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# Auxetic yarn made with circular braiding technology

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This paper reports a new type of auxetic yarn made with circular braiding technology to overcome the yarn slippage problem in the conventional helical auxetic yarn structure. Various auxetic yarn structures are firstly produced on a vertical circular braiding machine with 16 yarn carries by changing the number and arrangement of stiff yarn as well as diameter of elastic yarn and core yarn, and then tested under single and repeating tensile conditions. The results show that not only yarn slippage problem could be overcome in the newly developed auxetic yarn structure, but also an early activation and a higher magnitude of negative Poisson's ratio could be achieved. The results also show that all structural parameters including stiff yarn number and arrangement, core yarn and elastic yarn diameter have an influence on the auxetic

effect of the novel yarn structure. Since the new auxetic yarn is produced by using standard braiding manufacturing technique and conventional non-auxetic yarns, there are few technological barriers for its large-scale manufacture for practical application.

## 1. Introduction

Auxetic materials are a special type of materials and structures with negative Poisson's ratio (NPR).[1] They have received considerable attention over the last three decades due to their counter intuitive deformation behavior in which materials laterally expand when stretched and laterally contract when compressed. This special deformation behavior has led to the enhancement of a series of material properties, such as increased shear stiffness, enhanced fracture toughness, superior indentation resistance,[2, 3] improved acoustic behavior[4] and synclastic curvature on out-of-plane flexure. [5]

Since it was firstly reported in an elasticity book by Love,[6] auxetic behavior has been found in different types of materials, ranging from naturally occurring single crystal arsenic[7] and cubic metals [8] to biological materials such as skin[9, 10] and bone[11] and to synthetic materials and structures such as foams,[12-14] fabrics[15-19] and composites.[20-24] Among all auxetic materials, auxetic textiles including fibers, yarns and fabrics are highly attractive as they provide another route for the development of auxetic materials by using textile technologies and therefore open up broader commercial exploitation routes for practical applications.[25-29]

One of the pioneering work in this field is the development of helical auxetic yarn (HAY) which was first reported by Hook in 2003.[30] As shown in **Figure 1**a, a HAY structure is formed with a straight elastomeric core and a stiffer yarn wound around it in a helical form. Under the tensile loading, the stiff yarn is straightened and displaces the core yarn into a crimped form, resulting in an expansion of the structure in the lateral direction (Figure 1b). This deformation behavior makes HAY attractive for many applications including color change in woven fabric when stretched, composite reinforcement, blast protection and filtrations.[31] Nevertheless, HAY has its own structural limitations. One of them is the slippage of the stiff yarn on the surface of the core yarn under repeated extension, which in turn could impair the performance of HAY.[32-34] In addition, the uneven surface of HAY could raise trouble in handling and structural uniformity when manufacturing other auxetic products from it.

Some efforts have been made to overcome these limitations. One of the solution is to coat the HAY with a sheath of silicone rubber gel.[35] Coating not only improves the surface evenness of the HAY, but also provides a good binding between the stiff yarn and the core. However, the deficiency is that auxetic behavior of the HAY structure can be restricted by the coated sheath. It was reported that adding a 5 mm coating onto the HAY could reduce its maximum NPR value from nearly -0.75 to around zero, and the auxetic behavior of the HAP structure could be directly eliminated while the coating thickness reached 9 mm.[35] Recently, another method by using a modified circular braiding technique to produce the improved HAY structure was proposed by the authors.[36] In this method, a braided sheath was added between the stiff yarn and the core so that the stiff yarn could be fixed by braiding yarns. The advantage of this method is that the slippage problem of the stiff yarn can be avoided while the auxetic behavior of the HAY is still conserved. The deficiency, however, is that a specially developed tubular braiding machine is required to produce this type of HAY structure because an additional wrapping process of the stiff yarn is employed with the braiding process. The complex manufacturing process leads to the very low productivity of that new HAY structure.

In this study, a novel type of braided auxetic yarn structure (BAY) that can be produced by using standard circular braiding technique and can overcome limitations in conventional HAY system is proposed. The geometry and manufacturing process of the new structure is first descripted. Then, its structural geometry stability and auxetic behavior under repetitive tensile condition are identified and compared with those of the conventional HAY structure. At last, the influence of various factors including the stiff yarn and component yarn diameter is analyzed by comparing the auxetic behavior of BAYs made with different set parameters.

## 2. Experimental

### 2.1 Design and fabrication

The geometry of the BAY structure proposed in this study is schematically illustrated in **Figure 2**a. Three components were used to produce it, namely, stiff wrap yarn, low modulus elastic wrap yarns and low modulus elastic core. Different from the conventional HAY structure where the stiff yarn is directly wound onto the core, the stiff yarn in the BAY structure is now interlaced with other elastic wrap yarns and helically covers the core together with elastic wrap yarns, as shown in Figure 2a. It is expected that this interlacement effect could make the stiff yarn uniformly wrapped onto the core, at the same time, avoid possible slippage during the manufacture and use. As elastic wrap yarns and the core are designed to have similar low modulus, the same deformation mechanism as HAY is expected in BAY structure, as shown

Figure 2b. On the other hand, compared to the method used in our previous study[36] where additional wrapping process is needed, the BAY structure can be easily produced via a standard tubular braiding process. This is because the stiff yarn is now directly braided with other elastic yarns instead of being helically wound onto the braided structure. Since there is no additional wrapping process, existing braiding machines can be directly used to produce the BAY structure.

The component yarn materials used to produce the BAY structure are listed in **Table 1**. Stiff yarns with two colors were employed in order to distinguish stiff yarn from other yarn components. In this work, seven types of BAY structures with different parameter settings and one conventional HAY structure were designed and produced. Five samples were manufactured for each structure on a conventional vertical circular braiding machine with 16 yarn carriers (**Figure 3**a) and were tested according to the methods provided in the following paragraphs. As shown in Figure 3b, to produce a typical BAY structure, the stiff yarn was firstly mounted on one selected carrier while elastic yarns filled up the rest fifteen carries. The core then was placed in the center hole of the machine as mandrel. Upon rotating the machine, carriers are equally divided into two groups (8 carriers in each group) and perform two opposite circular movements, this is, one group moves in the clockwise direction and the other group moves in the counter-clockwise direction, thus forming a tubular braided structure. After all carriers finish a complete circular movement, one geometry unit of BAY structure is obtained. It is worth noting that clippers with fixed weights and low operating speed were employed during the whole producing process in order to keep a constant yarn tension. Based on the above technique, other BAY structures with different parameter settings can be produced by varying the number of stiff yarns used and yarn arrangement on the machines; while HAY structure can be easily produced by mounting the stiff yarn on one carrier only. The detailed manufacturing process and geometric features of the produced HAY and BAY samples can be found in **Table 2**. The initial wrap angle was kept unchanged as 35º for all fabricated structures in order to facilitate a systematic analysis. In practice, this initial wrap angle of BAY (equal to its braiding angle) can be changed by adjusting the ratio between the rotation speed of the braiding machine and the take-up rate of the braided yarns. On the other hand, from Table 2, it can be seen that BAY samples can be split into three groups according to the parameters to be considered. The first group includes samples BAY1, BAY2 and BAY3, which are produced with different number of stiff wrap yarn. The second group includes samples BAY3, BAY 4 and BAY5, which are produced with different arrangements of stiff yarns. The last group includes BAY1, BAY 6 and BAY7, which are produced with different diameters of component yarns. The photographs of the produced BAYs and HAY are shown in **Figure 4**.

### 2.2 Tensile testing

In order to assess the auxetic behavior of produced yarn structures, tensile measurements were performed on all samples of each structure. The tensile tester used was an Instron 5944 tester (Instron Worldwide Headquarters, Norwood, Massachusetts, USA) with a loading cell of 50N. During the test, the sample was mounted vertically between the two clamps and secured manually using mechanical jaws of which the face size is 2.5 cm × 2.5cm. A special sample gauge length $L_G$=150mm was chosen according to the following condition:

$$L_G \geq 10\lambda \quad (1)$$

where $\lambda$ is the cyclic pitch of stiff yarn in a helical arrangement. This condition is adopted based on the numerical study by Wright et al.[37] to ensure a minimum number of wrap cycles within a specimen gauge length regardless of the yarn geometry. Tensile tests were then performed up to a tensile strain of 25% for each sample with a crosshead speed of 0.3 mm/s. The applied load and tensile strain of samples $\varepsilon_l$ were recorded using the Bluehill® Software (http://www.instron.co.uk) that is compatible with the Instron testing system. Prior to recording data, samples were stretched cyclically to 0.01 strain at a rate of 0.1mm/s for several cycles as a 'bedding in' process to minimize the pretension induced during fixation of the samples on the jaws.

Particularly for samples BAY1 and HAY, additional cyclic tensile tests were performed in order to compare the yarn structural stability between them under repeated stretch conditions. In this case, the final loading strain was set as 25% while the crosshead speed for loading and unloading was set as 0.3 mm/s. The tensile cycle was five and the holding time at the preset final strain and zero strain was kept the same as 5 seconds.

To measure the transversal deformations of samples, an in-situ photograph system consisting of a high-resolution CMOS camera (Canon EOS 800D, Tokyo, Japan) and a remote switch was used, as shown in **Figure 5**. By using the system, a photograph of the tested sample was taken at every 1% loading strain during tensile test. The photographs obtained were then used to calculate the transverse strains of samples. In this case, the Digital Image Processing (DIP) technique was used to treat the images obtained, as shown in **Figure 6**. Firstly, each captured photograph (Figure 6a) was binarized via software Adobe Photograph CC and Matlab R2017a to remove the color noise. After that, threshold and line refill were applied to the obtained binary image so that the edge of the sample could be distinguished from the back ground (Figure 6b). Finally, the influence of the yarn hairiness was removed by using the syntax *bwareaopen* in Matlab R2017a and the effective transverse width of the sample was calculated by counting the pixels existing between the upper and lower boundaries (Figure 6c). With the transverse width obtained, the transversal strain $\varepsilon_t$ can be calculated from Equation 2.

$$\varepsilon_t = \frac{\mathrm{H}-\mathrm{H}_0}{\mathrm{H}_0} \tag{2}$$

where H and $\mathrm{H}_0$ are effective transverse widths of the sample at the stretched and initial states respectively. From here, the Poisson's ratio ($\nu$) can be calculated from Equation 3.

$$\nu = -\frac{\varepsilon_t}{\varepsilon_l} \tag{3}$$

## 3. Results and discussion

### 3.1 Comparison between HAY and BAY

The comparison between HAY and BAY was made in order to verify whether the slippage problem of the stiff wrap yarn in conventional HAY is overcome in BAY and whether the BAY exhibits a significant auxetic behavior as HAY under tensile condition.

#### *3.1.1 Slippage of stiff wrap yarn*

It is known that the slippage of stiff wrap yarn could result in a poor binding between stiff yarn and the core as well as inconsistent wrap angle. Based on this, the performance of HAY and BAY structure in these two aspects were evaluated. **Figure 7** shows the still image of HAY and BAY1 samples before and after five times repeated stretches. A preload of 0.2N was added herein to samples so that they could be straightened and compared in the same condition. It can be seen that the binding between stiff yarn and core is better in BAY structure than that in HAY structure under the repetitive tensile condition.

As shown in the Figure 7a, small voids were generated between the stiff yarn and the core in HAY structure after repeated stretches. Meanwhile, that is not the case for BAY (Figure 7b). This difference between the HAY and BAY is mainly due to the fact that the stiff yarn in HAY is floated on the core without any lateral fixation, and thus the close contact between the stiff yarn and the core loses easily upon repeated extensions. In contract, the stiff yarn in BAY is laterally secured by other elastic yarns. Therefore, good contact between stiff yarn and the core can be maintained after the repeated stretches (Figure 7b). As proposed by the previous studies,[32, 37] voids between the stiff wrap yarn and the core could impair the performance of HAY structure, especially its auxetic effect. In addition, less change in transverse width of sample BAY1 (1 pixel compared to 3 pixels in that of the HAY sample) indicates that the absence of voids also provides the BAY structure with a better dimensional stability than the HAY structure.

The second characteristic, this is, the consistency of wrap angle, is evaluated by measuring 10 different wrap angles of the sample before and after five times of repeated stretches. The results together with means (AVG) and standard deviations (STDEV) are listed in **Table 3**. It can be seen that the STDEV for the BAY after stretching is much smaller than that of the HAY, indicating that better consistency of wrap angle under repeated extensions could be achieved via the use of elastic wrap yarns. This is because the elastic wrap yarns used in BAY structure tend to recover to its original position after the stretching and thus could pull back the stiff wrap yarn and alleviate the inconsistency of wrap angle caused by the slippage along the structure axis. As a result, the STDEV for the BAY after stretching is much smaller than that of the HAY even though they have the same STDEV at the initial state and the same change in the average wrap angle after the stretching.

*3.1.2 Auxetic effect*

The significant auxetic effect under stretch is the key advantage of the HAY structure compared to other yarn structures and is also the main property needed to be conserved in BAY structure. **Figure 9** presents the Poisson's ratio – strain curves of HAY and BAY1 samples. It can be seen that the significant auxetic effect of HAY is not only conserved in BAY structure but also enhanced by the new structural design.

By comparing the Poisson's ratio – strain curves of HAY and BAY1 samples at 1$^{st}$ stretch as shown in Figure 9, it can be found that an earlier activation of the auxetic effect with larger NPR is achieved in the BAY structure. We believe this is because the use of elastic yarns in BAY structure increases the initial diameter of the core from $D_C$ to $D_{C+E}$ and thus reducing its difference with the initial transverse width of the structure $H_0$, as shown in **Figure 10**. As a result, when the core is deformed into a helix shape under stretch, its external helix diameter can exceed the value of $H_0$ earlier and result in an early activation of the auxetic effect. Meanwhile, the early activation of the auxetic effect decreases the tensile strain to reach the maximum NPR effect and thus present larger NPR value. The other reason is that the BAY with elastic wrap yarns in BAY structure also has a larger diameter and thus the cross-sectional contour size increase in the structure is more significant.

By comparing the Poisson's ratio – strain curves of HAY and BAY1 sample between the 1$^{st}$ and 5$^{th}$ stretch as shown in Figure 9, it can be found that the Poisson's ratio of HAY changes hugely after the 5$^{th}$ stretch while that change in BAY structure is much smaller, especially before a tensile strain of 5%. This can be attributed to the fact that voids were generated between the stiff yarn and the core in HAY structure after repeated extensions while that is not the case for BAY structure. When there are voids between the stiff yarn and the core, the straightening of stiff yarn under stretch would narrow voids firstly before causing a lateral deformation and thus causing a noticeable decrease in the transverse width of the structure. As a result, the Poisson's ratio of HAY structure at small strains increases largely after the repeat extensions while that of BAY structure is remained almost same, demonstrating a more stable auxetic effect under repeated extension. However, it can be seen that the onset of the auxetic behavior of HAY and BAY was both impeded by the repeated extension. This is because the repeated extensions cause an overall increase in the wrap angle of the stiff yarn (see Table 3). As suggested by previous studies,[37, 38] a higher wrap angle leads to a later activation of the auxetic effect.

Based on the above analysis, it can be found that repeated stretches could cause a difference in auxetic behavior for both BAY and HAY structures. In order to further investigate the influence of repeated extension on the auxetic performance of HAY and BAY, the Poisson's ratio – tensile cycle curves at different strains for both HAY and BAY1 samples are plotted in **Figure**

**11**. As the Poisson's ratio values are not constant with regard to tensile strain, the Poisson's ratio values obtained at 5, 10, 15, 20 % tensile strains are selected for plotting the curves. It can be seen that the auxetic effect of both HAY and BAY are weakened with the repetitive stretch and the biggest change arises from the 1st stretch to the 2nd stretch, especially for HAY. This is mainly because the repeated stretches weaken the compact construction of the auxetic yarn structure. As a result, the core cannot be displaced by the stiff yarn efficiently and thus a later activation of the auxetic effect is exhibited. Meanwhile, as the structure tends to be stabilized after several times stretches, the change in the Poisson's ratio value between every two stretches becomes smaller with the increase of stretching times. On the other hand, it can also be seen that only small changes are demonstrated in Poisson's ratio at larger tensile strains for both structures, indicating that the influence of repeated extension is alleviated by increasing the tensile strain. This is because the repeated extension could only influence the value of the transverse strain of the structure but not its longitudinal tensile strain. As the Poisson's ratio is calculated by dividing the transverse strain to the longitudinal tensile strain, the changes in the Poisson's ratio value at low extensions between every two stretches become large due to low longitudinal tensile strain and high variation in transverse strain under the repeated extension. The changes in the Poisson's ratio value at large extensions between every two stretches then become smaller than those at low extensions because the longitudinal tensile strain increases while the value differences of the transverse strain caused by repeated extension stay at the same level as at low extensions.

*3.1.3 Surface damage*

Despite the above two aspects, a concern of the BAY structure is that the use of the elastic wrap yarns could cause the surface damage in either or both the stiff and elastic wrap yarns arising from their contact during the stretching, which can in turn impede the performance of the BAY structure. In order to address this concern, a highly zoomed-in view on the crossing of the stiff and elastic wrap yarns in BAY7 was taken after five cycles of stretching and is presented in **Figure 8**. It can be seen that the friction between two wrap yarns did not cause a surface damage in both the stiff and elastic wrap yarns.

### 3.2 Effects of structural parameters

In addition to the geometry stability, the auxetic effect of the structure itself is also greatly influenced by its parameter settings. Different parameter settings will lead to different auxetic behavior of the structure. Here, we evaluate three critical structural parameters, namely the number of stiff yarn used, the distance between two stiff yarns, the diameters of elastic yarns and core, for BAY structure and discuss the possible causes of their influences.

#### *3.2.1 Effect of number of stiff yarn*

Since the use of stiff yarn is the major reason that triggers auxetic effect in the conventional HAY structure, a lateral thought is how the BAY structure will behave when the stiff yarn is replaced by elastic yarns or when more than one stiff yarns are used in the structure. In order to address this question, the Poisson's ratio-strain curves for BAY samples with zero, one and two stiff yarns in structure are shown in **Figure 12** for a comparison. It can be seen that the number of stiff yarn has an obvious influence on the auxetic effect of the BAY structure.

Firstly, by comparing the curves of BAY1 and BAY2, it can be found that using all low modulus elastic yarns without stiff yarn to cover the core could eliminate the auxetic effect of the structure. This is consistent with our expectation and in line with the previous studies conducted on HAY[32] that the use of a wrap yarn having a modulus close to that of the core cannot result in a lateral displacement of the core, and therefore cannot trigger the auxetic behavior of the structure. Thus, the BAY which has no stiff yarn (stiffer than the core) in structure behaves like a conventional braid and exhibits a positive Poisson's ratio under extension.

Secondly, by comparing the curves of BAY1 and BAY3, it can be found that the introduction of additional stiff yarns causes a small difference in the auxetic effect. As shown in Figure 12, the BAY structure with two adjacent stiff yarn presents an earlier activation of auxetic effect compared to the BAY with one stiff yarn. This is because the increase in the transverse width of the structure is related to the overall lateral displacement of the core caused by all stiff yarns in the structure. When two adjacent stiff yarns are used in the structure like BAY3, the core is easier to be displaced laterally at initial action of the stiff yarns, resulting in an earlier activation of auxetic effect than the structure with one stiff yarn like BAY1. On the other hand, it can be found that the NPR effect of the BAY structure with two adjacent stiff yarns stops its increase earlier, presenting a smaller maximum NPR compare to the BAY structure with one stiff yarn. A possible explanation on this is that the lateral expansion of the BAY structure with two adjacent stiff yarns at larger tensile strain depends on the straightening effect of two stiff yarns. When tensile strain increases, both two stiff yarns tend to be straightened along the center line of the structure. However, the movement of two stiff yarns are not fully coincident with each other as there exists a phase difference between two helical curves formed by them. As a result, the straightening of one stiff yarn is impeded by the other stiff yarn and both of two stiff yarns are less straightened compared to the case when there is only one stiff yarn in the structure. Therefore, the smaller straightening effect of the two stiff yarns in the BAY structure will result in early stop of the transverse width increasing at larger tensile strains. The further stretching of the BAY structure will decrease the NPR as the diameters of component yarns are continuously decreasing with the increased tensile strain. As a result, the transverse width of BAY3 decreases earlier at large tensile strains and presents a smaller maximum negative Poisson's ratio than that of BAY1 with one stiff yarn.

*3.2.2 Effect of distance between two stiff yarns*

From the above analysis, it can be known that the additional stiff yarn will influence the auxetic effect of the BAY structure. However, this influence may vary because the two stiff yarns in BAY structure can be arranged to different positions and the distance between them can be changed. In case of our 16-yarns braided structure, there are four different arrangement possibilities of two stiff yarns, as shown in **Figure 13**. In order to analyze the influence of this parameter, the auxetic effect of BAY samples with (a), (b) and (d) structures were evaluated. The BAY samples with (c) structures were not manufactured and analyzed in this paper because it is a middle form of (b) and (d) structures. **Figure 14** presents the Poisson's ratio - strain curves of these three structures with different arrangements of two stiff yarns. It can be found that the distance between two stiff yarns has significant influence on the auxetic behavior of the structure.

From Figure 14, it can be found that the auxetic effect of BAY is weakened by increasing the distance between two stiff yarns. This phenomenon can be explained by constructive and destructive interference between two waves. As the stiff yarn is helically wrapped onto the core in a BAY structure, the deformation of the core caused by the stiff yarn in the plane is in a wave shape. In case there are two stiff yarns in the structure, the overall deformation of the core under extension becomes a resulting wave of two wave shapes caused by each stiff yarn individually. Thus, as the increase in distance between two stiff yarns increases the phase difference between two waves, the lateral displacement of the core caused by them is smaller than that caused by each stiff yarn. As a result, the auxetic effect of the structure is weakened and a smaller NPR effect is displayed. Especially, when two stiff yarns are wrapped onto the core with a phase difference of $\pi$ (like BAY5 sample), the auxetic effect of the BAY structure is eliminated. This is because the wave shape (or lateral displacement) of the core caused by one stiff yarn is opposite to that caused by the other stiff yarn. **Table 4** presents the photographs of three samples with two stiff yarns at different critical tensile strains, from which it can be seen that the overall deformation of the structure under extension is influenced by the position of two stiff yarns.

*3.2.3 Effect of component yarn diameter*

It is known that the diameter ratio of the core yarn to the stiff yarn is an important property of the conventional HAY structure and could influence its auxetic effect under extension.[37] In

BAY structure, this core/stiff diameter ratio is further expanded to diameter ratios among three components, namely, the stiff yarn, the elastic yarns and the core. Under this circumstance, the auxetic behavior of three different types of BAYs made with the same stiff yarn, but with different elastic yarns are compared based on their Poisson's ratio-strain curves as shown in **Figure 15**. It can be seen that the auxetic effect of BAYs is also greatly influenced by the diameter of component yarns used.

By comparing the curves of BAY1 and BAY6 in Figure 15, it can be found the effect of the elastic yarn diameter is evident at both small and large strains. The BAY structure with larger elastic yarn diameter exhibits a higher positive Poisson's ratio at small tensile strains. This can be attributed to the fact that the major deformation of the BAY structure at small tensile strains is the reduction in the cross-section size, which is resulted from the diameter decrease in single yarn components. As the Poisson's ratio of the elastic yarns used here is higher than that of the core, the use of larger elastic yarn diameter also causes a larger reduction in the cross-section size of the BAY structure and thus yielding a higher positive Poisson's ratio. This situation, however, is inversed after the tensile strain exceeds 8%. The BAY structure which has larger elastic yarn diameter triggers its auxetic effect earlier and presents a larger maximum NPR than that of the BAY structure with smaller elastic yarn diameter. This result can be attributed to the phenomenon as explained before, that is, the employment of elastic yarn reduces the value difference between the initial diameter of the core and the initial transverse width of the BAY structure. As a larger elastic yarn diameter leads to a larger reduction in that difference, an earlier activation of auxetic behavior is presented. At the same time, this early activation of auxetic effect also leads to a larger maximum NPR under a same degree of structural deformation. The other reason is the BAY with larger braiding elastic yarn diameter also has a larger braid diameter and thus the cross-sectional contour size increases in the BAY structure is more significant. Because of these reasons, the NPR effect of the BAY with larger elastic yarn diameter is activated earlier and kept larger than that of the BAY with smaller braiding yarn diameter up to a tensile strain of 25%. Note that the effects of mechanical properties (Young's modulus and Poisson's ratio) of component yarns B1 and B2 on the Poisson's ratio-strain responses of the BAYs are not considered here because they can be negligible compared to the effects of component yarn diameter based on the following considerations. Firstly, the Young's modulus of both B1 and B2 are close to that of the core yarn and thus it is believed that both B1 and B2 cannot displace the core yarn laterally when stretched and cannot influence the Poisson's ratio-strain responses of BAY1 and BAY6. Secondly, the effect of Poisson's ratio also reflects on the diameter change of component yarns. Therefore, only the effect of component yarn diameter is considered here.

By comparing curves of BAY6 and BAY7 in Figure 15, it can also be seen that the auxetic effect of the BAY is significantly influenced by the core diameter. An earlier activation of the auxetic effect as well as a larger maximum NPR is exhibited in BAY structure with larger core diameter. This phenomenon is consistent with the findings in conventional HAY system,[38] where a higher core/stiff diameter ratio provides a better auxetic performance. The main reason for this phenomenon is that BAY structure with larger core diameter also has a larger lateral displacement under extension and therefore presenting a higher maximum NPR. Meanwhile, the increase in diameter of the core simultaneously increases the diameter ratio between core/elastic yarns so that the effect of elastic yarn on the transverse width of the structure is weakened. As a result, the decrease in the transverse width at small strains of BAY structure with larger core diameter is smaller, thus presenting an earlier decrease in the Poisson's ratio.

## 4. Conclusions

Based on the results and above discussion, the following conclusions can be reached:

1. By virtue of the intertwining effect gained from braiding process, the stiff yarn in BAY now is well fixed by the other elastic yarns and thus the slippage problem during the manufacture and use is overcome.

2. Owing to the special structural design, the significant auxetic effect of HAY structure is not only well conserved in BAY structure but also enhanced. An early activation of the auxetic effect as well as a larger NPR effect under extension is obtained in BAY structure due to the additional cover of elastic yarns on the core.

3. All the structure parameters have significant effect on the auxetic effect of the BAY structure. Among them, the number and the position of stiff yarns in structure can be utilized as a new design parameter to tailor the Poisson's ratio of BAY.

4. The BAY structure with large elastic yarn diameter, large core diameter has a better auxetic performance.

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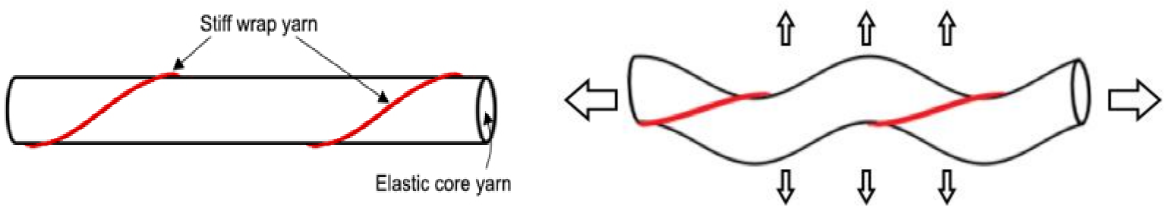
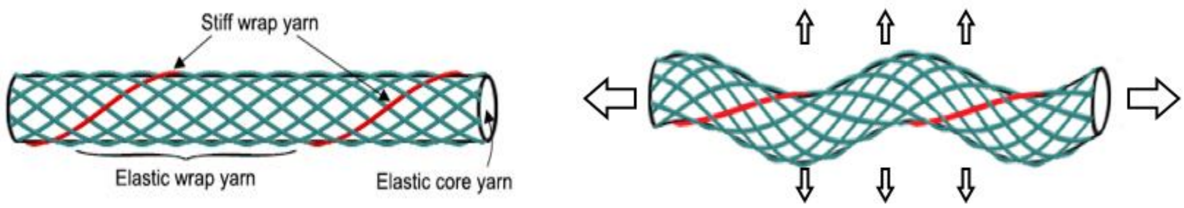


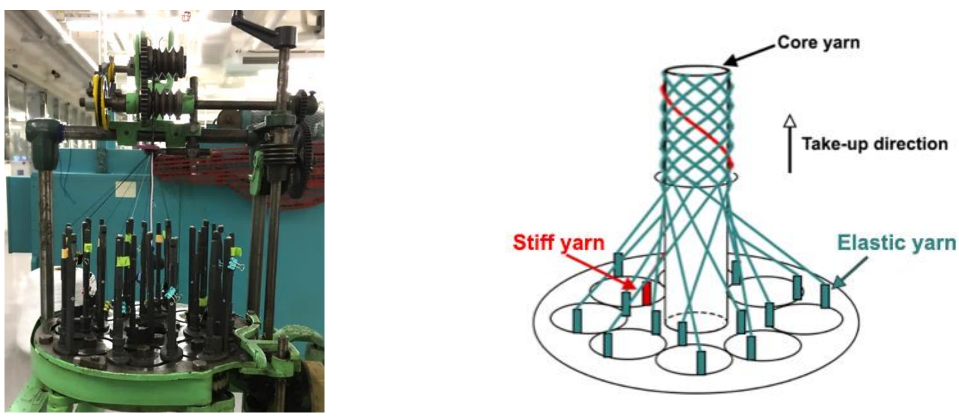

(a) (b)

**Figure 1.** HAY structure: (a) in the initial state; (b) under extension.




(a) (b)

**Figure 2.** BAY structure: (a) in the initial state; (b) under extension.




(a) (b)

**Figure 3.** Fabrication of BAYs: (a) braiding machine used; (b) schematic of braiding process.

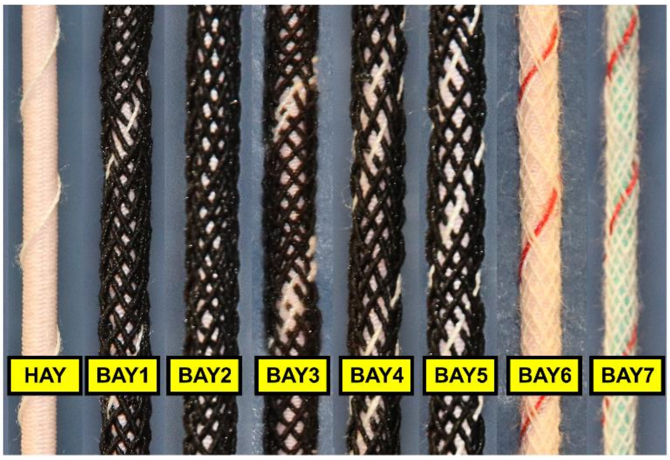
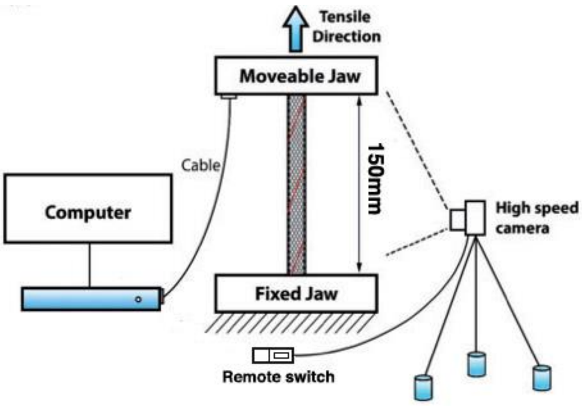
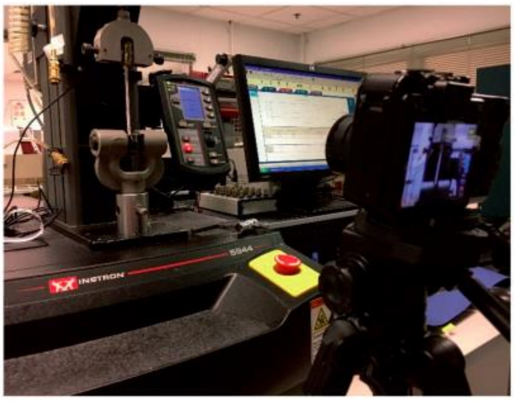



**Figure 4.** Photographs of the HAY and BAY samples produced.



(a) (b)

**Figure 5.** In-situ photograph system used for sample image acquisition: (a) schematic; (b) photograph.

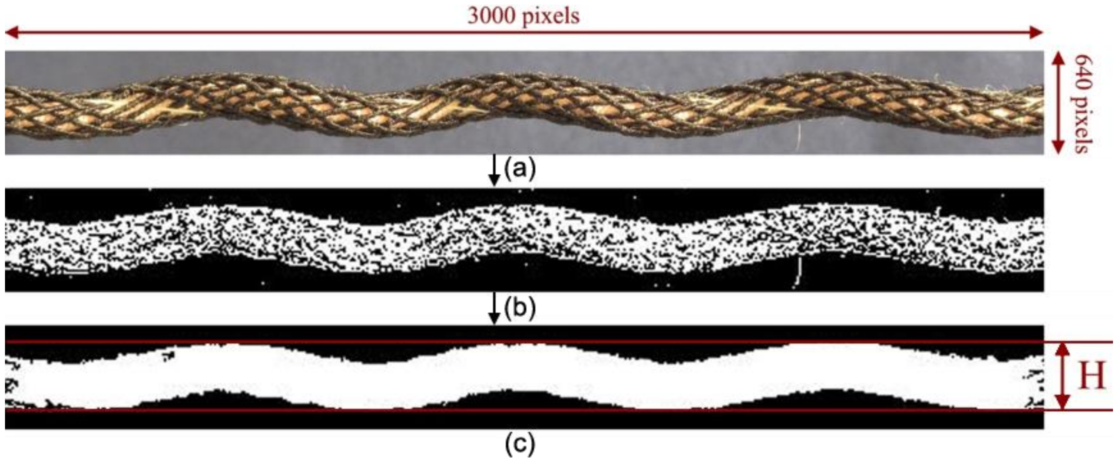



**Figure 6.** Digital Image Processing for yarn image obtained: (a) captured photograph; (b) binary and threshold image; (c) image for calculating effective transverse width of auxetic yarn.

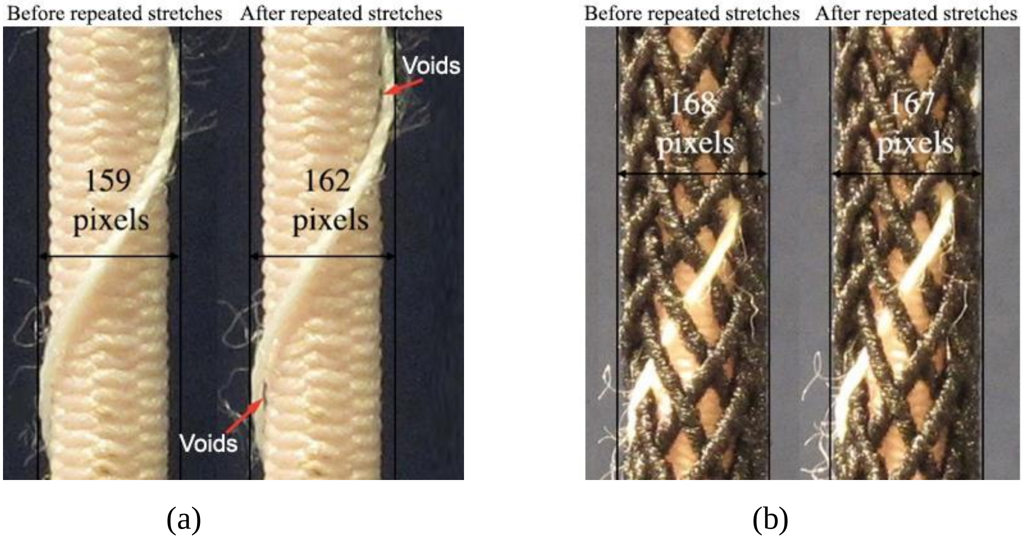



**Figure 7.** Still images of auxetic yarns before and after five times of repeated stretches: (a) HAY; (b) BAY1.

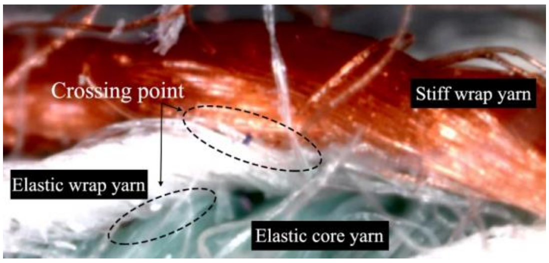



**Figure 8.** A closed-up photo of BAY7 on the crossing of stiff and elastic wrap yarns after five cycles of stretching.

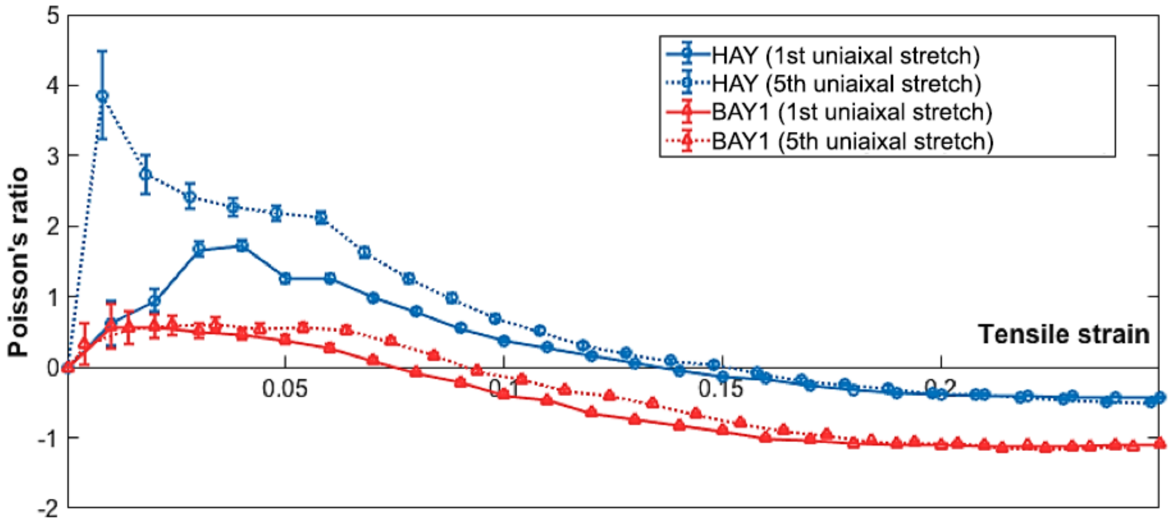



**Figure 9.** Poisson's ratio-strain curves of HAY and BAY1 samples at 1st stretch and 5th stretch.

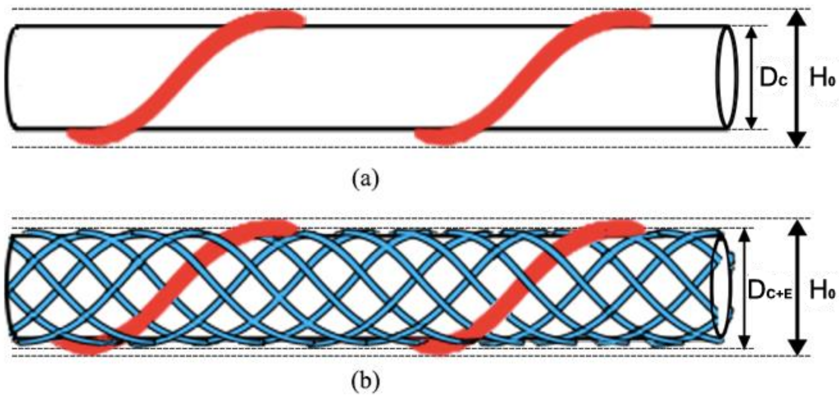
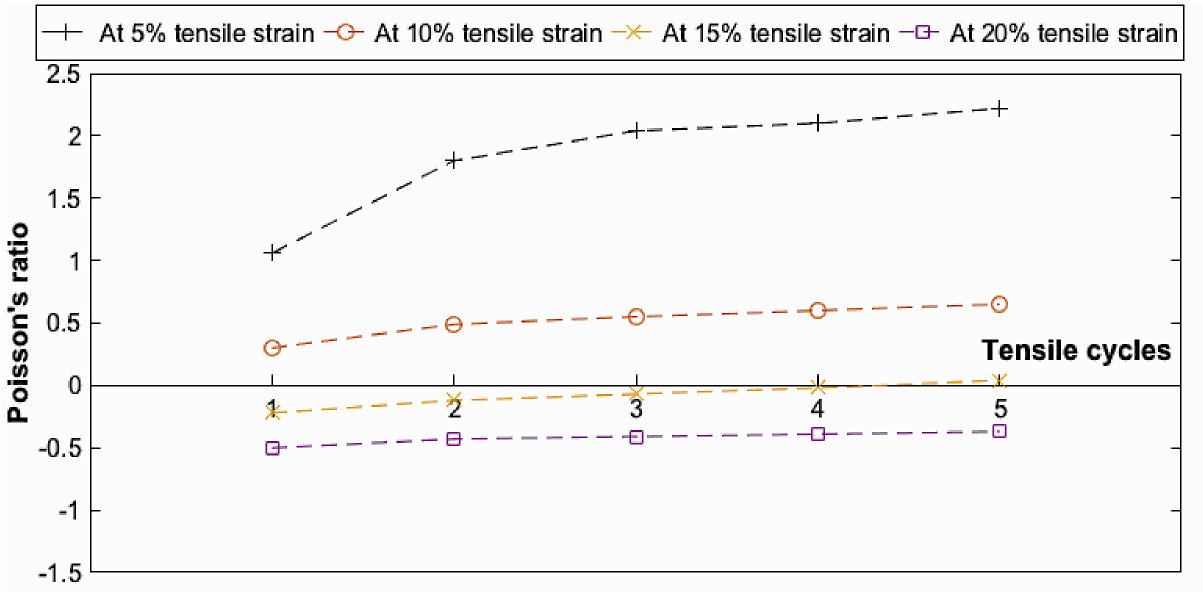
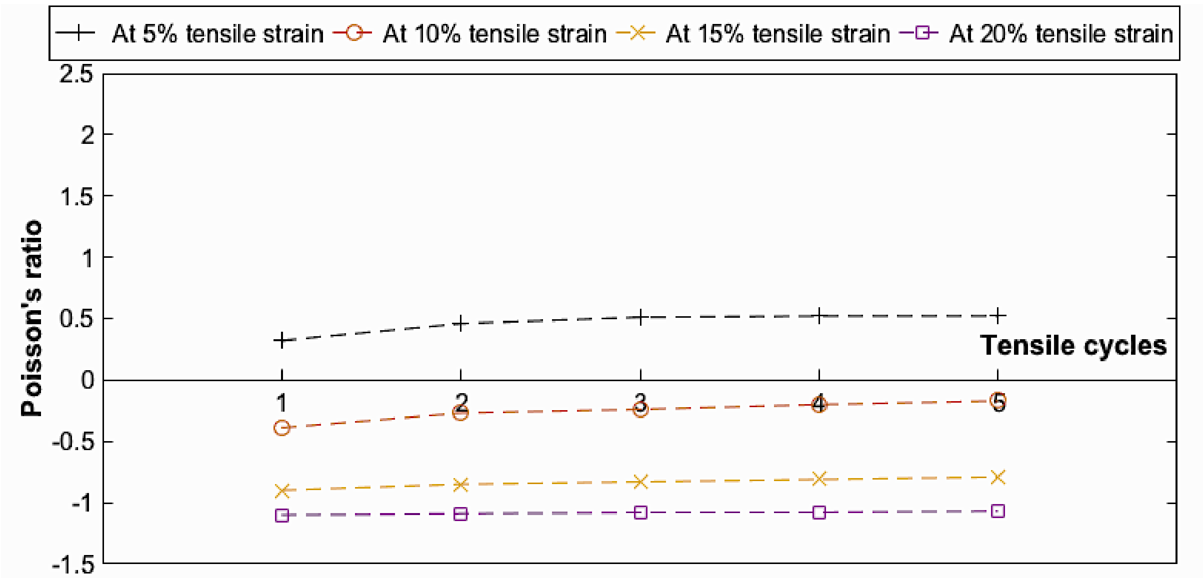



**Figure 10.** Surface of auxetic yarn structure: (a) HAY; (b) BAY.




(a)




(b)

**Figure 11.** The auxetic effect under repeating extensions: (a) HAY; (b) BAY1.

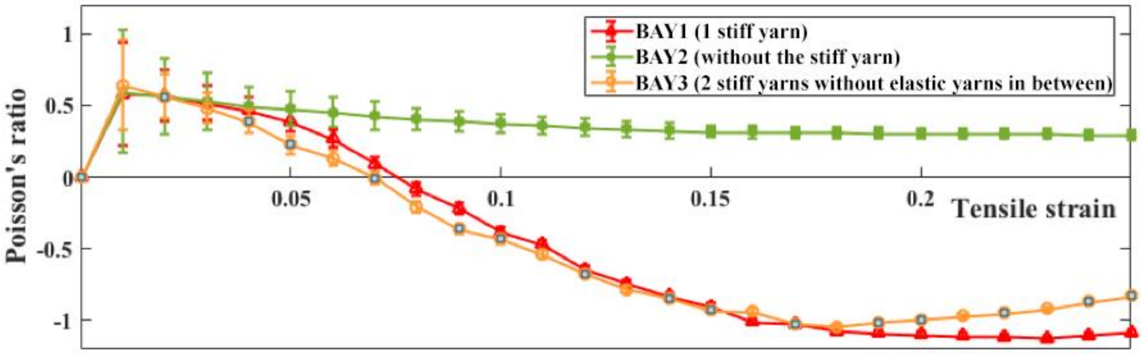
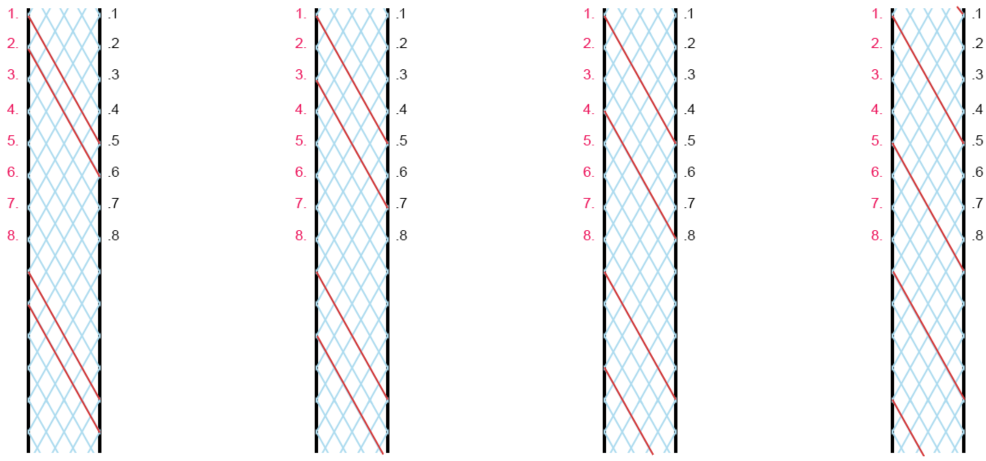



**Figure 12.** The Poisson's ratio-strain curves for BAY samples with different number of stiff yarns.



(a) (b) (c) (d)

**Figure 13.** Different arrangements of two stiff yarns in BAY structure: (a) without elastic yarns in between; (b) with one elastic yarn in between; (c) with two elastic yarns in between; (d) with three elastic yarns in between.

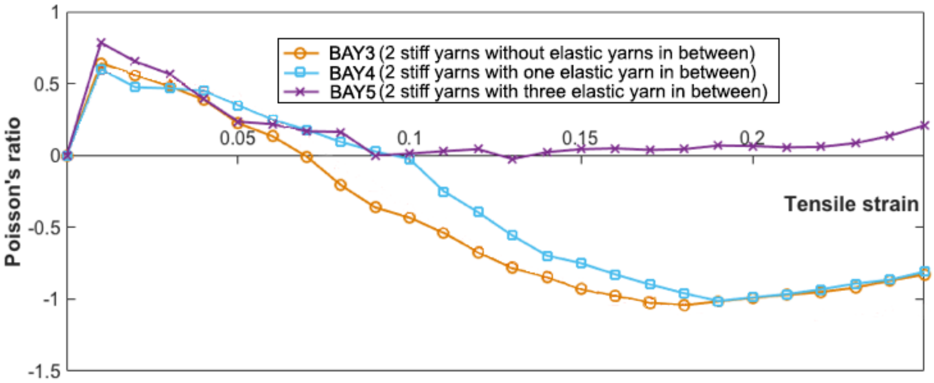



**Figure 14.** The Poisson's ratio-strain curves for the BAY samples with 2 stiff yarns in different arrangements.

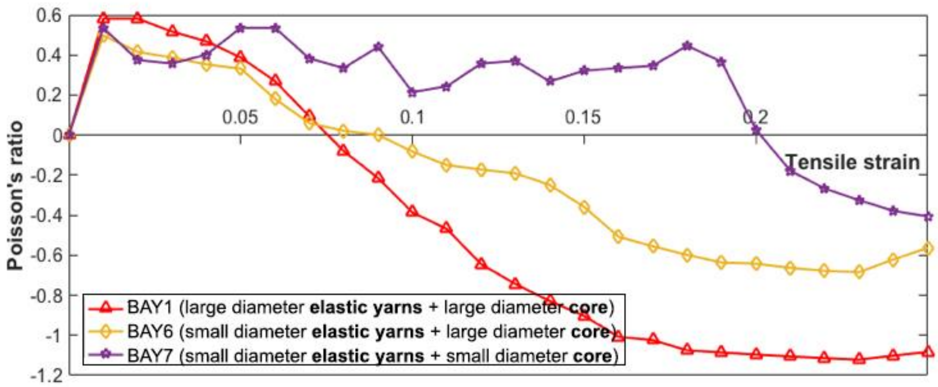
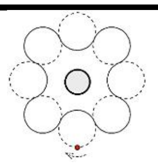
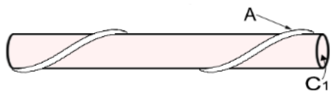
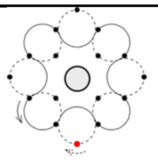
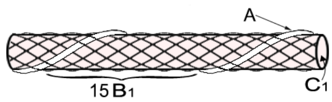
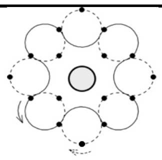
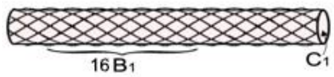
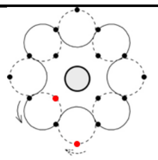
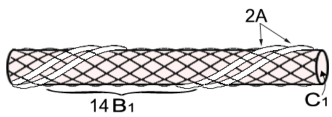
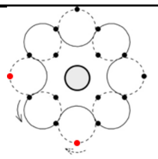
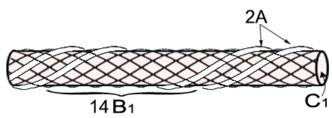
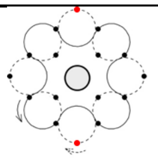
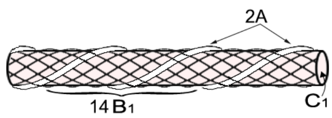
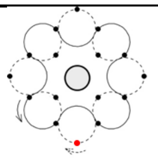
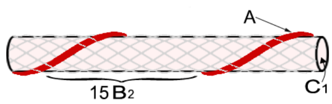



**Figure 15.** Poisson's ratio-strain curves of the BAY samples with different component diameter.

**Table 1.** Component yarns used.

| Component | Code | Yarn constituent | Diameter (mm) | Young's modulus (MPa) | Poisson's ratio | Color |
|---|---|---|---|---|---|---|
| Stiff yarn | A | Polyester | 0.36 | 1892 | 0.65 | white/red |
| Elastic yarn | B1 | Polyester and Rubber | 0.37 | 3.92 | 0.47 | black |
| | B2 | Cotton and Spandex | 0.20 | 5.75 | 0.52 | white |
| Core yarn | C1 | Polyester and Rubber | 2.16 | 4.23 | 0.29 | pink |
| | C2 | Polyester and Rubber | 1.45 | 4.23 | 0.29 | green |

**Table 2.** Production of HAY and BAY samples.

| Sample code | Component yarn combination | Component yarn arrangement ● stiff yarn ● elastic yarn ◯ Core | Structure illustration |
|---|---|---|---|
| HAY | $A+C_1$ |  |  |
| BAY1 | $A+15B_1+C_1$ |  |  |
| BAY2 | $16B_1+C_1$ |  |  |
| BAY3 | $2A+14B_1+C_1$ |  |  |
| BAY4 | $2A+14B_1+C_1$ |  |  |
| BAY5 | $2A+14B_1+C_1$ |  |  |
| BAY6 | $A+15B_2+C_1$ |  |  |

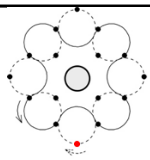
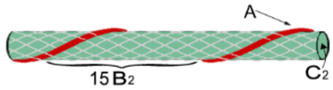
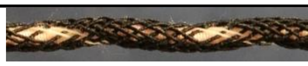
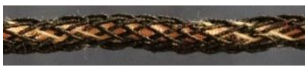
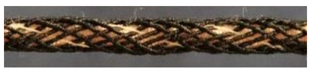
| | | | |
|---|---|---|---|
| BAY7 | $A+15B_2+C_2$ |  |  |

**Table 3.** Wrap angle measured in different structural units before and after repeated stretches.

| Sample | State | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | AVG | STDEV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HAY | Before | 35.4 | 32.7 | 33.8 | 35.9 | 34.8 | 33.6 | 35.9 | 36.1 | 35.7 | 34.4 | 34.8 | 1.1 |
| | After | 35.1 | 35.9 | 38.4 | 33.6 | 32.3 | 35.7 | 34.4 | 29.6 | 37.5 | 39.8 | 35.2 | 2.8 |
| BAY1 | Before | 34.8 | 35.6 | 36.5 | 34.3 | 33.6 | 34.9 | 35.6 | 33.4 | 34.1 | 33.1 | 34.6 | 1.0 |
| | After | 35.0 | 38.2 | 35.2 | 35.1 | 33.5 | 35.2 | 37.6 | 33.4 | 33.3 | 33.7 | 35.0 | 1.6 |

**Table 4.** Deformation of the BAY samples with 2 stiff yarns in different arrangements.

| Tensile strain | 5% | 15% | 25% |
|---|---|---|---|
| BAY3 |  $\nu = 0.22$ |  $\nu = -0.92$ |  $\nu$ =-0.80 |
| BAY4 |  $\nu = 0.35$ |  $\nu = -0.75$ |  $\nu$ =-0.81 |
| BAY5 |  $\nu$ =0.23 |  $\nu$ =0.04 |  $\nu = 0.21$ |