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Warp yarn damages prediction regarding to the evolution of yarn tension during 3D weaving process

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Abstract. Interlock weaving process is still difficult to manage and lead to significant damages on warp yarns, causing a serious loss of mechanical properties on the final composite, and affecting the good execution of the process. The aim of this study is to have a contribution to 3D weaving process optimization, regarding to yarn-to-yarn friction. To predict damages due to this friction, evolution of warp yarn tension can be a good indicator. Firstly, evolution of the yarn tension during a weaving cycle has been precisely analysed. Then, great differences of tension have been highlighted, function of types of crossing. Specific yarn crossings generate very high peaks of tension on the studied yarn, leading to severe damages until yarn breakage. A significant difference has been noticed between the polyester and glass investigated yarns. The study shows the evolution of tension can be helpful for process monitoring and optimization. Nevertheless, in order to anticipate yarn damages, a direct measurement of yarn interactions has to be developed.

Keywords: yarn damages, yarn friction, tension, weaving process.

1. Introduction

Woven reinforcements for high performance composite applications are already widespread in several domains mostly as replacements of former pieces made of steel or aluminium alloys. Woven composites are particularly used in aeronautic industries, like military and commercial aviation, thanks to their great mechanical properties and their ability to make pieces of complex shapes [1, 2]. In order to stay competitive with other materials, composites have to be robustly manufactured. Textiles processes such as weaving, give a large diversity of 2D or 3D dry preforms which are perfectly compatible with composite production. 2D fabrics are the first kind of fabrics used for composite reinforcements, different layers of fabrics are assembled in a stratified structure to form a composite piece. Stratified composites are quite easy to manufacture but have a major drawback due to their structure, which is delamination between layers. Delamination is a serious threat leading to composite breakage, therefore solutions were found to reduce this weakness. 3D woven composite is a good option to avoid this issue, which explains their fast growth. Many studies have presented a comparison of mechanical properties between 2D and 3D. In almost all cases 3D woven reinforcement have showed better properties. Mouritz *et al.* presented that 3D woven composites have better mechanical properties than 2D reinforcement composites such as ballistic damage resistance, impact tolerance resistance, tensile strain, and interlaminar fracture toughness [2]. Ding *et al* found also that 3D composites have greater performance in fatigue behaviours than 2D structures [3].

It exists many ways to weave 3D fabrics, one of the most common is 3D interlock process, which have the advantage to be employed on a conventional weaving loom. In this study, we are focusing on 3D warp interlock weaving, in which some warp yarns link several or all layers together [4]. Interlock weaving process is not fully managed yet and leads to significant damages on warp yarns, causing a serious loss of mechanical properties on the final composite and impacting on the good execution of the process [5, 6]. Many studies have been performed about the effects of friction between yarns and weaving loom elements on mechanical properties at different scales. L. Lee *et al.* worked on the effect of weaving process on the

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tensile properties of glass yarns woven reinforcements composites. No significant effect have been noticed on tensile stiffness of yarns, but a 30 % decrease of the tensile strength value of dry woven yarns has been observed [7]. In the same document, they observed warp yarns breakage due to friction against loom elements. Rudov-Clark *et al.* preconized to cover loom machinery with wear-resistant coating to reduce abrasion damage [8]. Lefebvre *et al.* investigated the loss of mechanical properties on para-aramid warp and weft yarns [9]. The study showed that warp yarns are more impacted than weft yarns, and interlock pattern also has an influence on the loss of properties.

It was shown that Warp yarn damages during weaving process impact the reinforcement quality, but only few studies had investigated the causes, and even less presented results on yarn-to-yarn friction. Decrette *et al.*, presented an optimization strategy based on warp yarns degradations count during a weaving process, and proposed to reduce yarns damages by using Jacquard UNIVAL 100 parameters [6]. The aim of this study, is to make a contribution to 3D weaving process optimization and monitoring, regarding evolution of warp yarns tension during weaving process. Yarn tension is linked to several parameters such as yarn-to-yarn interactions, yarn wear or fibres breakage, moreover, this parameter is quite simple to measure during the process. A specific pattern has been designed and woven to induce different kinds of yarn-to-yarn interactions, and yarn tension has been analysed during this process to confirm if it is relevant as a good indicator for damage prediction.

2. Materials and methods

2.1. 3D weaving process

Experiments have been performed on a sequential weaving loom fitted out with a Jacquard machine shedding device. The shedding system is a UNIVAL 100 working with several individual motors where each one drives a Jacquard string. Therefore, each motor is linked to one yarn and controls its movement and position. This mechanism offering lots of possibility in pattern design, appears to be really appropriate for 3D weaving. To let each yarn evolves independently, a 512 bobbins creel is used in our case. The weaving loom has other characteristics like:

- Weft insertion with unilateral rapier
- Rectilinear reed movement,
- Horizontal take-up,
- 16 yarns per reed dent,
- 1.5 mm of space between reed dent

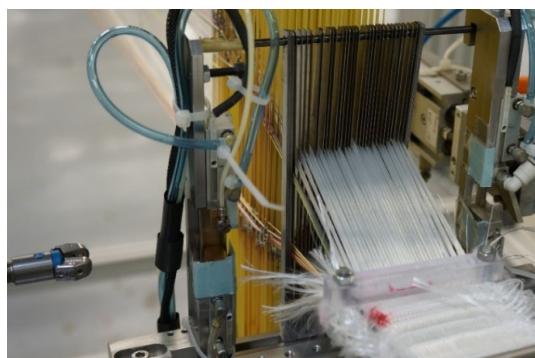


Fig. 1: Weaving machine loom.

The aim of this part is not to weave a specific interlock fabric but to investigate different types of crossing interactions between yarns during that kind of process. A test pattern has been done to scan a sample group of nine crossings and determine their effects on the yarn tension value and evolution in time. This weave pattern is presented in figure 2, it has been designed regarding 16 yarns of the same reed dent

corresponding to a single harness column, to be sure that yarn to yarn interactions are generated during a

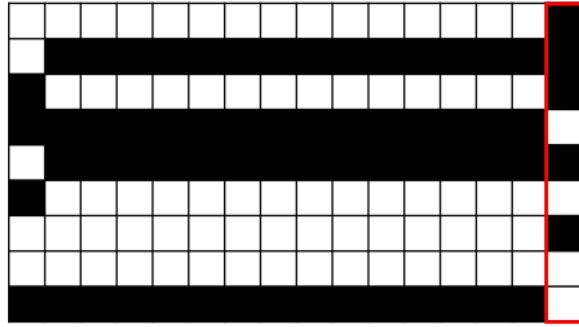


Fig. 2: Test weave pattern.

measurement.

The red frame, in figure 2, indicates the evolution of the studied yarn, which is connected to a tensiometer. In order to contribute to process optimization and monitoring, crossings could be classified function of their impact on the measured yarn tension. Crossings can be depicted by other graphical representations, as it is illustrated on figure 3. In this representation, red circles and red arrows represent respectively the studied yarn and its movement, bold grey arrows show the movement of the whole other yarns of the column and small grey arrows the movement of a single yarn which is not the studied one. Experiments has been performed on two different yarns:

- 170 tex,PET yarns
- 600 tex E-glass yarns,

PET and glass yarns have very different mechanical behaviours, like brittleness which is interesting to

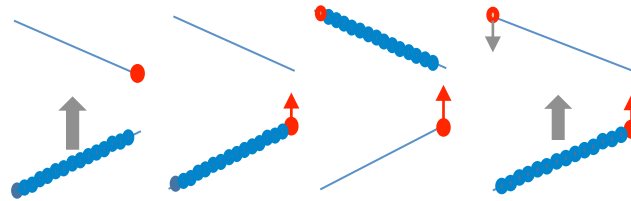


Fig. 3: Few crossings from test pattern on lateral harness view.

compare on tension evolution.

2.2. High speed camera

The sequential organisation of the weaving loom implies that only one machine element is working at a time, and waiting times isolate each sequence. Waiting times were unfortunately unknown and not editable, but are essential to understand the global machine time line. High speed camera has been used to define precisely all machine movement and the sequences duration. This study is imperative to know which stage happens at what time. This information is used for tension evolution analysis.

Table 1: Weaving machine time line

Stages	Mean time (ms)	Standard deviation (ms)	Variation coefficient
Beat up	107.5	1,7	1,5%
Dead time	57.37	6,1	10,5%
Shedding	153.71	8,7	5,6%
Dead time	135.02	6,8	5,0%
Back reed movement	234.80	8,3	3,5%
Whole 3 stages	688.40		
Remaining part of cycle	1252.	7,0	0,6%

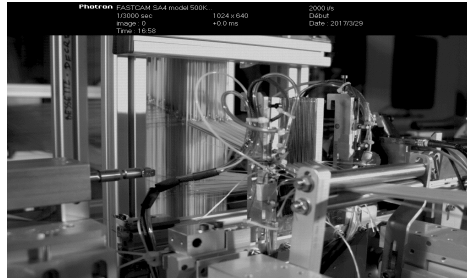


Fig. 4: Screenshot from camera recording.

Weft insertion stages do not affect warp yarns interactions, no friction happens at that time, this is why those stages are not taken into account in table 1. Figure 4 presents a screen shot of a camera recording.

2.3. Yarn tension measurement

Warp yarn tension is an easily measurable parameter on a weaving loom, and possibly useful for process management. In this study, a 0-10N range tensiometer has been placed on the machine, between harness back and in front of the condensation slab, which makes a geometrical link between creel dimension and harness. Figure 5 is an illustration of the set-up; the arrow shows the tensiometer.

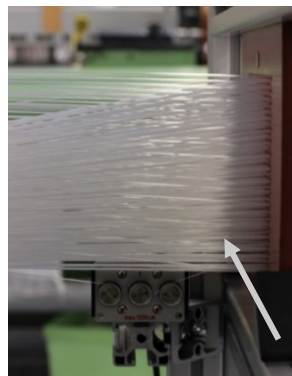


Fig. 5: Tensiometer position.

Preliminary studies have been hold to make sure that tensiometer position does not interfere in the weaving process, and does not create new friction surfaces between yarns. This way, tension is measured continuously during the process, and can be correlated with high speed camera images. Thereby, every tension variation or peak is associated to a machine stage. Tension value is determined for every crossing and its evolution in time is measured. Tension function of time curves give some information:

- Which kind of stage impacts the most yarn tension?
- Which kind of pattern crossing affects the most yarn tension?

Afterwards, a spectral analysis has been made on tension curves during hundreds of cycles, to identify a correlation between yarn damages and yarn tension. All the results are showed and analysed in results and discussion part below.

3. Results and discussion

3.1. Yarn tension function of time

First of all, yarn tension function of time has been analysed during several weaving cycles. Preliminary measures have been hold to make sure that yarn-to-yarn friction impacts on yarn tension and can be detected by the tensiometer. Crossing pattern has been woven, on 16 PET yarns and then on 16 glass yarns.

PET yarns

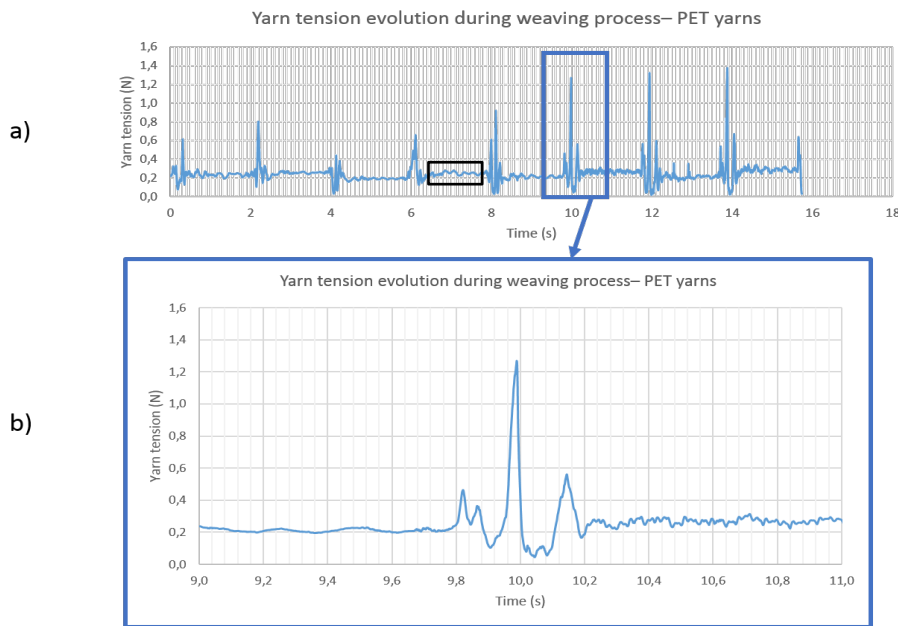
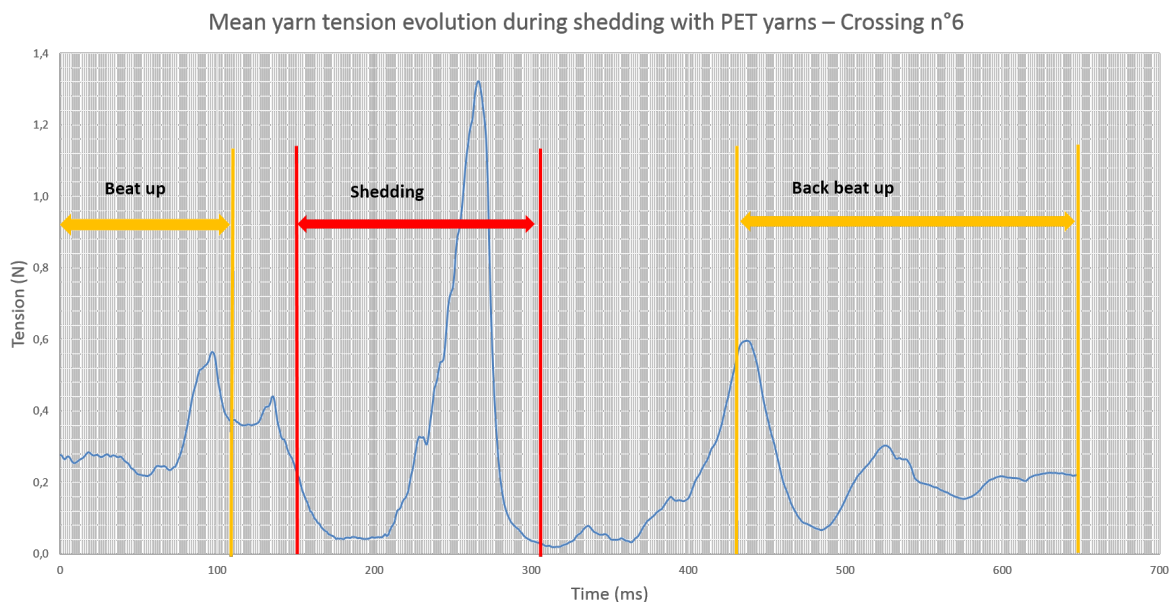


Fig. 6: Warp yarn tension evolution for PET yarns

Figure 6a illustrates a significant example of yarn tension as a function of time for PET yarns during a complete weaving pattern cycle. Two areas can be distinguished: i) a huge range of tension variation, one of them being highlighted by a blue frame on the figure and ii) a low amplitude of variation, like a steady state, represented by a black frame. Thanks to the high speed camera, machine stages have been linked to the tension evolution. The high range variation is corresponding to beat-up, shedding, and back reed movement steps. At the opposite, low variation occurs during the weft insertion stages. Those results are consistent with the hypothesis that no friction occurs during weft insertion, and is in accordance with Boussu *et al.* study on weaving process monitoring [10]. Moreover, focusing on the high variation area, difference between crossings is highlighted. Some tension peaks due to specific crossings are higher than others. Series of five identically experiments have been hold to confirm these tendencies. Results are similar to the one presented in figure 6a. Figure 6b is an enlargement of blue frame, i.e. tension variation where peaks are more perceptible.

The high speed camera results are overlaid on curve of tension evolution of a one crossing in figure 7. This crossing corresponds to maximum value of tension obtained during experiments. This curve is the



average of 5 different tests for the same crossing. Several peaks are observed, due to different events.

At 100 ms after the beginning of reed movement, a peak appears, corresponding of reed beat-up. A second huge peak, around 270 ms is a consequence of shedding, and a third peak at 430 ms is linked to reed back movement. Small peaks are also observable, at 130 ms and 520 ms, they must result from yarn vibration on the tensiometer sensor. Thanks to the analysis of a high camera recordings, it has been found that the third peak is also due to yarn vibration. The back movement of the reed seems to have an insignificant effect.

This kind of curve clearly indicates that interactions occurring during shedding strongly impact yarn tension. It can be noticed that it is during that specific sequence. That yarn tension changes the most. The maximum peak value is reached during shedding for any type of crossings. This maximum value is the chosen parameter to classify crossings with each other. Several crossings emerge as “critical” ones, given their high tension generation. They are represented on figure 8 (crossings 6, 7 and 8). The same colour code as employed in figure 3 is used and the graphical representation has been made considering a reed dent front view.

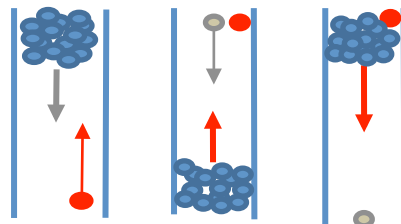


Fig. 8: Critical crossings for PET yarns

For every critical crossing mentioned, the majority of yarns are in movement, the tension is severely impacted even if the studied yarn is motionless.

Glass Yarns

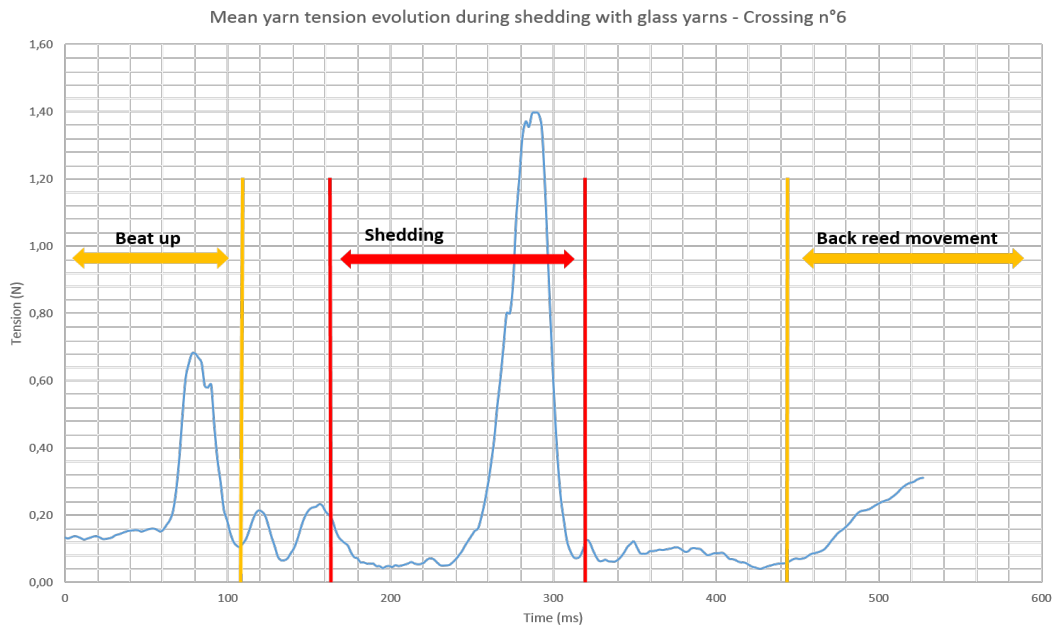


Fig. 9: Glass yarn tension evolution with machine sequence

Glass yarns are used for technical applications, and their mechanical behaviours is quite different compared to PET. For example, glass yarns are more sensitive to fibrillation, because of material brittleness. Same tests as PET yarns have been conducted. Results for the complete weave pattern (as figure 6a), are not presented here, as they are very close to PET results. The maximum values of tension appear at different

crossings, but the same shape of curve is obtained. Tension peaks occur at the same time and weft insertion has similarly no impact on tension. Figure 9 shows the evolution of the mean glass yarn tension (5 repetitions) during the same crossing presented in figure 7 for PET (No. 6 of the pattern), overlaid with machine sequences. The first peak appears at the same time, during beat-up stage, and is higher than PET results. The second peak during shedding is comparable to the one obtained with PET yarns. Contrary to PET results, any third peak is noticed and yarn vibrations are lower maybe due to higher yarn count.

Other differences are noticeable between PET and glass yarns results; critical interactions occur for different crossings. For glass yarns, three critical crossings are found, which are No. 2, 4 and 6. Those critical crossings are depicted in figure 10 with a reed dent front view. In the glass yarns case, critical interactions occur only when the studied yarn is in movement with an ascending motion. Descending motion have obviously less effect on tension. However, crossing No. 6 is critical for PET and glass, interactions occurring during this shedding strongly impact the warp yarn tension, due to an important friction mechanism.

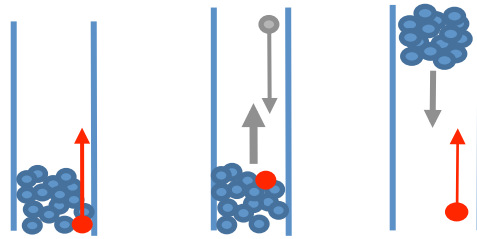


Fig. 10: Critical crossings for Glass yarns

3.2. Spectral analysis

Tension can be used to distinguish some crossings from the others, and seems to be sensitive to yarn-to-yarn friction. To determine if tension can be used as a damage state indicator for a warp yarn, a spectral analysis has been done for hundreds insertions in a row. Time-frequency graphs are obtained and the corresponding spectral power has been calculated. From a weft insertion to the following, a FFT spectrum is obtained. So for every crossing, a FFT spectrum is related. Each spectrum is successively plotted in a time-frequency graph, showing if some interactions seems to be more critical than others. Moreover, for each FFT spectrum, corresponding to a specific crossing, spectral power is calculated using the following relationship:

$$P(\Delta f) = \sqrt{\frac{\sum_{\Delta f} RMS(f)^2}{C}}$$

f: frequency (Hz)

Δf : spectre frequency range used (Hz),

RMS(f): Root Mean Square of yarn tension at frequency f (N),

C: coefficient corresponding at Hanning window function used in this case, equal to 1.5.

Spectral power function of pick number is plotted for three hundred cycles in a raw for PET and plotted until yarn breakage for glass yarns.

PET Yarns

Only one crossing is really notable in the graph presented on figure 11, corresponding to insertion No. 6. Peaks are present at 12, 24 and 32 Hz. This result is matching with tension evolution analysis, that kind on graphical representation can be used as an indicator. The advantage of this time-frequency graph is to visualize more cycles in a raw, which is more convenient for process monitoring.

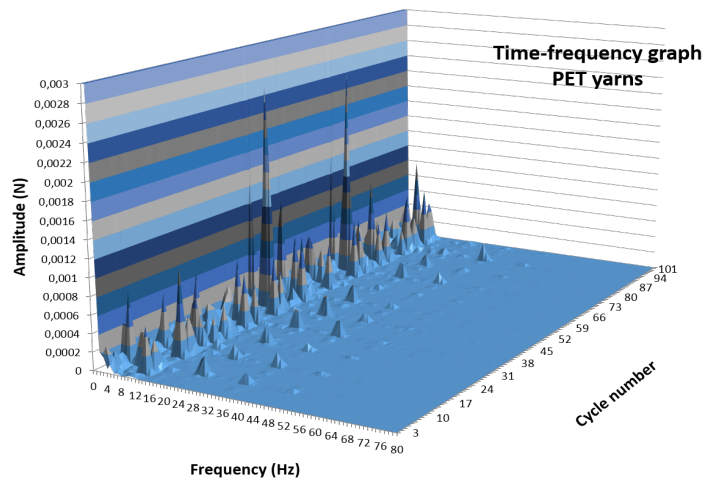


Fig. 11: Time frequency graph during 100 crossing cycles for PET yarns

Spectral power evolution is shown on figure 12. Measurement is made on 300 cycles in a row, making a global evolution noticeable. From 1-50 cycles, spectral power increases linearly, then from 51-end, power is stabilized around 0.7 N. Moreover, power value is dependant of the type of crossing. Once more, crossing No. 6 gives the higher value of spectral power. No yarn breakage happened during those tests, but a significant wear appears on yarns surface.

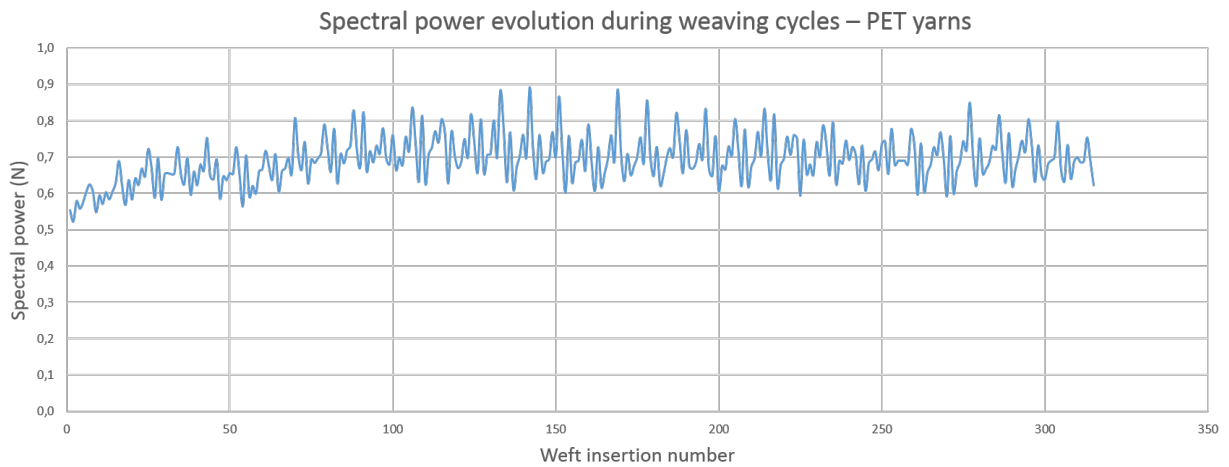


Fig. 12: Spectral power evolution over cycles- PET yarns

Glass Yarns

As it has been done for PET yarns, spectral analysis has been hold with glass yarns. Figure 11 presents a time frequency graph and Figure 13, the spectral power evolution is illustrated. Like for PET yarns, crossing No. 6 is highlighted by the representation: it is the only crossing with high peaks visible at 24 Hz and 36 Hz frequencies.

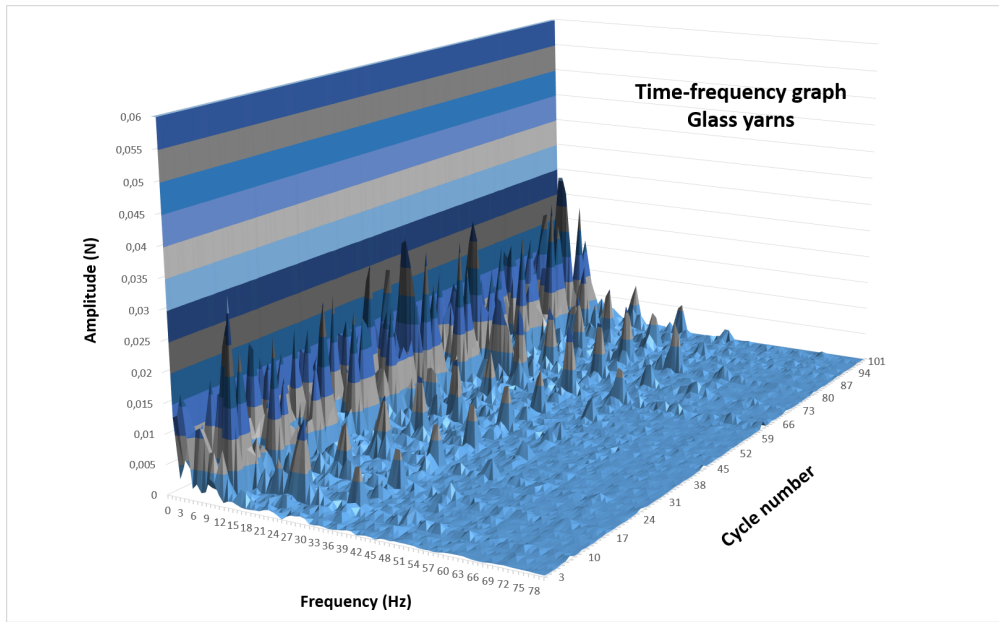


Fig. 14: Time frequency graph during 100 crossing cycles for glass yarns

Spectral power evolution is really relevant in this case, because studied yarn has broken during the test. This breakage occurred around 180th cycles, and corresponds at power drop on the curve. Before tension fall, three areas can be distinguished. From 1 to 40 weft insertions, power increases linearly, in the same way as PET result. From 41 to 140 weaving cycles, spectral power is stabilized around the same value as PET spectral power threshold, which is 0.7N. From the 140th insertion to the yarn breakage a sharp increase occurs leading to breakage.

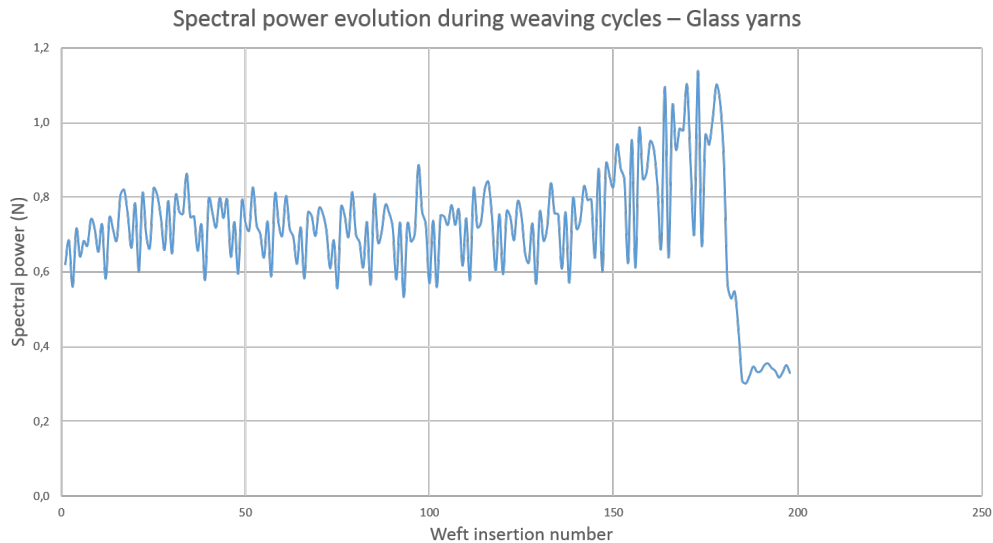


Fig. 13: Spectral power evolution over cycles - Glass yarn

This curve is really interesting because a clear correlation between PET and glass results can be made. PET studied yarn did not break during experiment, but has been progressively damaged, whereas the monitored glass yarn has been hardly damaged and then broken. These different damage states seems to match with spectral power evolution. A spectral power evolution theoretical profile composed of three areas, can be proposed in figure 15. The first is a linearly increase corresponding at an initialisation leading to a stabilization of the value. The second part is a steady state of spectral power, when yarns are not too hardly damaged. The third part is consisting in a huge tension increase, corresponding to a critical damaging zone for yarns, leading quickly to breakage. The duration of each area depends on the material considered and certainly other parameters which need to be investigated like yarn sizing.

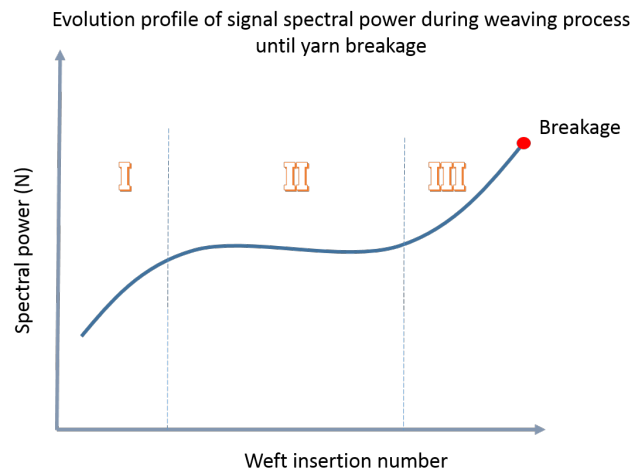


Fig. 15: Spectral power evolution profile

4. Conclusion and Perspectives

Those tension tests respond to several issues, such as identifying which kinds of crossing and which events of the weaving cycle lead to very strong yarn-to-yarn interactions. The results obtained in this study prove that tension evolution measurements can capture yarn damages, which can be helpful for process monitoring and optimization. A correlation between yarn damages and spectral power of tension signal has been made, which represent a high potential of use for process monitoring. Nevertheless, yarn-to-yarn interactions need to be more precisely characterized in order to anticipate, and at long term, to avoid yarn damages.

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