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