Chapter 13
Acoustic Fatigue

Abstract This chapter briefly addresses the typical damping characteristics of FMLs in context of the acoustic fatigue properties. Results of high frequency bending experiments are discussed to illustrate the excellent performance of FMLs with respect to this mode of excitation.

13.1 Introduction

Acoustic fatigue or high bending fatigue is an aspect related to thin-walled stiffened structures subjected to variable high-frequency loads due to random noise and vibrations. These vibrations may be caused by engines (like turbofans) or operation of equipment. The requirements with respect to increased engine performance for turbojets and minimization of airframe weight result in structural components subjected to high stresses at high-intensity pressure fluctuations.

Most structural parts sensitive to acoustic fatigue are located in regions of separated flow behind protuberances such as air brakes, in surface areas near the plane of a propeller rotation and in bomb bays, where pressure fluctuations occur during bay door opening at high speed.

Compared to the subjects discussed in previous chapters, the topic of acoustic fatigue in FMLs has received only limited attention. The topic mostly received attention in the early days when developing ARALL for wing applications or studying the application of ARALL to the empennage of turboprop aircraft like the Fokker F27. This chapter briefly summarizes the available research and highlights the main results and observations.

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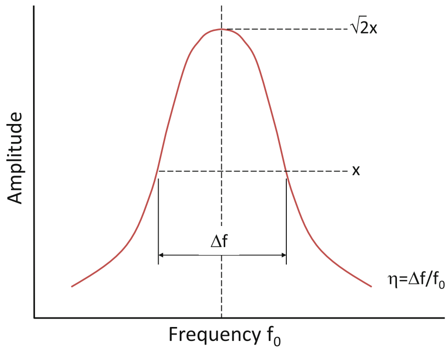
13.2 Damping Characteristics

To understand the phenomenon of acoustic fatigue, two factors affecting the behaviour should be distinguished: the mechanical response and the fatigue characteristics of a structure. The complete description of the mechanical structural response to high-frequency excitation requires knowledge of all vibration modes of that particular structure, the resonant frequencies and the damping characteristics. The damping characteristics of various FMLs (ARALL and GLARE) have been investigated by several researchers [1, 2]. These studies have indicated that adhesively bonded laminates exhibit improved vibrational damping properties compared to monolithic counterparts. In general, FMLs show two to three times better damping behaviour than aluminium [3]. This benefit of FMLs can be attributed to the internal damping capability of the visco-elastic layers, which reduces the stress by a factor 2 compared to monolithic aluminium 2024-T3 [1].

Nonetheless, the work by Waleson [1, 4, 5] has illustrated that one should take care in correlating results like in Fig. 13.1. For example, in [5], Waleson evaluated the vibrating beam, the impedance or direct method and the resonance method. To extract the loss factor from the vibrating beam, he evaluated the half-energy bandwidth method, the Kennedy-Pancu method and the resonance dwell method. In correlating the results, he observed that some methods resulted in values that could be up to 2.5 times higher than the results of other methods.

In addition, he could clearly identify the influence of air as environment on the damping characteristics, the influence of specimen clamping and the influence of normal stresses in the visco-elastic layers. Here, he observed that the internal damping characteristics of ARALL2-2/1 were fairly small, similar to monolithic aluminium, opposite to the findings in Fig. 13.1 [3].

In case of ARALL1 [3], the internal residual stress system after curing has been modified with post-stretching (explained in Sect. 3.4.1). This means that comparison between the acoustic fatigue properties of ARALL1 and monolithic aluminium



Material	Loss factor η
Arall 1-3/2 (longitudinal)	$21.0 \cdot 10^{-4}$
Arall 1-3/2 (transverse)	$16.0 \cdot 10^{-4}$
Aluminium 2024	$7.2 \cdot 10^{-4}$
Aluminium 6061	$6.7 \cdot 10^{-4}$

Fig. 13.1 Correlation of damping characteristics of ARALL1-3/2 laminates in both the longitudinal and transverse direction with those of aluminium 2024 and 6061 [3]

mostly demonstrated the influence of favourable compressive residual stresses in the aluminium layers of ARALL1.

For Waleson [1], this was the reason to perform similar damping experiments on ARALL2-2/1 (without post-stretching), which was in the as-cured condition with tensile residual stresses in the aluminium layers. In that correlation, the benefit of ARALL2 over monolithic aluminium is still there, but evidently much smaller. Waleson reports that the transmission loss of ARALL2-2/1 is slightly lower than that of 1-mm-thick aluminium 2024-T3.

For the studied case, the bending stiffness of the ARALL laminates is about 45% of that of 1-mm-thick aluminium, with a surface density of about 30%.

Exploring the influence of different prepregs illustrated that a similar lay-up but with a thermoplastic resin improved both the loss factor and bending stiffness by at most 20%. Based on these findings, Waleson [1] recommended to focus on the acoustic fatigue response and damage tolerance, rather than the damping characteristics.

13.3 Acoustic Fatigue

There are various ways to experimentally assess the acoustic fatigue behaviour of a structure or material. Structural parts may be subjected to in-service acoustic loading induced by high power engines, while they are assembled in the complete airframe, or structures may be placed in a wind tunnel set-up to induce the aerodynamic loading. This type of tests is very expensive and can only be performed when the structure is assembled.

Without assembling into a structure, parts can also be subjected to acoustic loading induced by reverberant chambers or sirens. A simple and most often applied experimental method is high-frequency bending testing with shaker equipment. This type of test can only be performed on a material level, enabling generic comparison of different materials. The experimental data presented here are based on this shaker type of experiments, as discussed in more detail in the next section.

13.4 High-Frequency Bending Fatigue Experiments

13.4.1 Specimen Configuration and Test Set-up

High-frequency bending fatigue tests were performed by Syamaun [2] on shaker test specimens, which are illustrated in Fig. 13.2 [2]. The specimens were clamped at the mid-span stiffener to a shaker, with which a sinusoidal waveform was generated using a waveform generator. All specimen configurations were tested at a

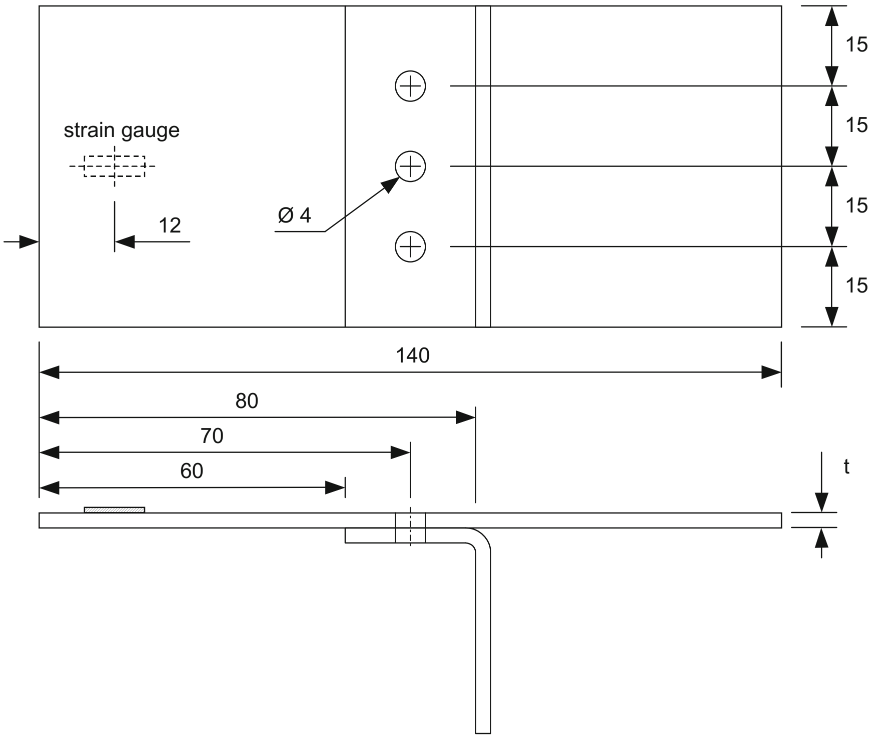


Fig. 13.2 High-frequency bending test specimen; high-frequency excitation induced through the mid-span stiffener using a shaker (all dimensions in mm) [2]

constant strain level of 200 micro-strain at the strain gauge location indicated in Fig. 13.2.

13.4.2 Test Procedure

The specimens were tested in a shaker test set-up with the objective to generate S-N data for different joint configurations and materials. The specimens were vibrated at a resonance frequency to generate alternating bending stresses in the beam.

As the fatigue damage increases, the frequency decreases due to the change in beam stiffness. When the frequency drop was observed, the generator frequency was adjusted in such way that the strain amplitude reached again 200 micro-strain. This procedure to maintain the strain amplitude appeared to be somewhat difficult because conventional strain gauges do not have sufficient fatigue life themselves to last the entire fatigue life of the specimens at the given strain amplitude levels.

The time history of the specimen frequency is a measure for the fatigue damage developed in the specimen. The high-frequency bending tests were terminated at the moment that either the crack reached the edges of the specimen, the resonant frequency dropped below 100 Hz, or when the total testing time exceeded 900 min.

13.4.3 Performed Tests

Syamaun [2] tested several FML configurations based on either aramid or glass fibres, with in addition an FML based on carbon fibres. Because the tested ARALL and GLARE laminates contain either 2024-T3 or 7075-T6 as aluminium constituent, similar tests were performed on the monolithic alloys, with a plate thickness of 1 mm, both with and without clad layers. The entire set of tested materials is listed in Table 13.1.

Table 13.1 Overview of the high-frequency bending experiments reported in [2]

Group	Material	Lay-up	Post-stretch	Thickness (mm)	Weight (g)	Primed	Number of specimen
A B C D	Al 2024 bare Al 2024 clad Al 7075 bare Al 7075 clad			1.01 1.02 1.00 1.02	40.0 40.1 39.5 40.8		3 3 3 3
E F	GLARE1 (7R32) ARALL1 (7H32)	2/1 2/1	✓ ✓	0.92 0.94 0.82 0.84	36.1 37.1 33.2 33.5	✓ ✓ ✓ ✓	3 2 3 2
G H	GLARE2 (2R32) ARALL2 (2H32)	2/1 2/1		0.69 0.76	30.9 32.5		3 3
I J	GLARE1 (7R33) ARALL1 (7H32)	3/2 3/2	✓ ✓	1.55 1.55 1.36 1.40	47.1 47.1 42.1 43.1	✓ ✓ ✓ ✓	3 2 3 2
K L	GLARE2 (2R33) ARALL2 (2H33)	3/2 3/20		1.10 1.25	41.2 41.1		3 3
M	Carbon ARALL	2/1		0.82	34.5		2
N	GLARE3	3/2		1.35	46.6		2

13.5 Results and Observations

An illustration of the test results on the high-frequency bending tests on monolithic aluminium and two GLARE2 laminates is given in Fig. 13.3. Here, one should note that a direct comparison between the high-frequency bending fatigue behaviour of aluminium and GLARE is in fact not possible, since parameters such as thickness and, more importantly, weight are not equal for these tests, see Table 13.1.

However, from Fig. 13.3, it can be seen that the monolithic aluminium specimens have resonant frequencies at the start of the test that are comparable to GLARE2-3/2-0.3. The difference in thickness between the monolithic aluminium specimen and the 3/2 lay-up is fairly small. However, the 2/1 lay-up has significantly lower bending stiffness and as a consequence also a substantially lower resonant frequency at the start of the test.

The aluminium 2024-T3 bare specimen failed after 36 min, slightly longer than the clad specimen, which dropped below the 100-Hz level after 28 min. The reduction in the resonant frequency of both GLARE laminates seems similar in trend and illustrates the lower rate with which fatigue damage develops in the materials in comparison with monolithic aluminium. Because GLARE2-2/1-0.3 started at a lower frequency, it obviously required less time to drop below the 100-Hz level compared to the 3/2 lay-up

A comparison between the frequency bending behaviour of the various ARALL and GLARE laminates is illustrated in Fig. 13.4. From these results, it can be

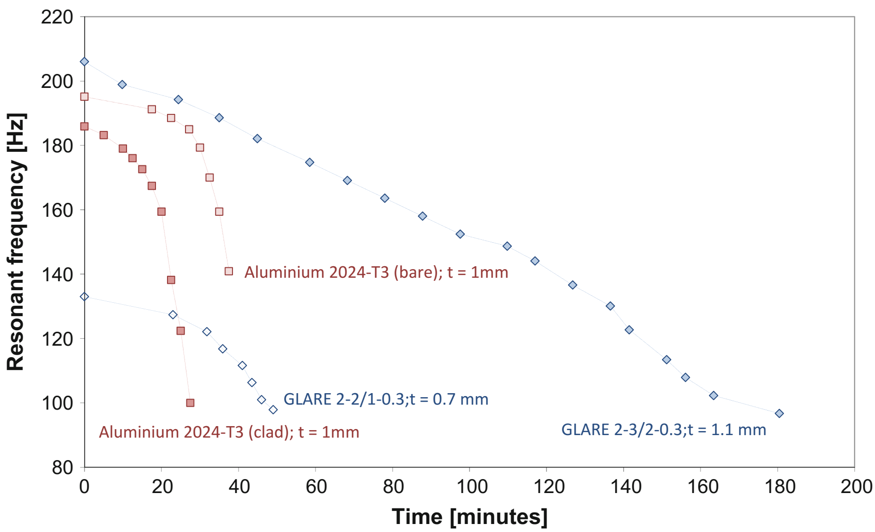


Fig. 13.3 Frequency versus time comparison between GLARE laminates and monolithic aluminium 2024-T3 using the shaker test on specimens illustrated in Fig. 13.2 with round-head rivets [2]

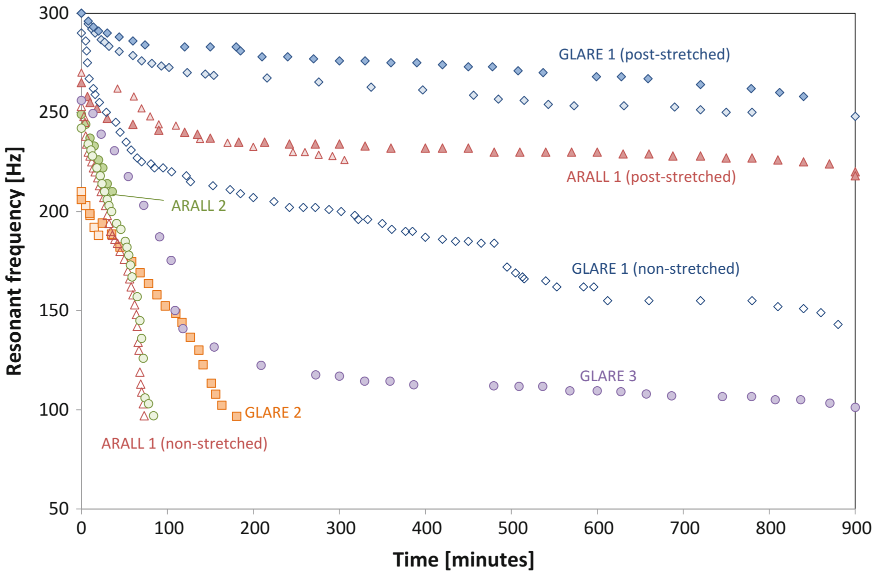


Fig. 13.4 Frequency versus time comparison between various ARALL and GLARE laminates with and without post-stretching using the shaker test on specimens illustrated in Fig. 13.2 with round-head rivets [2]

concluded that the unidirectional GLARE laminates performed better than the unidirectional ARALL laminates. This could be attributed to the greater strain to failure of the glass fibres in comparison with the aramid fibres.

Another observation one can make is that the post-stretched laminates perform significantly better than the laminates in as-cured conditions. At the start of the test, the as-cured laminates have the same resonant frequency as their post-stretched counterparts. However, the post-stretched laminates easily sustained 900 min, while maintaining high frequencies. This is obviously related to the favourable residual stress system in the post-stretched laminates that delays the initiation and progression of fatigue damage in comparison with the as-cured laminates.

The only cross-ply laminate in Fig. 13.4, GLARE3-3/2-0.3, initially quickly dropped in frequency, almost similar to the as-cured ARALL laminates, but after about 200 min the degradation reduced substantially. In the end, the resonance frequency of the GLARE3 specimen still exceeded the 100-Hz level after 900 min.

13.6 Concluding Remarks

The studies by Waleson [1, 5] and Syamaun [2] have illustrated various aspects related to the high-frequency bending fatigue performance of FMLs. First, the increase of acoustic fatigue life of FMLs over monolithic aluminium becomes larger for thicker laminates. The thin 2/1 lay-up hardly yields an improvement in either damping characteristics or acoustic fatigue properties. This can be explained with the position of the fibre layers in thickness direction. In a 2/1 lay-up, all fibre layers are located near the neutral line, which makes them fairly ineffective in restraining crack opening by bridging. Only for 3/2 lay-ups or thicker laminates, do the fibres become effective and evidently contribute to the acoustic fatigue performance.

Furthermore, the studies made clear by comparing non-stretched and post-stretched FMLs that post-stretching substantially increases the fatigue life due to the favourable residual stress system. In addition, the failure strain of the fibres likely has a dominant contribution, because the GLARE laminates performed better than both the ARALL laminates and the laminate based on the carbon fibres.

With respect to the fact that thicker laminates perform better than their thinner counterparts, one may assume that for structural applications where the laminate lay-up is at least 3/2, damping characteristics and acoustic fatigue likely are not a subject of concern when compared to monolithic aluminium. Only when very thin laminates are considered, like the 2/1 lay-up, do the properties demand assessment of the acoustic fatigue characteristics.

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