Fatigue analysis of an asymmetric composite structure composed of dissimilar materials

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Abstract

The use of composite materials, in particular sandwich structures, has increased in recent decades in various areas and industries. In turn, its increasing use has led to the innovation of the materials sector and new compounds consisting of dissimilar materials are being tested more and more.

This paper aims to analyse the flexural fatigue behaviour a composite structure composed by 2 dissimilar materials: a rigid face (stone) and a viscoelastic core (cork), while varying the testing temperature, under fatigue. For this purpose, a proposed methodology for fatigue tests is given so that an assessment of the behaviour of the material can be conducted by means of stiffness and deformation evaluation, while taking into account temperature influence.

The results show that the material’s viscoelasticity behaviour is of most importance when validating the test methodology. Furthermore, regarding the material’s behaviour under fatigue, it was observed that increasing the temperature decreases the stiffness of the material as well as its fatigue life and that stiffness increases over the cycles and the material fails mainly due to an excessive displacement. Moreover, there is no dependence on the initial test load.

Keywords
Composite materials, sandwich structures, viscoelastic core, fatigue, temperature influence

Introduction

Sandwich materials are becoming more complex due to the use of new demanding requirements imposed by most engineering areas. Its main advantages such as high stiffness, good fatigue resistance and low weight ratios tend to be improved. However, in some fields these features are also linked with design and aesthetical appearance, originating composite materials that use uncommon materials such, for instance, cork cores and stone, mostly employed in the case of coatings and flooring areas. In order to use these materials is necessary to have the knowledge about its behaviour and properties under certain loading conditions, as well as understanding their intrinsic failure mechanism.

More than its behaviour under static conditions, it is the analysis of the behaviour under cyclic conditions and determining the fatigue life limits that represent the great challenge of a great majority of composite structural characterization, taking also into account that there are no standard methodologies to follow. Many works have been made in an attempt to predict fatigue behaviour of composite materials, but most of them require a
huge amount of tests and specimens, instead of a
generalized knowledge about the material
properties, as well as time, and are based in
statistical methods such as the Weibull distribution
or analytical ones that rely on S-N curves
approximations, stiffness reduction or strength
reduction and cumulative damage [1]. More over,
there are no standard procedures that guide any
fatigue test and so most of the work normally
conducted envisages only to verify the influence of
essay parameters such as frequency, load conditions
and temperature. The fundamentals of sandwich
constructions and reviews of experimental and
analytical methods are described by Allen [2].
Stiffness reduction is suggested to be a good
indicator of damage for many composite structures
since it is an accurate method, easy to measure and
interpreted, directly related with the microscopic
damage that can be monitored non-destructively
[3]. Furthermore, stiffness presents a greater change
during fatigue early stages, tending to stabilize with
the increase of the number of cycles where only
small changes occur [4]. Regarding the essay
parameters, several publications have reported that
increasing frequency has a detrimental effect on the
fatigue life of sandwich composites due to the
conforming increase in core temperature, that
leads to deterioration of core shear properties [5]. In
the other hand, Kanny and Mahfuz [6] have
published a contradictory view where it has been
concluded that for glass/vinylester sandwich
constructions with close cell PVC foam cores the
higher the frequency, the greater the number of life
cycles. The explanation given was based on the
concept that energy input is equal to energy
dissipated plus energy stored and so, considering
that the energy/work input is constant for any
frequency, if with an higher frequency we do reach
an higher core temperature, less energy is left
stored to fuel the damage process. Regarding load
conditions, most of the fatigue testing work
involves constant amplitude sinusoidal loading
tests, although composite structures are rarely
subjected to uniform constant amplitude loads in
service, Harris et al. [7] studied the effects of block
loading conditions in carbon-fibre-reinforced
laminates and showed that it leads to significant
reductions in total fatigue life. Relatively to
temperature, previous work has shown that at
elevated temperatures the degradation of the core
increases, thus reducing fatigue life of the
component [8].

The aim of the present study is to evaluate the
flexural fatigue life behaviour of a laminate
sandwich structure composed by glass fibre, core
cork and stone under a proposed cyclic test method,
as well as intends to evaluate the temperature
influence thus contributing to develop a standard
test method for this these family of materials.

Material

In the present analysis, a sandwich structure is
tested. The material is composed by two dissimilar
materials that are bond together through a fiberglass
reinforcement. Those consist in a hard and brittle
material (stone) and in a viscoelastic material
(cork), which are arranged so that the loadings
incurred under its service environment request the
overall material in a way that the hard and brittle
material is always under compression, as
demonstrated by Figure 1.

Production of test specimens was carried out by
hand lay-up under controlled environment
conditions and with the specific materials.

![Figure 1-Sandwich structure scheme.](image)

Rigid material
Viscoelastic material

Adhesive
Adhesive
**Experimental model**

The following experimental analysis will be made taking into account the four point bending standard ASTM C393, through which it will be possible to evaluate in a qualitative way the evolution of the structure’s behaviour and its mechanical properties. For this purpose, it is also proposed a fatigue test method capable of allowing the analysis of specific parameters, which reflect the cumulative damage, as well as the influence of load variations and temperature over time under cyclic conditions.

The tests were then conducted developing a method using a mixed controlling system; a simultaneous load and machine displacement control where the maximum load and the displacement between extremes were defined. Further, every 100,000 cycles an increase of 10% of the maximum static load (MSL) was applied, until the maximum fatigue load equals the maximum static load. Also, different initial loadings were tested in order to verify the influence of it in the material’s fatigue life, 50%, 60% e 70% of MSL were the values used and are for now on defined as tests E1, E2 and E3, respectively. All the tests were conducted at a frequency of 10 Hz, using constant displacement amplitude of ±1 mm. These test conditions were repeated under three different temperatures: room temperature, 45°C and 75°C.

Experimental procedure was executed in a servo-hydraulic machine Instron 8800 with a temperature-controlled chamber Instron 3119-006, Figure 3. Figure 4 illustrates the supporting scheme. All the tests with higher temperature were started after as heating stabilization time of the specimen of one hour.

![Test setup](image)

**Figure 3**-Test setup.  **Figure 4**-Test support distances where \( L_2 = 180 \text{ mm} \).

**Results**

**Quasi-static tests**

Monotonic tests at room temperature were made in order to define the reference value for the fatigue tests, namely MSL. Results obtained can be observed in Table 1.

**Table 1**-Monotonic test at room temperature results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. load (N)</th>
<th>Max. displacement (mm)</th>
<th>Apparent stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#40</td>
<td>2595</td>
<td>15,27</td>
<td>151,5</td>
</tr>
<tr>
<td>#45</td>
<td>2404</td>
<td>12,80</td>
<td>192,1</td>
</tr>
<tr>
<td>#50</td>
<td>2175</td>
<td>13,00</td>
<td>151,6</td>
</tr>
</tbody>
</table>

Further, an assessment of the influence of temperature was made so it would be possible to predict some consequences on the materials.

![Example scheme of the fatigue test proposed](image)

**Figure 2**-Example scheme of the fatigue test proposed.
behaviour under fatigue at higher temperatures. The results of those are found in Table 2.

<table>
<thead>
<tr>
<th>Temperature (ºC)</th>
<th>Max. load (N)</th>
<th>Max. displacement (mm)</th>
<th>Apparent stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room</td>
<td>2595</td>
<td>15,27</td>
<td>151,5</td>
</tr>
<tr>
<td>45</td>
<td>2428</td>
<td>14,27</td>
<td>155,4</td>
</tr>
<tr>
<td>75</td>
<td>2253</td>
<td>16,20</td>
<td>125,8</td>
</tr>
</tbody>
</table>

It is concluded that for higher temperatures near glass transition of the adhesive layer, 75ºC, there is a decrease in the apparent stiffness of the material, as well as there is a decrease in the maximum load of the material. Other tested temperatures, room temperature and 45ºC, had similar results.

In order to proceed for the fatigue testing, it was considered the MSL as the minimum maximum static load observed at room temperature and so the reference parameter MSL takes a reference value of 2175 N.

**Apparent stiffness evolution**

The graphs represented in Figures 5 and 6 correspond to the variation of the apparent stiffness for E1 tests at all the temperatures and the evolution of apparent stiffness at 45ºC for the entire different initial loads, respectively.

![Figure 5](image1.png)  ![Figure 6](image2.png)

From the analysis of the Figures 5 and 6 the following conclusions can be reached:

- With increasing temperature there is a slight but still evident decrease in initial apparent stiffness. Although this stiffness can not be compared with the calculated in the quasi-static four point bending test, because despite having the same unit, it results from calculations and measurements of a different methodology;
- The apparent stiffness tends to increase gradually over the cycles due to the fact that the viscoelastic core is constantly loaded and becomes increasingly compact, thereby resulting into an increase of the apparent stiffness of the material;
- The apparent increase in stiffness over time and between each step does not appear to be influenced by initial load or by the test temperature.

The analysis results show that, as expected from the static test, there is a decrease in the apparent stiffness with temperature. However, contrary to what was observed previously, reduction is evident at the three different temperatures, where before there was only a significant reduction for testing at 75 ºC, the Tg of the adhesive layer. Meaning that the temperature influence on the apparent stiffness of the material appears to be more evident in fatigue that in quasi-static tests, even for elevated temperatures that are not near the Tg.
Strain and recoverability

For viscoelastic materials, recovery depends not only on the type of load, but also on the frequency applied and, if there is not enough time between successive cycles, so the material entirely recovers, it accumulates a permanent deformation throughout the test, which tends to grow with time. Note that this permanent deformation during the test is not the same as that after the discharge of the same.

Figures 7 and 8 intend to analyze this effect and to understand how this can be influenced in the fatigue test.

- With increasing temperature there is a greater permanent deformation associated with the fact that the total strain in the first load level is greater;
- The recover effect tends to decrease over time with increasing applied load, keeping the same behaviour when the material is subjected to constant load, i.e., within each level;
- "Jumps" between levels appear to have very similar values regardless of the initial test load, and tend to decrease for the higher load levels. Considering temperature, there have been greater changes between steps at 75°C than at 45°C or at room temperature, with the latter two cases very similar to each other.

The decrease of recovery capacity with temperature is consistent with the fact that the apparent stiffness in fatigue also decreases with increasing temperature. At higher temperatures the material undergoes a greater deformation, resulting in a lower percentage of full recovery at each cycle, since it has a greater deformation with the same space of time between cycles to recover. For the same reason there is also a decrease in recovery capacity with increasing load. In relation to the increase of permanent deformation throughout each step, this results due to the fact that in each cycle the sample does not fully recover, there is always a remaining flexural displacement that after new request tends to increase because, although the same load is applied, the displacement is added to the remaining deformation amount, resulting in a higher total strain. In respect of transition discrepancies between levels, their tendency to decline over the test is influenced by the increase in apparent aforementioned stiffness. Regarding the influence of temperature, one should note that for 75 °C there are larger shifts between levels, while for the remaining temperatures the material behaviour is identical.
Consider also the detailed analysis of the 70% of MSL level for the two specific cases illustrated in Figures 9 and 10.

- Relatively to the influence of temperature in the same level, tests at 75°C appears to have a higher rate of displacement than the tests at room temperature and 45°C, which have identical evolutions;
- For the same level, it should be noted that there is a trend toward greater displacement rate if the level is the first level of the fatigue cycle, otherwise the displacement rate does not appear to be influenced by the initial charge.

Findings from the detailed analysis of the levels of 70% of the MSL are consistent with what was observed up to this point. The deformation rate within each level is equivalent to the recovery capability of the material therein and is larger at 75°C and similar for the room temperature and 45°C, although the total displacement is different for the three temperatures. Relatively to the higher cumulative deformation rate in the first level of the fatigue cycle, compared to the deformation of the same level as the second or third step of the test, this may be due to the fact that, as mentioned above, there is a compression effect of the viscoelastic, having it greater deformations when it is less compressed and, therefore, having also a lower recovery. While at certain levels, when the load is not the initially applied, the viscoelastic material can already be compacted so that the evolution of the curves is identical because the compaction effect in no longer relevant.

**Failure**

Regarding material failure, the Table 3 summarizes the failure level of all the trials.

<table>
<thead>
<tr>
<th>Test</th>
<th>Room Temperature</th>
<th>T=45°C</th>
<th>T=75°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>90%</td>
<td>90%</td>
<td>70%</td>
</tr>
<tr>
<td>E2</td>
<td>90%</td>
<td>80%</td>
<td>70%</td>
</tr>
<tr>
<td>E3</td>
<td>90%</td>
<td>80%</td>
<td>70%</td>
</tr>
</tbody>
</table>

Analysing the results presented in Table 3, it is not clear a relation between the initial load and the fatigue life of the material. In fact, one can conclude that the fatigue life is not dependent on the initial load of the tests.
Regarding the point at which the failure occurs, Figure 11 illustrates the results for room temperature. This result is equivalent to what occurs on tests using the remaining temperatures.

- The maximum permissible force, and the maximum displacement are lower than those observed in the monotonic four point bending test to any temperature;

- The final displacements tend to be higher with decreasing initial load.

The effect of compression due to the cyclical load causes the testing machine support claw to penetrate less into the cork and so, its advancement corresponds to a greater bending of the specimen, which results in a fracture with a lower corresponding total displacement, opposite to what occurs in static tests, in which the initial advancement of the piston of the machine only penetrates the core and do not contribute in the same way to increase the bending of tested material. On the other hand, the initial load influences the degree of compression of the core, and the higher its value, the more it will be compressed in the initial cycles, corresponding to a greater compression and in a lower displacement of the machine.

Relatively to failure modes, Figures 12 and 13 illustrate the differences between the failure after a cyclic and a monotonic test. Both conducted at room temperature and represent of the overall sampling results.

In the monotonic test failure, higher stresses on the load application point on the rigid face, which is a brittle material, leads to the formation of an initial crack in this area. The resulting cracks tend to propagate up to the adhesive interface, which helps to stop the crack growth in the transverse direction to the material, and towards the extremity of the test specimen, Figure 12.

The failure upon cyclic application appears to be more complex due to the existence of a larger amount of visible damage of the structure, where it is possible to observe not only the failure of the facing material but also the core (Figure 13). In fact, although there is no way to proof the sequence in which the damage mechanisms are initiated, it is logical to say that the first cracks are formed, as in the static test, in the load application zone on stone, spreading in the same manner. The remaining cracks in other stone points are a result of the compression in that face and of the reverse bending suffered at the end of the specimen, which are also likely to occur in static test. The large difference is the extent of damage occurring in the core material. After the initial cracking reaches the adhesive interface, sharped stone flaws are initiated near it. The cyclic test makes that each time the material is required, the rigid face is subjected to compression,
causing the edges to penetrate the adhesive layer, and core, having a cutting effect that ultimately create a transgranular crack that propagates towards the bottom face and the end of the specimen. It should be noted that penetration of the rigid face does not cause the failure of the first resin layer, only the core, and this becomes the factor responsible for maintaining bonding of the various elements of the material after the test.

Regarding the influence of temperature on the fatigue life of the material, it is concluded that it has negative effect and, therefore, the higher the temperature the lower the number of cycles that the material will withstand without breaking.

**Conclusions**

A study was conducted to provide an assessment on the behaviour of a sandwich composite structure composed by two dissimilar materials, a rigid face and a viscoelastic core, under fatigue. For that purpose a fatigue methodology has been proposed and used and the following results were achieved.

The apparent stiffness of the material tends to increase over time due to the fact that the viscoelastic material experiences a compression effect, this increase is independent of the initial loading and the increase in temperature decreases the apparent stiffness of the material under fatigue conditions;

Recover effect tends to decrease over time with increasing applied load, and within each level of MSL because the material undergoes a higher deformation and still has the same recovery time between cycles. The existing variation between each level does not seem to be influenced by the initial load. Regarding the influence of temperature, it was observed that its increase has led to increased deformation for the same load value, which is justified by the fact that there is a decrease of apparent stiffness with temperature. Moreover the variations between levels proved to be superior when the temperature 75°C;

For the same load level, it was observed that a higher rate of permanent deformation took place for the temperature of 75°C, while the results were identical between the remaining temperatures. The transition discrepancy to the same level was also higher when this was the first test level, not being observed a dependency of the initial test load to other situations than the previous one;

Regarding test specimen failure, initial loading has no influence on the point where it occurs, unlike temperature, it was showed that the higher the latter, the lower the fatigue life of the material;

For the same temperature, the material failed under approximately the same machine displacement and for the overall results this value was always between 8 and 10 mm;

Comparing the fatigue behaviour with the static tests, it was concluded that the maximum permissible load and the maximum displacement were smaller in cyclic conditions due to the fact that under fatigue exists a compression effect of the viscoelastic material that does not happen in quasi-static tests. Further, in the latter tests, there is a displacement component that corresponds to a penetration of the supports on the viscoelastic material that does is not happen in fatigue and so, the final displacements tend to be smaller in fatigue and by increasing the initial load of the test;

Failure modes were similar among all the tests carried out and distinguished from failure static
tests due to the fact that the cyclic loading instils a spread of damage to the structure’s core, creating a transgranular crack that propagates towards the bottom resin layer and the end of the specimen.

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**References**