Static and Dynamic Strength of Paperboard Containers Subjected to Variations in Climatic Conditions

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Abstract: The variability in climatic conditions during product distribution, especially across large distances, can be significant and is well known to affect the mechanical properties of many packaging materials. As the use of environmentally friendly materials, such as paperboard and bio-cushions, increases, the challenge associated with overcoming the effects of extremes in temperature and relative humidity in the distribution chain becomes critical. To-date, in the case of paperboard boxes, this is dealt with by accounting for the loss of static (compression) strength with increasing relative humidity (RH). However, no method exists to address the dynamic loads induced by vehicle shocks and vibrations especially for configurations that involve stacked boxes and where the vibration intensity within the stack is influenced by the dynamic characteristic of the boxes themselves. In such scenarios, it is the variation in the stiffness of the box as a function of environmental conditions and dynamic load that need to be established. This paper describes the evaluation of the fatigue resistance of paperboard boxes subjected to random excitation and compares the results with those obtained from quasi-static compression tests under various environmental conditions. Results reveal a lack of correlation between the static and dynamic tests. This finding is attributed to changes in internal damping of the paperboard box samples which, when reduced, results in increased dynamic force. The paper concludes that static testing alone is insufficient to establish the fatigue resistance of stacked packaging subject to variations in climatic conditions.

Keywords: Paperboard, humidity, fatigue, natural frequency, vibrations

Introduction

In line with a global trend to minimise the impact of packaging waste, concerns related to the use of many traditional protective packaging materials have been raised. As a result, the use of environmentally friendly alternatives is increasing. However, given that many of these alternatives consist of fibrous compostable/biodegradable materials, their engineering characteristics are often affected by variations in environmental conditions. Specifically, loss of strength with increases in relative humidity (RH) is a primary concern. Such concerns are not limited to new/exotic materials but also apply to any natural fibre-based materials including more traditional non-waxed corrugated paperboard.

Over the years there has been extensive literature published on the stresses applied to paperboard packaging as a result of variations in climatic conditions. Kellicutt and Landt [1] investigated the influence of moisture content on corrugated fibreboard and developed an equation for determining the loss of compressive strength of corrugated fibreboard containers when compared to the same sample with a different moisture content. They also presented results for the time to failure under a constant static load for various levels of moisture content. A relationship between moisture content and compressive strength for specific corrugated samples was also presented by Hung *et. al* [2]. Gunderson and Laufenberg [3] also evaluated the load carrying capability of corrugated board but under cyclic humidity environments (50-90% RH) using long term load, edgewise compression and multi-point bending tests. The work clearly identified the susceptibility of uncoated paperboard samples at elevated levels of RH with multiple failures at the 90% RH cycles. Further work on evaluating the strength of paperboard samples with variations in RH was performed by Modzelewska [4] who evaluated the resistance to burst, resistance to edge crush, resistance to flat crush and box resistance to static compression. Test which evaluate other static material properties, such as Young's modulus, of paperboard using tensile tests over a range of environmental conditions have also been carried out by Allaoui *et al.* [5] who established that paperboard's elastic characteristics evolve significantly beyond 70% RH and reductions in Young's modulus of 50% are observed at 90% RH. Similarly, Wang and E [6] and E and Wang [7] carried out compression tests to determine the mathematical relationship between Young's modulus versus RH and yield strength versus RH. Again the results showed that beyond 70% RH the elastic properties of the samples decreased rapidly as did the yield strength with any increase in RH above 40-50%. Wang and E [6] and E and Wang [7] used the results to develop mathematical models for the energy absorption properties and stress plateau, respectively, of corrugated paperboard. Other notable studies on the effects of RH on paperboard include the work of Marcondes [8] who evaluated the static and shock performance characteristics of paperboard with variations in climatic conditions and Sek & Kirkpatrick [9] who studied the effect of RH on the shock performance (cushion curves) of corrugated paperboard cushions. A further review on the effect of climatic conditions on the strength properties of corrugated paperboard samples is given in [10].

Overall, the focus of the majority of research manuscripts which study the influence of RH on the performance of paperboard samples is storage (static loading) or mishandling (single shock loading). There appears to be little emphasis on the cumulative effects of the dynamic loading in packaging that is arranged to carry a load (stacked) caused by vibrations during distribution and the ultimate evolution of packaging fatigue.

A recent study by Huart *et al.* [11] presents an attempt at predicting the fatigue life of paperboard containers using mono-frequency excitation and Wohler curves. The results for mono-frequency excitation show promise and could potentially be applied over a range of climatic conditions. However, when packages are stacked atop one another, the dynamic loading to the packaging varies in accordance with the frequency response function (FRF) of the stacked system (load magnitude varies with frequency) [12, 13]. This means that prediction of fatigue life for items subjected to broad-band excitation cannot be made using a mono-frequency technique. Although acknowledged by Huart *et al.* [11], this shortcoming is not addressed. Furthermore, variations in the dynamic properties of the system (natural frequency and damping) resulting from damage alter system's transfer function and, as a result, the dynamic loading to the system. Variations to the damping ratio alter the magnitude of the dynamic loading and variations in natural frequency alter the point of resonance. The latter of these two variations means that even mono-frequency fatigue tests based on a worse case (resonance) would be difficult since the point of resonance is constantly shifting throughout the tests. Resonance search-and-dwell techniques (which often employ phase-locked control) can be applied to overcome this but are often found to be problematic for all but very simple single degree-of-freedom (SDoF) systems [14].

Extensive work has previously been carried-out by the authors towards the development of a post-processing technique which can determine the condition of packaging samples as a function of time. Various techniques have been developed [15, 16, 17], most of which make use of the overall system's FRF to extract continuous estimates of the system's natural frequency which are in turn used as a quantifiable measure of damage (loss in stiffness).

This study will use the short-time Fourier transform based technique developed by the authors [15, 16] to monitor the condition of empty corrugated paperboard samples subjected to dynamic loading under a range of climatic conditions. Compression tests will also be performed on visually identical corrugated paperboard samples and the fatigue resistance and the static strength of the containers will be compared.

Experimental Design

The static and dynamic performance of the paperboard containers was evaluated for three climatic conditions. The conditions were selected to allow for a comparative evaluation for climates ranging from extreme humidity to extreme dry conditions that are relevant to Australian exports into the Asian markets. The International Safe Transit Association (ISTA) [18] provides a set of standard test conditions and these were used as the basis for the experiments. The environmental conditions used are outlined in Table 1.

Table 1: Conditioning Table [1].

Environmental Conditions	Min. Time (hrs)	Temperature (°C ±2°C)	Relative Humidity (% ± 5%)
Standard	72	23	50
Hot, dry	72	60	15
Tropical	72	38	85

During all testing exposure to the laboratory environment was minimised wherever possible. However, the environment surrounding the testing apparatus used only allowed for temperature control which meant that the samples were exposed to ambient laboratory conditions. The conditions within the laboratory were recorded regularly during the tests and were found to be within ± 2°C and ± 5% RH of standard conditions for each measurement taken. Tests were performed to evaluate the effect of exposure to the moisture content within the samples. This was achieved by placing the preconditioned samples in the laboratory environment on a digital weighing scale connected to a PC for automatic mass recording at 30 second intervals.

The Samples

The paperboard container samples where constructed from double-walled, single flute, type E corrugated paperboard (1.7 mm thick) and where rectangular in shape. The external dimension of the containers was 195 mm high, 165 mm long and 95 mm wide.

Dynamic Test

The dynamic fatigue experiments were designed to induce dynamic compressive loads to the pre-conditioned paperboard samples while enabling the FRF of the system to be monitored. The experiments were carried out using a servo hydraulic vibration table connected to a vibration controller which was programmed to generate band-limited white noise of a pre-determined level over a frequency range of 2 – 100 Hz. The frequency range was selected to ensure that the primary resonance mode of the dynamic system was within the excitation band-width and to allow sufficient spectral content for modal parameter extraction (curve-fitting). The samples were configured to support a guided mass as, illustrated in Fig.1, while the acceleration of both the vibration table and the guided mass were recorded continuously and simultaneously. The samples were subjected to a low level of excitation for 5 minutes to allow for settling at the start of each test.

Insert Fig. 1

Figure 1: Experimental layout for dynamic (vibration) testing.

The recorded acceleration time histories were analysed using specially-designed software that used a modified, short-time Fourier transform (STFT) based, Welch method [19] to extract average FRF estimates using ensembles as shown in Fig. 2. This technique allows for the configuration of various parameters namely, spectral averaging overlap, sub-record length and temporal resolution. These were adjusted to achieve a temporal resolution of 30 seconds and a spectral resolution of 0.2 Hz.

Insert Fig. 2

Figure 2: Schematic for post-processing tool.

Using a least-squares algorithm, the software tool automatically applies a curve-fit of the theoretical transmissibly equation (SDoF) to each of the FRFs (see Fig. 3 for a typical example) in order to estimate the system's 'short-time' natural frequency (f_n) and damping ratio (ζ). The technique and the influence of each of the analysis parameters is described in detail by [16, 19].

Insert Fig. 3

Figure 3: Example FRF and curve-fitting.

Static Test

Prior to completing the dynamic tests, quasi-static compression tests were carried out to establish the static strength of the paperboard containers for each environmental condition. The arrangement for the static tests was similar to that used for the dynamic testing except that the guided pattern was now rigidly fixed using a load cell connected to the cross beam to allow for force measurements to be recorded. Displacement was controlled using the servo-hydraulic actuator and associated controller. Displacement was applied to the system at a constant rate until reaching a pre-set value, after which the displacement was reversed. The force and displacement measurements were simultaneously recorded.

Results - Environmental Exposure Tests

The results obtained by exposing the preconditioned samples to the ambient laboratory conditions and recording their mass are presented in Fig. 4. The results are presented as a percentage of the samples' mass at standard conditions (23°C and 50% RH). The solid line indicates the mean of the data. As can be seen the uptake of moisture for the dried sample (b) is much more rapid than the moisture loss in the sample conditioned in a tropical environment (a). This variation in moisture content needs to be taken into account when analysing data from (longer term) vibration fatigue tests.

Insert Fig. 4

Figure 4: Sample weight change at ambient laboratory conditions (a) Tropical preconditioning (b) Hot dry preconditioning. Solid line indicates the mean of all data.

Results - Static Tests

The results for the static tests are presented in Figs. 5 – 7 for the samples conditioned at standard, hot dry and tropical environments, respectively. The results were obtained for a constant compression rate of 0.1 mm/s and a maximum compression of approximately 12 mm.

Insert Fig. 5

Figure 5: Compression characteristics of samples preconditioned under standard conditions (72 hrs).

Insert Fig. 6

Figure 6: Compression characteristics of samples preconditioned under hot dry conditions (72 hrs).

Insert Fig. 7

Figure 7: Compression characteristics of samples preconditioned under tropical conditions (72 hrs).

As can be seen, there is some variation in the compression characteristics recorded for each level of preconditioning. This is particularly evident for box 1 for the tropical conditions, which is stiffer than the other samples during the early stages of compression. This difference is a result of the manufacturing tolerance of the paperboard samples. As illustrated in Fig. 8, each wall and corner of the paperboard samples can be considered as a number of compression springs set in a parallel configuration. Due to manufacturing tolerances, some of these springs will not be making contact with the surface through which the compression is being applied and this results in a softer sample during the early stages of compression (box 1 has a more even initial contribution from each corner and wall and is more stiff).

Insert Fig. 8

Figure 8: Partial explanation for difference in compression results for visually identical paperboard containers.

For each set of results a typical sample has been identified (thick line on each figure). The results for each typical sample (each environmental condition) are compared in Fig. 9. As can be seen, with an increased exposure to moisture the yield point and ultimate compressive load (maximum compressive force held by the samples) of the samples is reduced.

Insert Fig. 9

Figure 9: Typical compression curve results for paperboard samples. Horizontal dashed line represents static load applied for dynamic (vibration) testing.

Table 2 compares the mean load resulting in yielding as well as the mean ultimate (compressive) load for each environmental condition. The results show a 12% increase in the load required to yield the samples once subjected to hot dry conditions when compared to samples conditioned at standard conditions, whereas, for tropical pre-conditioning the load reduces by 22%.

Table 2: Comparison of mean load to yield and ultimate load for all climatic conditions (± indicates range).

Condition	Mean load to yield [kN]	Mean ultimate load [kN]
Standard	0.5 ± 0.05	0.71 ± 0.04
Hot, dry	0.56 ± 0.09	0.84 ± 0.05
Tropical	0.39 ± 0.08	0.56 ± 0.02

Results – Dynamic Testing

The horizontal dotted line in Fig. 9 indicates the selected static load (30 kg total mass including guided platen) for the dynamic testing. The load was selected based on the quasi-static results to allow for fatigue to be induced in the samples without causing sudden failure (unfortunately the static load needed to be set closer than desired to the yield point of the samples preconditioned in a tropical environment in order to allow for fatigue to develop in the other samples).

At the start of each test, the samples were subjected to low intensity base vibrations (1.25 m/s^2 root-mean-squared) for 5 minutes to allow the samples to settle. Subsequent to the settling period the samples were subjected to an increased intensity level of 2.75 m/s^2 root-mean-squared (RMS) to induce damage to the samples.

The results for the dynamic fatigue testing are presented in Figs. 10 – 12 for the samples conditioned at standard, hot dry and tropical environments, respectively. Relative (when compare to initial state) natural frequency is used to indicate variations in stiffness, hence structural health. The results for the settling period have not been included here.

For each set of results the mean relative natural frequency for each point in time has been calculated (thick line on each figure). The mean results for each environmental condition are compared in Fig. 13 as the thick lines and the envelope of results (maximum and minimum values for the sample set) is indicated with the thin lines. As can be seen, the samples preconditioned under tropical conditions have by far the poorest fatigue resistance, which is to be expected considering the static test results. However, despite having slightly higher static strength, the samples preconditioned under hot, dry conditions appear to have less fatigue resistance than those preconditioned at standard conditions. This is anticipated to be a result of variations to the dynamic characteristics (modal properties) of the overall system.

Insert Fig. 10

Figure 10: Evolution of fatigue in paperboard under dynamic loading samples pre-conditioned at 23°C and 50% RH (standard conditions). Solid line indicates the mean of all samples.

Insert Fig. 11

Figure 11: Evolution of fatigue in paperboard under dynamic loading samples pre-conditioned at 60°C and 15% RH (hot dry climate). Heavy dotted line indicates the mean of all samples.

Insert Fig. 12

Figure 12: Evolution of fatigue in paperboard under dynamic loading samples pre-conditioned at 38°C and 85% RH (tropical climate). Heavy dashed line indicates the mean of all samples.

Insert Fig. 13

Figure 13: Comparison of evolution of fatigue in paperboard under dynamic loading samples at for all pre-conditioning conditions. Heavy lines indicate mean values and light lines indicate the full envelope (max. and min.) of results.

Table 3 compares the mean relative natural frequency decay rate and estimated time to failure of the samples for each environmental condition and the applied loading. The time to failure is a nominal value and represents the time that would be required for the samples to have a 25% loss in natural frequency. The results show a 33% and 90% decrease in the time to failure for samples preconditioned to hot dry conditions and tropical conditions, respectively, when compared to samples conditioned at standard conditions. These values correspond to decay rates that are increased by 1.5 and 10 times, respectively.

Table 3: Comparison of mean relative natural frequency (f_n) decay rate and time to failure.

Condition	Relative f_n decay rate [%/s]	Time to failure [s] (Nominal: 25% reduction in relative f_n)
Standard	0.02	1250
Hot, dry	0.03	833
Tropical	0.20	125

Results - Modal Analysis

Since there appeared to be a dynamic effect causing the samples preconditioned to a hot, dry conditions to fail more quickly than those conditioned at standard environmental conditions, modal parameter extraction was performed on the data recorded during the settling period of each test. This data was selected because, at the low level of excitation, damage was not induced to the samples and variations in the systems' modal characteristics were unlikely. Table 4 presents the results from the modal analysis.

Table 4: Modal parameter extraction results (data from settling/low excitation level period).

Environmental Condition	Mean f_n [Hz]	Mean ζ [%]	f_n Envelope [Hz]	ζ Envelope [%]	No. of Boxes
60°C 15% RH	23.4	6.5	23.0-24.4	5.5-8.0	5
23°C 50% RH	23.7	9.9	23.0-25.2	6.5-11.5	4
38°C 85% RH	23.8	8.8	23.3-24.2	7.5-9.7	4

The results show that, although the damping ratio varied significantly for each test, on average damping was reduced for samples preconditioned in the hot, dry environment. The result also show that the initial natural frequency of the samples is largely unaffected by variations in climatic condition. This agrees with the results from the static tests which show similar stiffness values (gradient of the force deflection data) at the applied load (0.3 kN).

Discussion

Results for static and dynamic tests (including modal parameter evaluation) have been presented. The results for the static tests show a decrease in sample strength with an increase in the RH of the environment they are preconditioned in. This loss of strength is related to increased moisture content within the sample. As aforementioned, the results show a 12% increase in the load required to yield the samples once subjected to hot dry conditions when compared to samples conditioned at standard conditions, whereas, for tropical pre-conditioning the load reduces by 22%.

The results for the dynamic test show a dramatic (900%) increase in the rate of fatigue (loss of stiffness) for the samples preconditioned in a tropical environment. These results correlate with the static tests, although the loss of strength is much more pronounced for the dynamic tests. Ideally the static load for these tests would be reduced to allow for more progressive fatigue development; however, this may have meant that fatigue did not develop for the other samples. For the samples conditioned under a hot dry environment, there appears to be no correlation between the static and dynamic results. In fact, despite the increase in static strength (albeit small), the samples pre-conditioned in a hot dry environment had significantly reduced fatigue resistance (50% increase in fatigue rate) when compared to those preconditioned in a standard environment. It is expected that this is a result of the dynamic characteristics of the system. The system was designed to mimic the dynamic loads induced in stacked packaging configurations. When packaging is arranged to carry a load, the dynamic loads within the system are not only dependant on the excitation to the system (eg. vehicle vibrations), but also the modal characteristics within the packaging stack. The modal analysis performed showed that the samples preconditioned under hot, dry conditions had the lowest equivalent viscous damping ratio and that the natural frequency of the samples was not largely affected the environmental conditioning. The reduced damping means that the system's transmissibility at resonance (acceleration response compared to acceleration input) is increased, thereby increasing the dynamic loading in the system. These results have shown that, variations in the system's modal characteristics can increase the dynamic loading within stacked packaging and that an evaluation of packaging performance using static tests alone is not sufficient. These findings may help to explain the cause of packaging failures during surface transport in regions of the world where the climatic conditions vary significantly (crossing the equator) which may have otherwise been considered as accidents.

One outstanding issue in the research is that the fatigue testing was not performed in an environment which matched the pre-conditioning other than for the samples pre-conditioned in a standard environment. This is particularly significant for the samples pre-conditioned in a hot, dry environment as the samples re-gained approximately 32% of the weight (moisture content) lost as a result of the pre-conditioning within 1000 seconds (approximate duration of the fatigue tests). In the same amount of time the samples pre-conditioned in a tropical environment lost approximately 14% of the weight gained as a result of the pre-conditioning. In saying this, the lack of a controlled environment is not anticipated to affect the findings discussed herein.

Conclusion

For practical reasons, it is often convenient to evaluate the performance of protective packaging using static tests alone, despite the fact that, during distribution, the packaging will generally be subjected to dynamic loads.

This paper presents the results from the analysis of empty corrugated paperboard containers. The containers were preconditioned under standard, hot and dry and tropical conditions and subsequently subjected to static and dynamic loads and their strength and fatigue resistance recorded. The results showed that, when packages are arranged such that they carry a load (i.e. a stacked configuration) static tests alone cannot be used as an indicator of resistance to fatigue and that dynamic tests are required. The lack of correlation between the static and dynamic test was suggested to be a result of the variation in internal damping of the packaging, more specifically an increase in dynamic loads as a result of reduced damping.

The results were also able to support existing literature, in that with an increase in moisture content, the static strength of the paperboard samples was reduced.

Further work which studies the evolution of fatigue within a controlled environment is required to complement this research.

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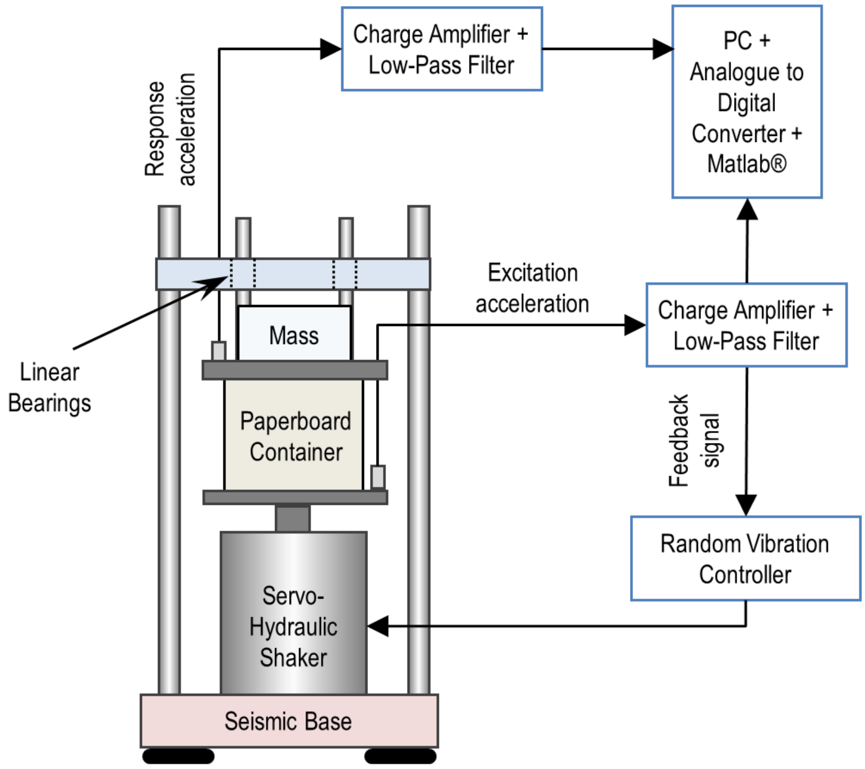

Figure 1: Experimental layout for dynamic (vibration) testing.

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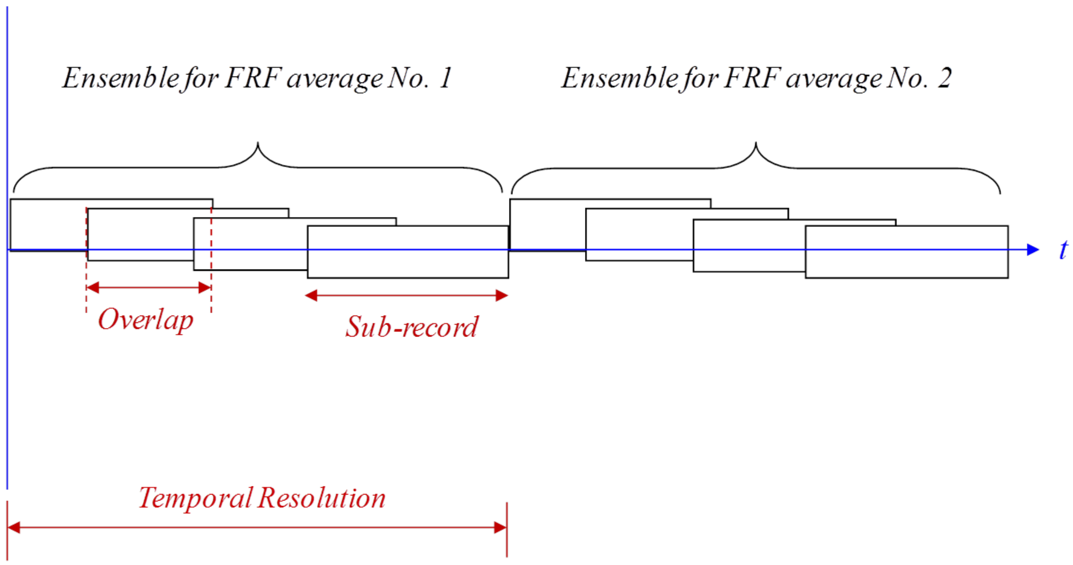
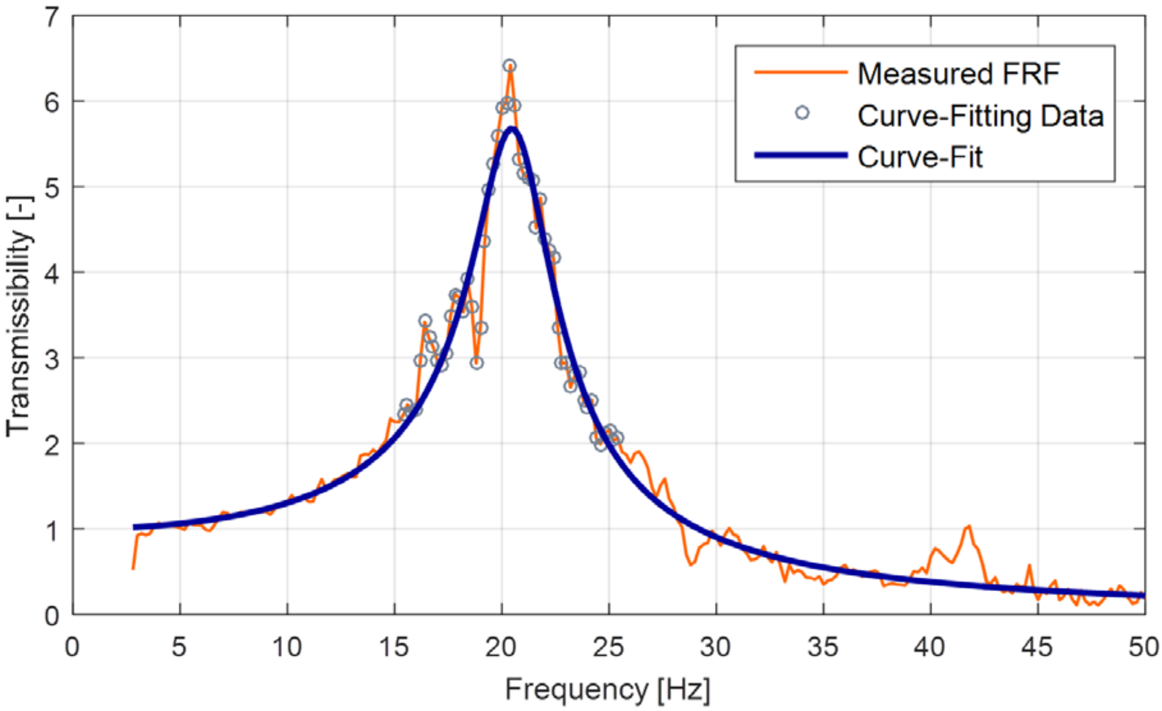


Figure 2: Schematic for post-processing tool.



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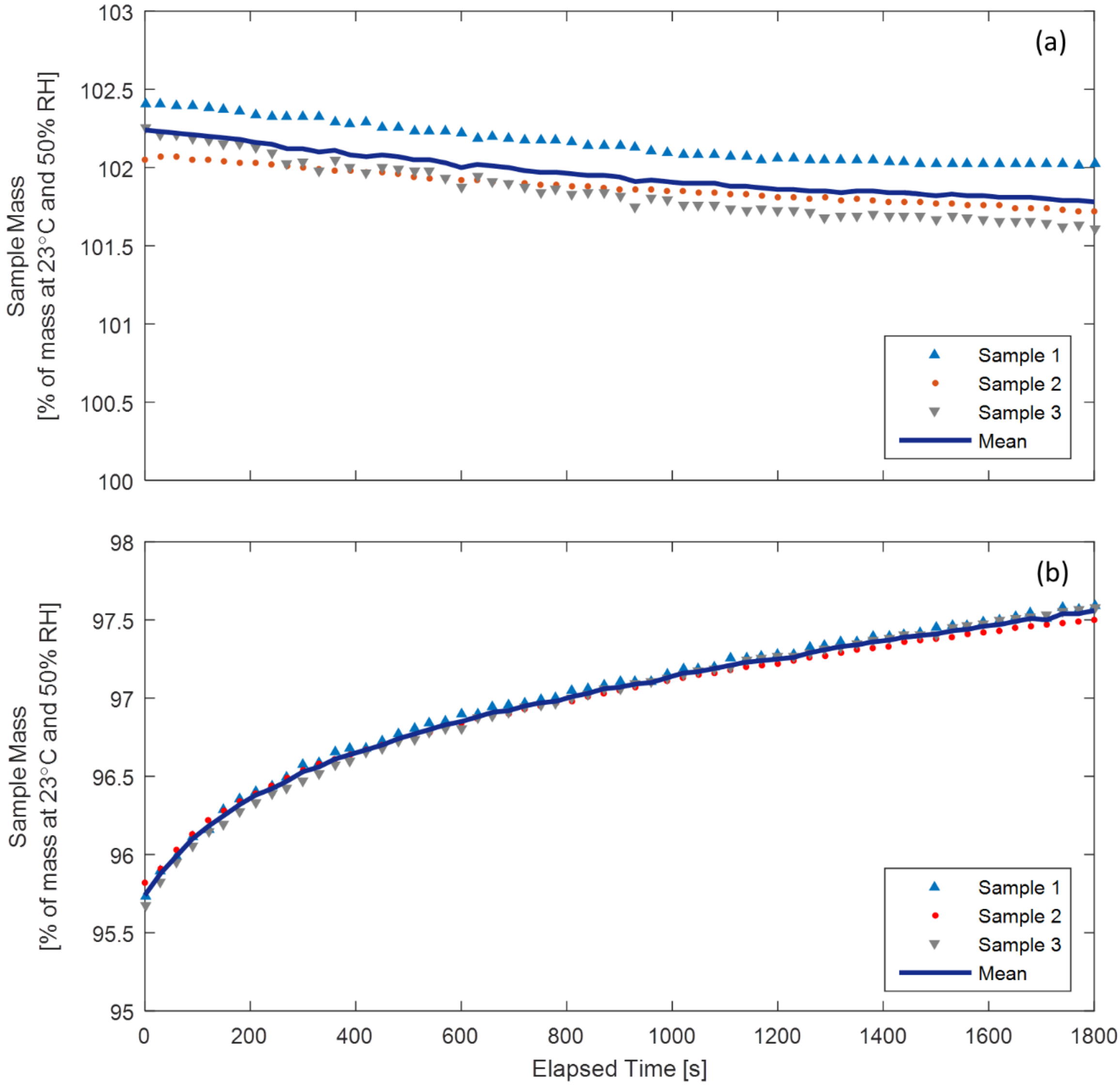

Figure 4: Sample weight change at ambient laboratory conditions (a) Tropical preconditioning (b) Hot dry preconditioning. Solid line indicates the mean of all data.

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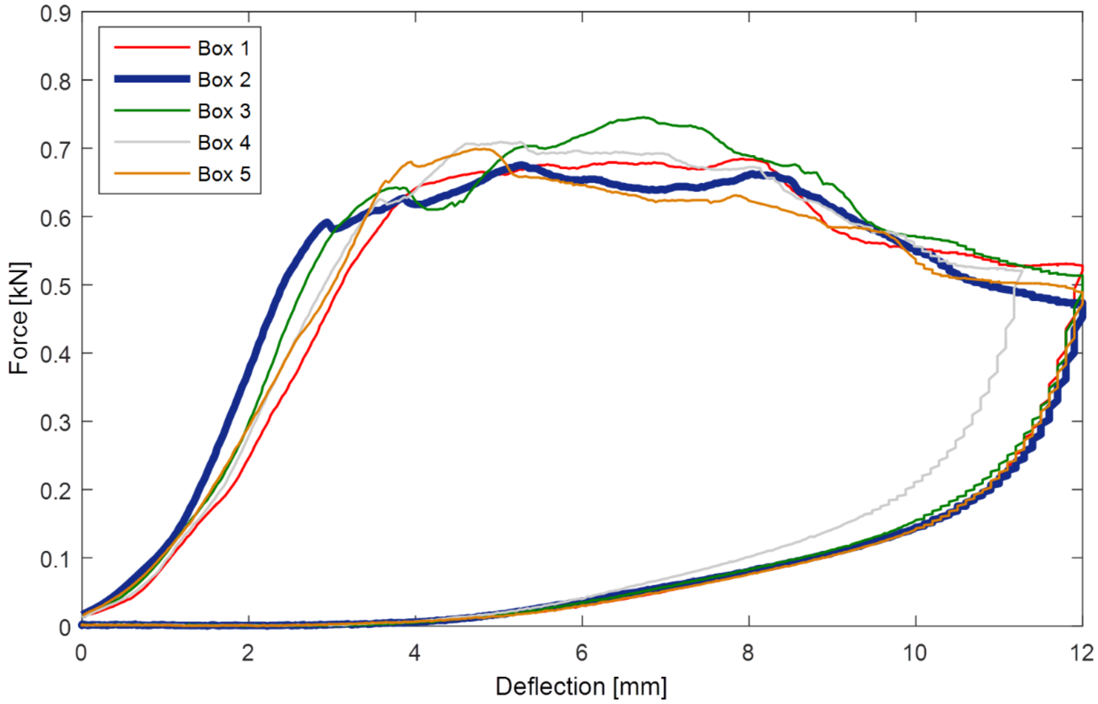

Figure 5: Compression characteristics of samples preconditioned under standard conditions (72 hrs).

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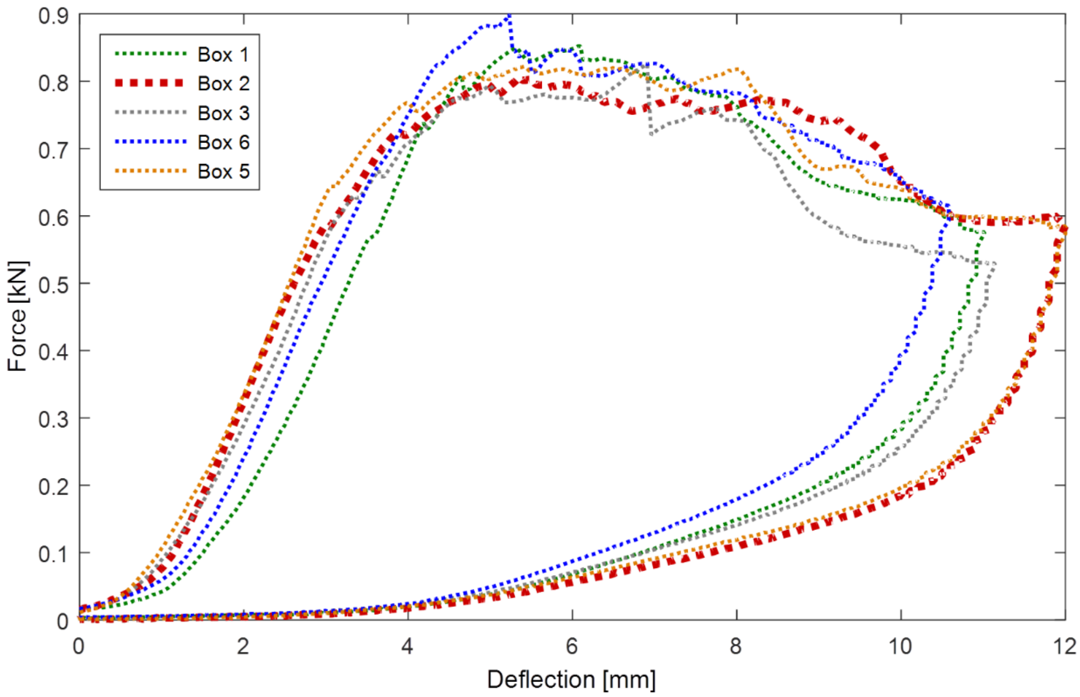


Figure 6: Compression characteristics of samples preconditioned under hot dry conditions (72 hrs).

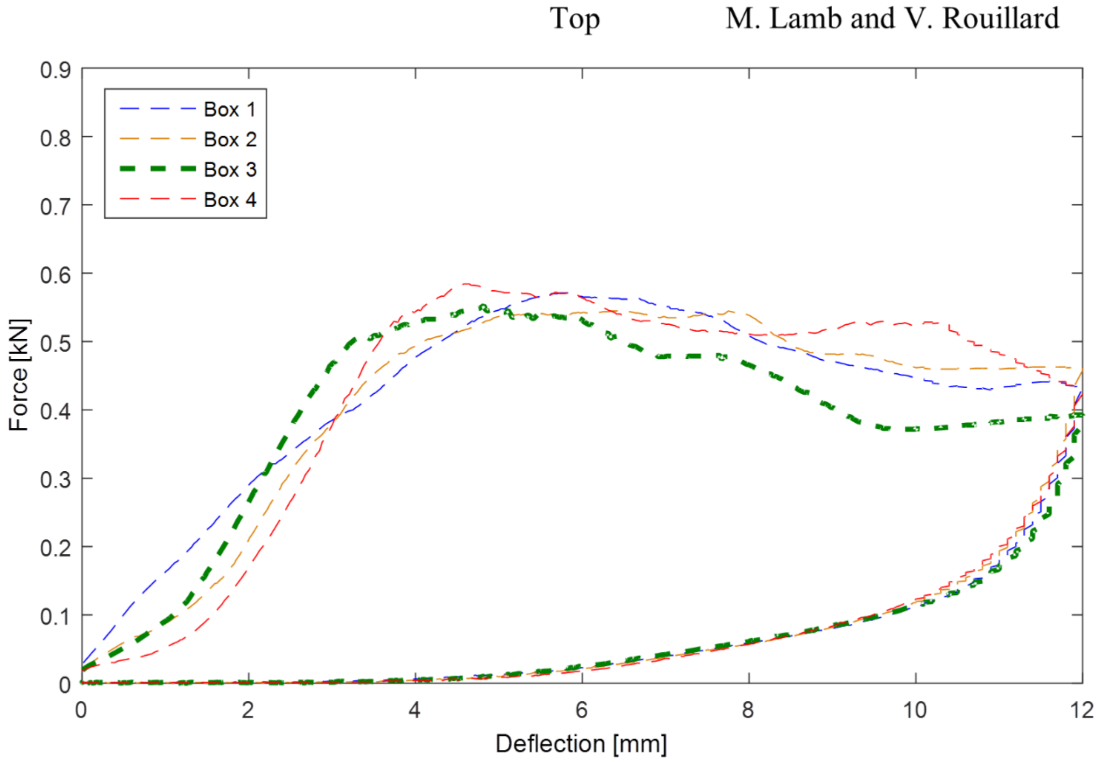
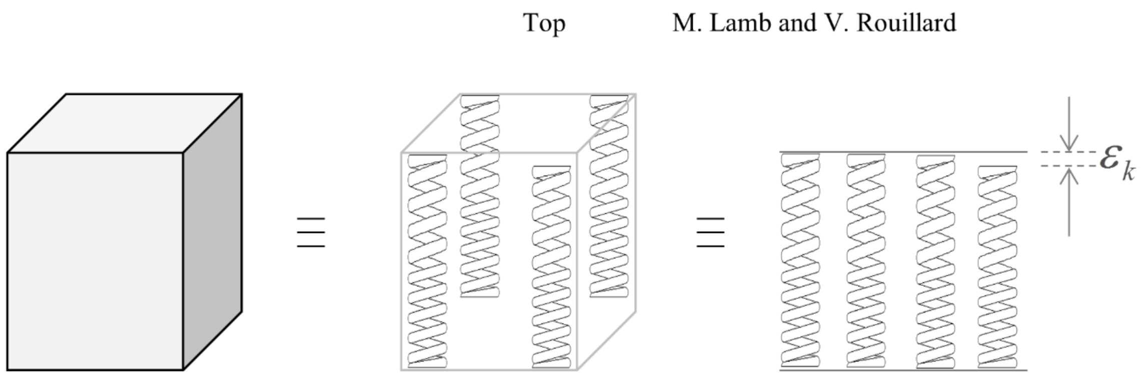


Figure 7: Compression characteristics of samples preconditioned under tropical conditions (72 hrs).



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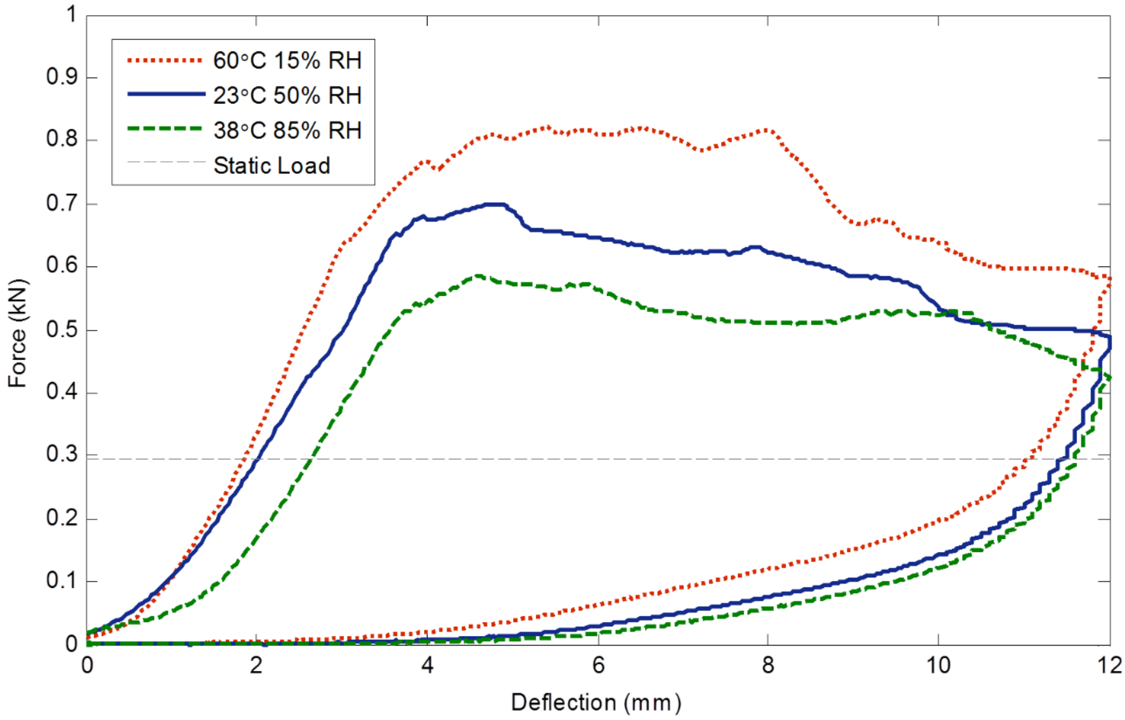


Figure 9: Typical compression curve results for paperboard samples. Vertical dashed line represents static load applied for dynamic (vibration) testing.

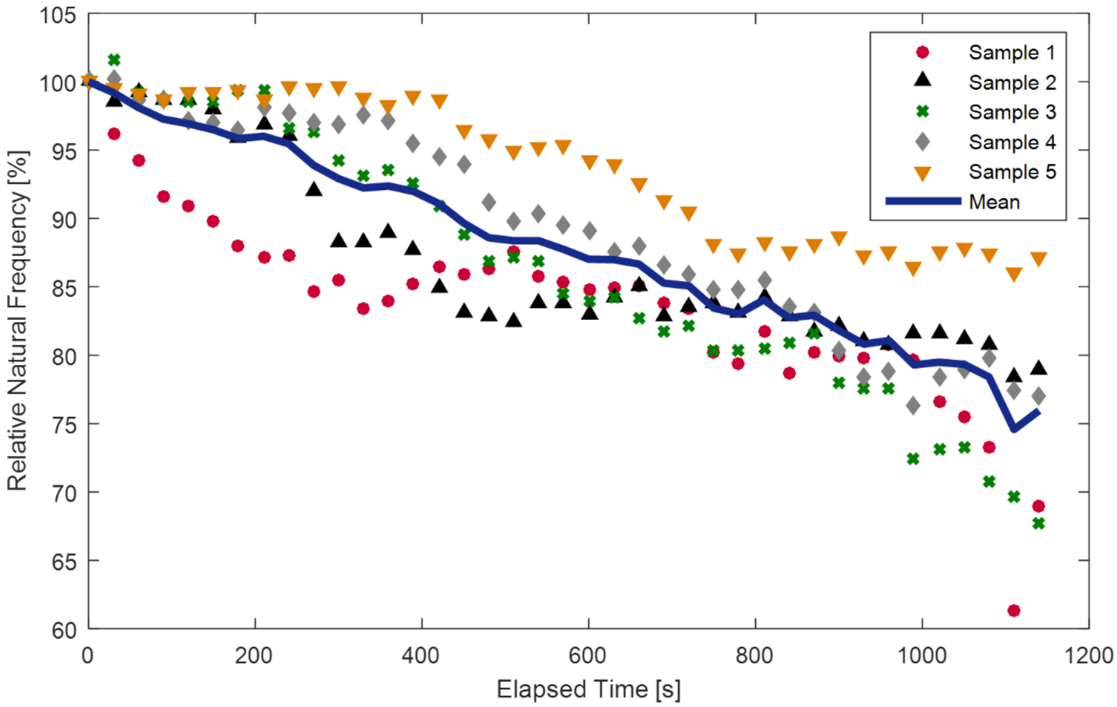


Figure 10: Evolution of fatigue in paperboard under dynamic loading samples pre-conditioned at 23°C and 50% RH (standard conditions). Solid line indicates the mean of all samples.

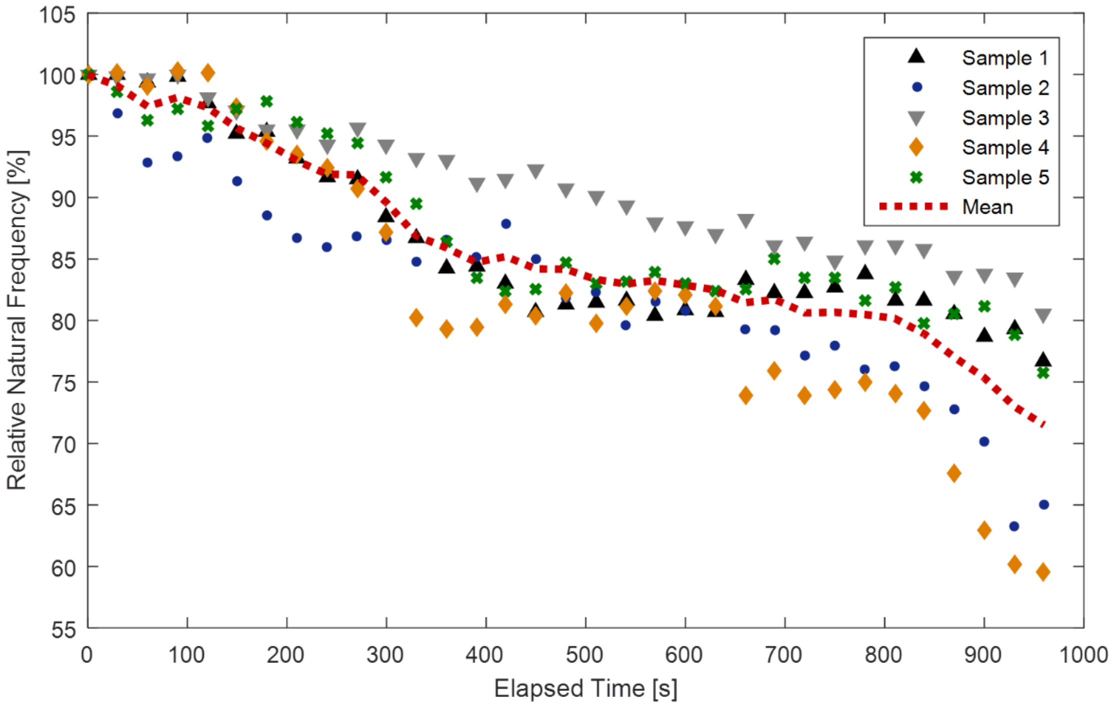


Figure 11: Evolution of fatigue in paperboard under dynamic loading samples pre-conditioned at 60°C and 15% RH (hot dry climate). Heavy dotted line indicates the mean of all samples.

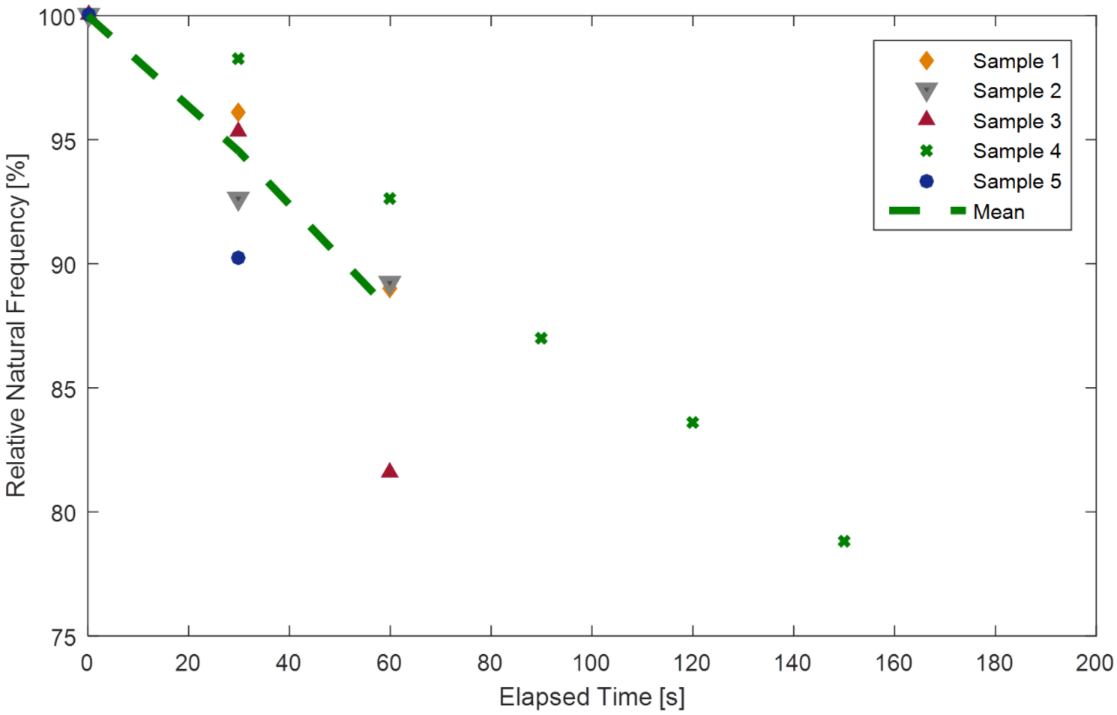
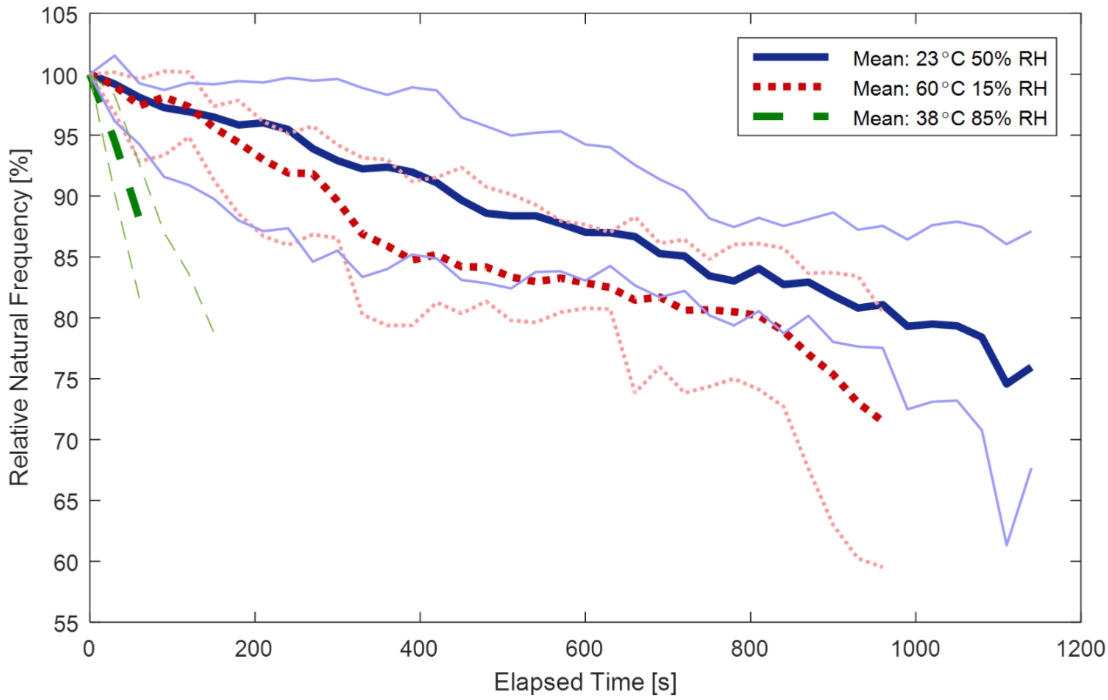


Figure 12: Evolution of fatigue in paperboard under dynamic loading samples pre-conditioned at 38°C and 85% RH (tropical climate). Heavy dashed line indicates the mean of all samples.



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