Chapter 11
Dynamic Behavior of Post-Buckled Fixed-Fixed Composite Skin Panels

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Abstract The purpose of this experiment was to observe the dynamic behavior of bi-stable composite plates with fixed-fixed boundary conditions. In particular, the team sought to observe the minimum energy required to induce snap-through of post-buckled carbon epoxy composites fixed inside an aluminum frame. Initially, students collected the time response of the plate using an impact hammer and laser vibrometer. From the frequency response, the natural frequencies of the plates were determined and compared to analytically predicted results based upon a model constructed using thin plate theory and classical laminate theory. Next, the dynamic responses of the plates were obtained by applying various loading conditions with the use of a shaker table. These tests yielded validating natural frequencies to impact testing and the resonant frequencies of post-buckled plates. The minimum loading conditions required to cause snap-through in a post-buckled plate were found and analyzed across various conditions. These results provide a basis for determining minimum energy requirements required to cause buckling behavior in composite plates for applications to the hypersonic environment.

Keywords Composites · Dynamic response · Snap-through · Natural frequency · Vibrations

11.1 Introduction

Composite skin panels are an increasingly attractive option for aerospace applications, and foundational research is advancing to develop the understanding of the scientific community with respect to their response under dynamic loading conditions. Much of the previous research that has occurred on this topic has been with free boundary conditions. For example, Ranaparkhi and Sarnobat compared experimental results while supporting composite plates with strings to create a free boundary condition and then found their experimental results to be congruent with finite element analysis results [1]. Pingulkar analyzed the vibration of composite plates in a cantilever configuration, and these experimental results were also found to closely agree with an associated finite element model [2].

In a hypersonic environment, thermal forces and aerodynamic forces can combine to force buckling and post-buckled behavior in flight. The specific phenomenon this study addresses is bi-stable snap-through of a representative composite panel through frequency response analysis. Different anisotropic panels were manufactured in both uniaxial and cross-ply configurations with carbon-epoxy laminates. This study adds to the research done by McLean et al. [3] by reassessing their predictive modeling code and its ability to predict natural frequencies of composite plates as well as further analyzing the minimum energy requirements to produce snap-through across various plate layering configurations.

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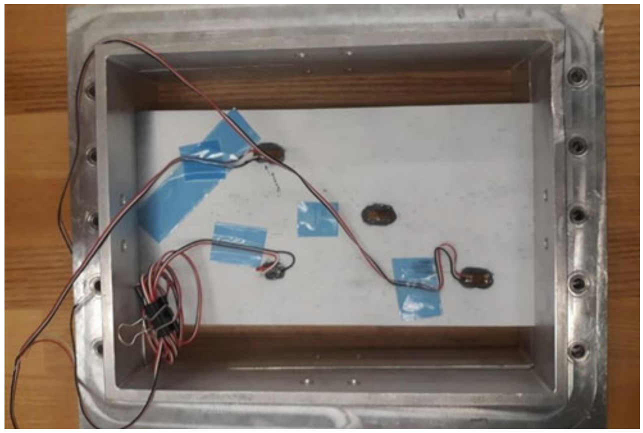


Fig. 11.1 Strain gage positioning on the composite plate

11.2 Experimental Methods

11.2.1 Testing Setup

Carbon-epoxy laminates were previously manufactured in-house using standard layup techniques [3]. The two specimens used in this study were plates with laminate configurations of $[0]_4$ and $[0/90]_s$ which were 5 × 12 in. These specimens were then uniformly marked with 15 grid points. For this study, the plates were affixed in an aluminum test fixture in order to maintain fixed boundary conditions on each end. When affixing the carbon epoxy composite specimen in the aluminum test fixture, the goal was to have zero strain on the composite plate after tightening the bolts of the metal frame. This ensured that no buckling was present in the system prior to experimentation. In order to do this, the bolts were tightened in an alternating pattern similar to that of torqueing down a tire. The strain on the plate was recorded using strain gauges shown in the setup above in Fig. 11.1. While it proved impossible to reduce the strain throughout the plate to zero and maintain suitable fixed-fixed boundary conditions, strain could be minimized using this method incrementally. The six surrounding bolts were first torqued to 5.42 Nm and then to 9.49 Nm. A possible source of error addressed by the team in this process was slight warping on a corner of the frame. In future testing, the team recommends examining better means to create a zero-strain environment either by using a medium inside the frame or creating a new testing frame.

11.2.2 Impact Testing

Once the composite plate was properly affixed inside the test fixture, the frame was inserted into a foam block to prevent vibration interference from outside noise as show in Fig. 11.2. A tripod holding the Polytec CLV 3D laser vibrometer was placed above the specimen. The laser from the vibrometer was oriented over a specific point. This point was not hit with the hammer; however, the remaining 14 points were. An impact hammer was used to deliver a firm, quick "tap" on the specimen's points. The data produced from the impact was recorded using VibSoft and exported to MATLAB. The vibrometer was set at six different locations on the plate as denoted by graphite squares to determine if results were consistent. The data from VibSoft was imported into MATLAB to plot the results.

11.2.3 Shaker Table Testing

Following completion of the impact testing, shaker table testing was conducted. The test fixture was mounted onto the table and two accelerometers placed on the plate according to Fig. 11.3 below. The same set of data collection was performed on each specimen.

Fig. 11.2 Impact testing setup showing vibrometer and foam holder with test fixture

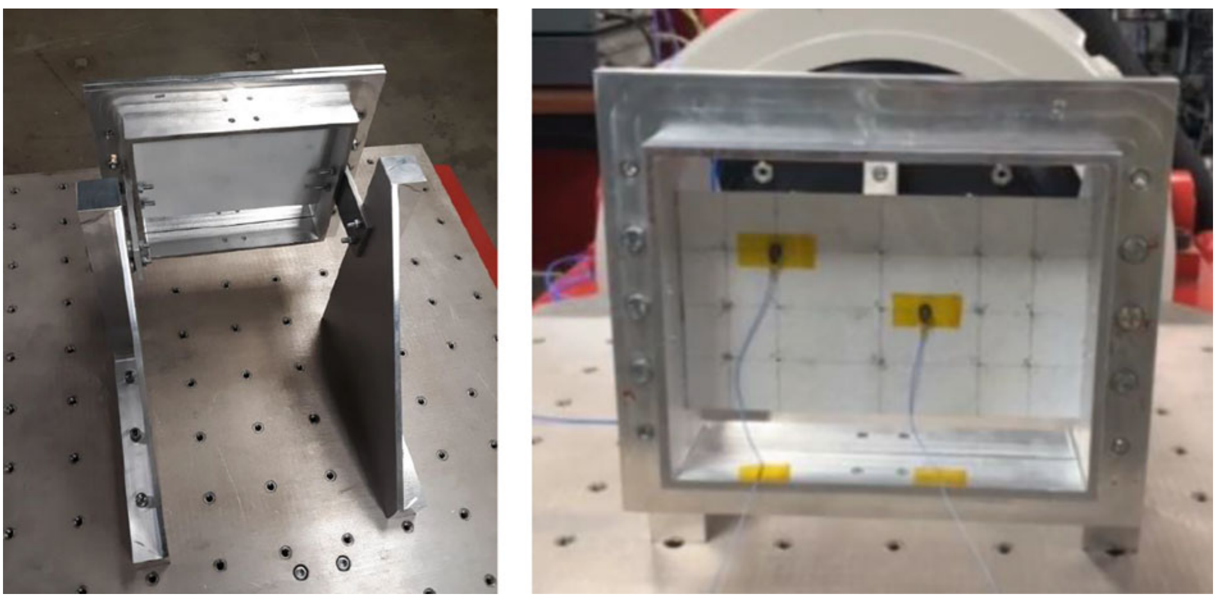


Fig. 11.3 Composite plate and metal frame system set transverse to the shaker table

Testing began with a low amplitude-frequency sweep at 0.25 g on the plates. Then, buckling was induced by putting pressure on the center of the plate evenly using a ruler to create a deformation of 1.5 mm, and the frequency sweep was again repeated at 0.25 g and the response data was recorded. Then, starting at 0.5 g, the amplitude of the loading was increased by 0.5 g increments up to 3 g in order to observe the frequency response to induced vibration. Finally, after determining the frequency at which the minimum energy necessary to induce a chaotic snap-through region, two tests were run. First, the plates were tested at a high amplitude of g loading which was decreased until the chaotic snap-through region ceased. Then, the opposite procedure was executed starting from a low g amplitude and moving up until the chaotic snap-through region was reached.

11.3 Results and Discussion

11.3.1 Determination of Natural Frequencies

Data collected from the impact testing experiments were analyzed in order to determine the frequency response of the plates. Magnitude responses from the six vibrometer-measurement locations were plotted against the corresponding frequencies. Peaks in these frequencies indicate the natural frequencies of the composite plates. Figures 11.4 and 11.5 show the results of this analysis for the $[0]_4$ and $[0/90]_s$ plates. Notable in these figures are the large spikes present around the 25 Hz location. The team believes that these peaks are most attributable to environmental factors in the testing location. This would explain the large magnitude of the peaks compared to the resonance peaks. The consistency in these spikes across tests conducted on multiple plate configurations and the lack of analytical evidence supporting a natural frequency at this frequency indicate these are from outside factors.

The results in Fig. 11.4 for the $[0]_4$ plate indicate the first three natural frequencies occurring at 118.3, 132, and 208.6 Hz. Analytical predictions for these frequencies were determined using the methodology described in [3]. This analysis considered the layup configuration of the plate and the fixed-fixed boundary conditions, and indicated the natural frequencies

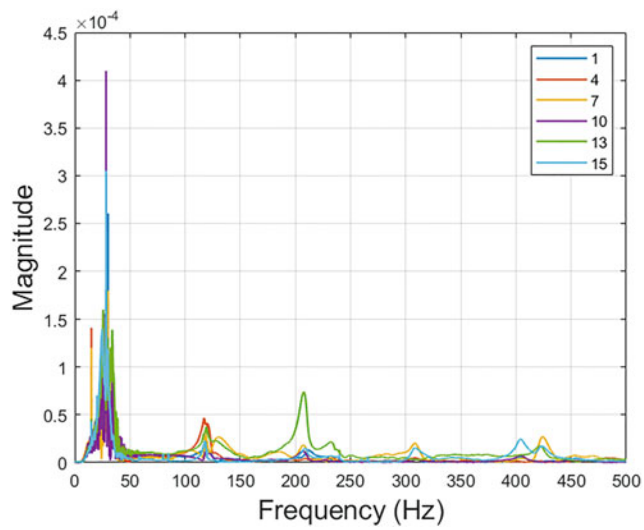


Fig. 11.4 FRF magnitude response for $[0]_4$ plate

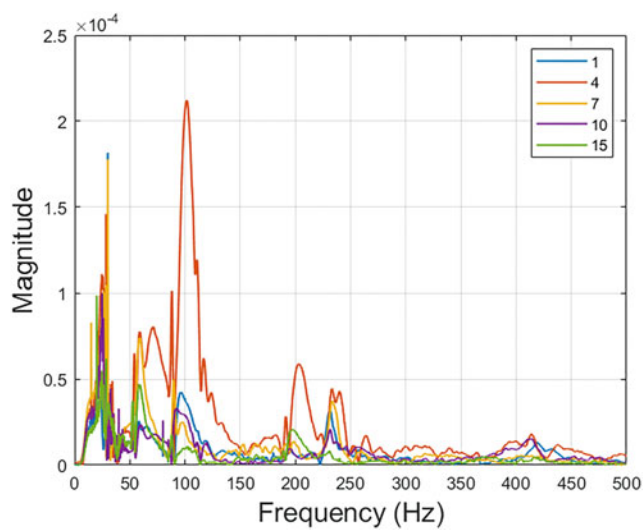


Fig. 11.5 FRF magnitude response for $[0/90]_s$ plate

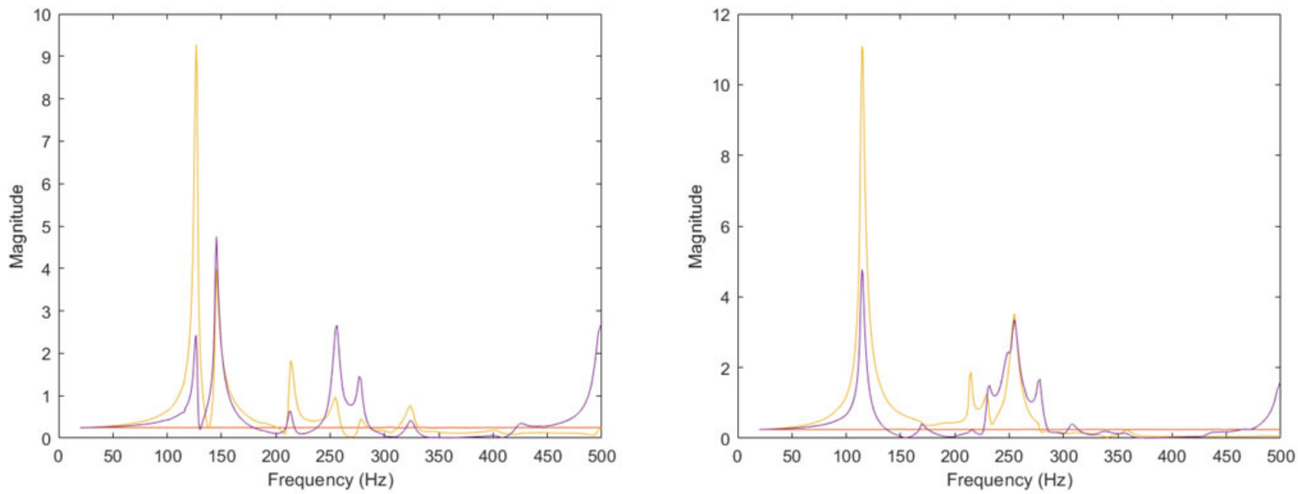


Fig. 11.6 Sine sweep magnitude responses of $[0]_4$ plate for non-buckled and buckled configurations

to be 103.5, 153.1, and 259.9 Hz. These results matched overall behavior, but they were not accurate in predicting specific values. Part of this may be due to inconsistencies in the boundary conditions from being truly fixed-fixed in the experimental testing. Additionally, inconsistencies in the material may further contribute to differing values.

Due to surface irregularities on the $[0/90]_S$ plate, noisier vibrometer data were collected at several of the testing points than the data found for the $[0]_4$ plate. This caused some difficulty differentiating between the peaks indicating the natural frequencies. Namely, referring to Fig. 11.5, there appears to be a resonance peak around 60 Hz. However, analysis on other plates with similar conditions showed that this peak is likely an artifact of the plate surface rather than the fundamental frequency. From this, the group concluded that the first three natural frequencies occurred at 101.3, 196.7, and 232.0 Hz. Analytical predictions based upon the geometry and material of the plate yielded natural frequencies of 97.1, 188.8, and 267.72 Hz. Similar to the $[0]_4$ plate, the analytical predictions vary from the experimentally obtained results. However, especially notable in these results is that the first two resonance frequencies closely match the predicted results compared to the third frequency. This suggests the analytical model may be more accurate in predicting natural frequencies associated with the lower modes than it is with the higher modes.

11.3.2 Changes in Natural Frequency of Post-Buckled Configuration

Following completion and analysis of the impact testing using a laser vibrometer, the plates were tested on a shaker table. The sine sweep using a flat, pre-buckled configuration for the $[0]_4$ plate yielded resonance peaks at 126.0, 145.5, and 206.6 Hz as shown in Fig. 11.6a. In this figure, the two data sets represent the two accelerometers attached to the plate. The observed natural frequencies closely match the predicted natural frequencies and those determined during the impact testing, thus confirming the team's conclusions concerning the experimentally used plates' natural frequencies. Following the reconfiguration of the plate to a post-buckled state, the sine sweep was re-run and the magnitude was again plotted against the frequency as shown in Fig. 11.6b. The resonance peaks for the buckled configuration were much less defined, apart from the fundamental frequency at 115.2 Hz. The results showed lesser defined peaks at 213.6 and 239.1 Hz. The slight shift left on the first natural frequency was expected, as buckling reduces the effective stiffness of the plate, thus lowering the expected fundamental frequency. Analysis focused on higher frequencies was not considered.

The same analysis was conducted on sine sweeps conducted on the $[0/90]_S$ plate. The non-buckled configuration shown in Fig. 11.7a had resonance peaks at 91.3, 173.5, and 215.0 Hz. In Fig. 11.7b, the buckled configuration had peaks 68.7, 159.9, and 213.6 Hz. These results correspond with the findings of the $[0]_4$ plate analysis. The fundamental frequency shifted left from the non-buckled configuration as expected. While the higher frequencies still saw some shift from the non-buckled configuration, the differences were not as drastic as the $[0]_4$ plate.

The summary of the results for the natural frequency behaviors of the two composite plates tested are shown in Table 11.1 below. These results indicate that there was consistency among the three test and analytical procedures in determining

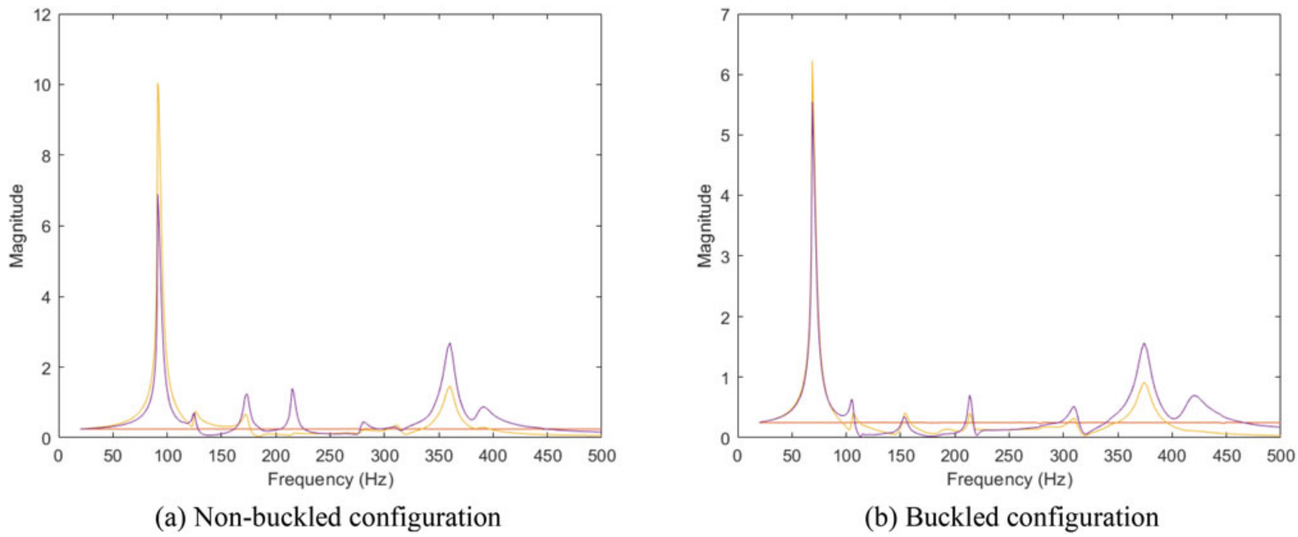


Fig. 11.7 Sine sweep magnitude responses of $[0/90]_S$ plate for non-buckled and buckled configurations

Table 11.1 Fundamental frequency for non-buckled plates across tests

	$[0]_4$ Plate (Hz)	$[0/90]_S$ Plate (Hz)
Predicted frequency	103.5	97.1
Impact test frequency	118.3	101.3
Shaker table frequency	126.0	91.3

the natural frequency of the composite plates. Of note is the relative inconsistency between the placements of the results. The predicted frequency based upon the analytically model was not always the lowest nor was the shaker table always the highest as indicated by the $[0]_4$ plate. Instead, the relative values of the natural frequencies varied across the tests. The researchers conclude that these differences were therefore most attributable to the testing conditions and inconsistencies within the testing frame and setups. Further experimentation is needed to find if these inconsistencies can be reduced.

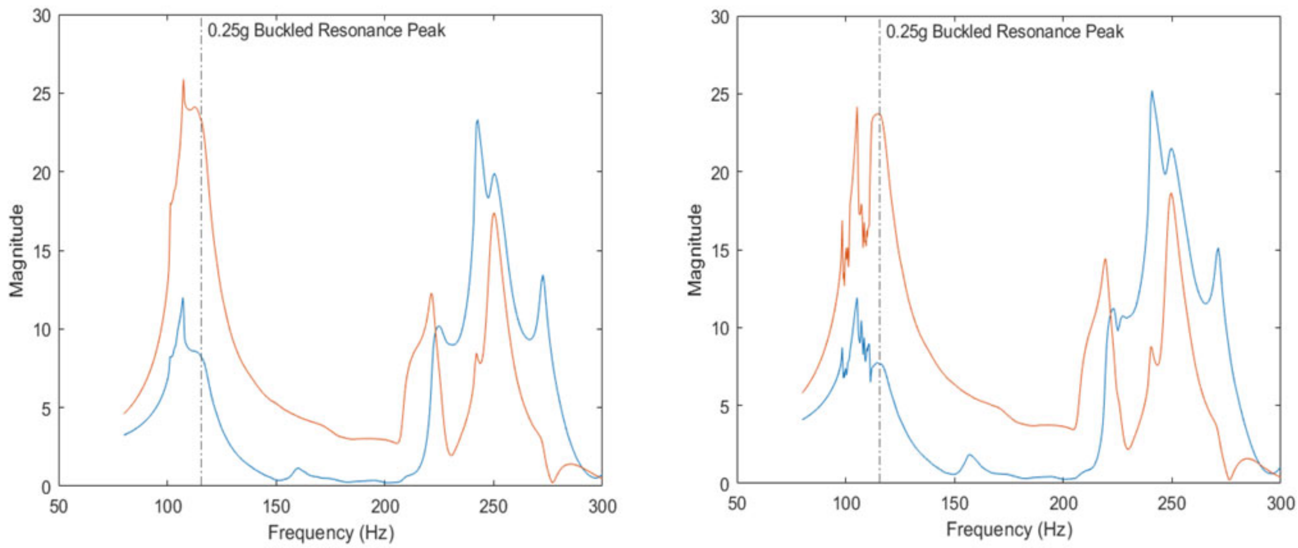
11.3.3 Determination of Minimum g-Loading

After determining the fundamental frequencies of the buckled plates, the minimum energy required to produce the chaotic snap-through effects was determined. Sine sweeps of the buckled plate configurations were once again analyzed to determine the g-loading at which snap-through occurs. Below in Fig. 11.8 is a demonstration of this phenomenon as seen in the magnitude response.

In the 2.0 g loading in Fig. 11.8a, there was a slight perturbation in the curve rising to the peak about the 101.5 Hz point. This represents the point at which snap-through was about to occur and caused non-uniform deflections detected by the accelerometers. Figure 11.8b fully shows this snap-through. At 2.5 g, there was significant disturbance from 98.4 Hz until 112.0 Hz. These disturbances reflect snap-through in the plate. The abnormal magnitude response detected by accelerometers corresponds to the abnormal plate motion. From this, one can conclude that the minimum g-loading required to obtain snap-through was within this range of frequencies and between 2.0 and 2.5 g.

Frequencies were set in increments in this range and the minimum g-loading determined. Referring to Fig. 11.9, this minimum g-loading occurred at around a frequency of 99 Hz. The team also found that the minimum g-loading required for snap-through depended on whether snap-through had already occurred or not. When higher g-loads were applied to generate snap-through and then reduced until snap-through ceased, the required loading was lower, as indicated by the blue line. However, when g-loading was gradually applied until snap-through occurred, the g-loading was higher, as indicated by the red line. The researchers postulate that such behavior is seen because there is a certain potential energy required to overcome inertia in order to initiate snap-through. This allows the minimum g-loading to maintain snap-through to be smaller than that required to cause snap-through. The minimums for the increasing and decreasing loads were 2.19 and 1.95 g respectively.

The g-loading test analysis was repeated with the $[0/90]_s$ plate to further analyze and confirm the results of the $[0]_4$ plate. Below in Fig. 11.10 are the sine sweep results of three different loading conditions showing the snap-through phenomenon.



(a) 2.0g loading condition (b) 2.5g loading condition

Fig. 11.8 Sine sweep magnitude responses of $[0]_4$ plate at varying g-loads demonstrating snap-through phenomenon

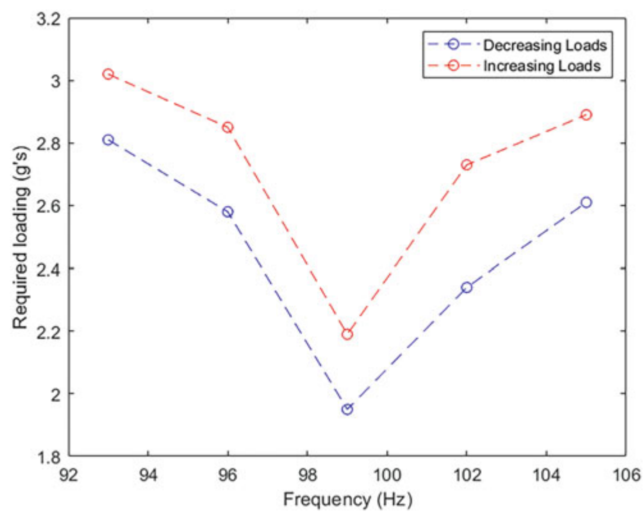


Fig. 11.9 Minimum g-loading required to incite snap-through behavior for $[0]_4$ plate

In (a), there is a slight disturbance indicating potential snap-through at 73.4 Hz. In (b) at 2.5 g, snap-through is evident from 71.5 to 78.9 Hz. This region expands in (c) at 3.0 g, ranging from 69.7 to 82.4 Hz. This region illustrates a chaotic snap-through region where the plate moved rapidly back and forth between the two stable equilibria. The expansion of the snap-through across a larger range of frequencies was expected, as the greater energy present in higher loading conditions allows snap-through to occur further from the resonance peak. As with the $[0]_4$ plate, the minimum g-loading to cause snap-through was examined. At a frequency of 70 Hz, snap-through could be maintained with a g-loading of 2.19 g. This corresponded to the same g-loading for the $[0]_4$ plate.

11.4 Conclusions

The results of these experiments demonstrated the usefulness of examining the dynamic response of bi-stable composite plates. The analytical model was capable of predicting generalized behavior of the natural frequencies of the composite plates. However, more analysis should be done to assess whether the differences were attributable to improper testing

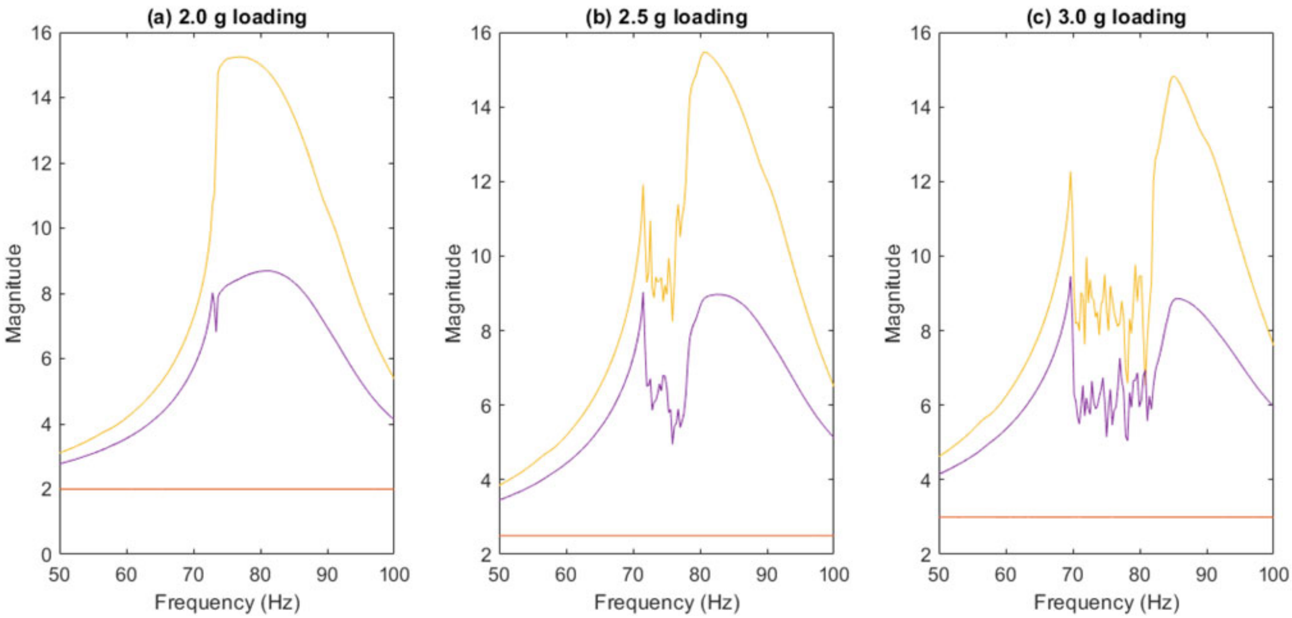


Fig. 11.10 Sine sweep magnitude responses of $[0/90]_S$ plate at varying g-loading conditions

environment procedures or whether the model must be refined. Moreover, the model does not yet predict the buckled behavior of the plates, which is necessary to predict the minimum g-loading.

The dynamic testing results showed that natural frequencies found for flat-plate, non-buckled configurations closely matched those obtained with the laser vibrometer. When moved to the post-buckled configuration, the resonant frequencies of the plates shifted downwards. As increased g-loading was applied, the snap-through behavior was observed. By incrementally increasing the loading about the fundamental frequency, the region of frequencies in which the snap-through behavior occurred also increased. Determining the minimum energy required for snap-through yielded two results. There was a minimum g-loading associated with maintaining snap-through behavior and a higher g-loading associated with causing snap-through behavior. Future analysis should focus more on the greater loads needed to initiate snap-through, as this is the primary concern for hypersonic applications. In our case analysis, both of the minimum loading conditions associated with causing snap-through behavior occurred at 2.19 g.

References

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