ANALYSIS OF THE TOW BUCKLING DEFECT DURING THE COMPLEX SHAPE FORMING OF A FLAX WOVEN FABRIC

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Abstract

A flax fibre plain weave fabric has been used to form a complex tetrahedron shape. The global shape has been obtained. Globally, the complex tetrahedron shape was obtained, but tow buckling was observed in specific zones of the shape. The main mechanism at the origin of this defect has been defined. The influence of the fabric architecture has also been discussed and a solution consisting in specifically optimising the architecture of the fabric was proposed and tested with success to prevent the appearance of the tow buckling defect.

1 Introduction

Natural fibres have long been considered as potential reinforcing materials or fillers in thermoplastic or thermoset composites. Numerous studies deal with the subject [1-6]. Natural fibres are particularly interesting because they are renewable, have low density and exhibit high specific mechanical properties. They also show non-abrasiveness during processing, and more importantly biodegradability. A large amount of work has been devoted to identify the tensile behaviour of individual fibres or group of few fibres of different nature and origin [7-10]. However, few studies deal with the subject of the mechanical behaviour of fibre assemblies and particularly analyze the deformability of these structures.

To manufacture high performance composite parts, it is necessary to organise and to align the fibres. As a consequence, aligned fibres architectures such as unidirectional sheets, non-crimped fabrics and woven fabrics (bidirectional) are usually used as reinforcement.

In the Liquid Composite Moulding (LCM) family, the Resin Transfer Moulding, (RTM) process has received a large attention in the literature [11] and particularly the second stage of the process dealing with the injection of resin in preformed dry shapes and the permeability of the reinforcements [12-13]. The first stage of this process consists in forming dry reinforcements. In case of specific double curved shapes, woven fabrics are generally used to allow in plane strain necessary for forming without dissociation of the tows.

The modification of the tow orientation and local variations of fibre volume fraction have a significant impact on the resin impregnation step as the local permeabilities (in-plane and transverse) of the reinforcement may be affected [14-15]. In the most severe cases, the ply of fabric can wrinkle or lose contact with the mould, hence severely reducing the quality of the finished product [16]. Another defect called tow buckling has also been reported for flax woven fabrics [17, 18]. As the quality of the preform is of vital importance for the final properties of the composite parts, it is important when forming of complex shape is considered to prevent the appearance of such defects.

Several experimental devices have been set up to investigate the deformation modes and the possible occurrence of defects during forming of textile reinforcements. Hemispherical punch and die systems were particularly studied because the shape is rather simple, it is doubled curved and because it leads to large shear angles between the tows [19-21]. In this paper, an experimental device is presented to form severe shapes. As an example, tetrahedron geometry is considered as it is much more difficult to form than hemispherical shapes especially if the radiuses of curvature are small.

This paper therefore proposes to analyse the feasibility of forming the mentioned complex shape with natural fibres based woven fabric reinforcements. A special attention is given on the defects that may appear during forming. The tow buckling defect is particularly discussed and a discussion upon the way to prevent their appearance is presented.

2 Experimental setup

A device specifically designed to analyze the local strains during the forming of reinforcement fabrics [22] is presented on Figure 1.a.

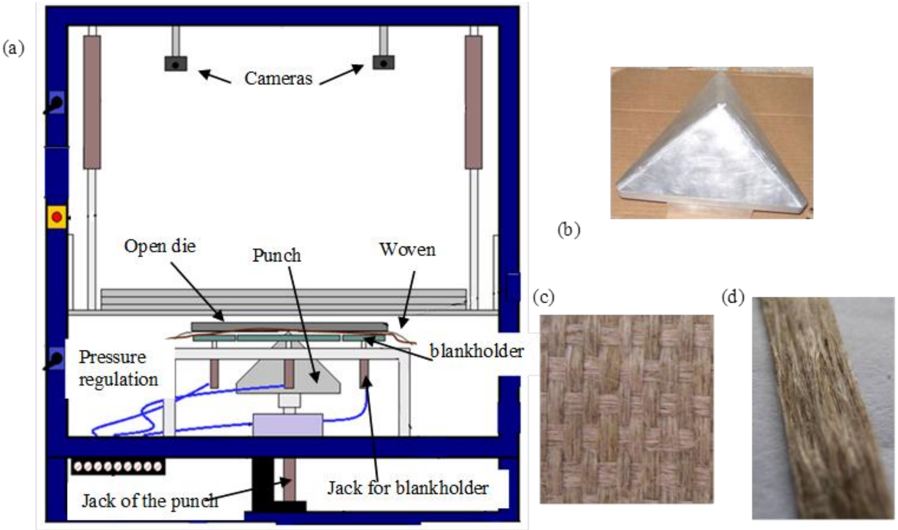


Figure 1: (a) Description of the device. (b) Tetrahedron punch. (c) Flax fabric (d) Flax tow.

The mechanical part consists of a punch/open die couple and a classical blank holder system. The die is open to allow the measurement of the local strains during the process with the cameras associated to marks tracking technique. The motion of the punch is given by a piloted electric jack. Nine independent blank holders associated to pneumatic jacks can be activated under the woven flat fabric. Dimensions, positions, and specifically variable pressure on each of these blank holders can be easily changed to investigate their influence on the quality of the final preform. This device has been developed to preform different shapes. Severe double curved shapes containing faces, edges and triple points at the intersection of the edge are considered. The tetrahedron punch used in this work is presented on figure 1.b.

3 Results

3.1 Materials properties and global preform analysis

The flax fabric (Figure 1.c) used in this study is a plain weave fabric which areal weight is of about 260 g/m^2 manufactured by the Groupe Depestele (France). The fabric is not balanced. This fabric is constituted of continuous tows (figure 1.d). Generally, when natural fibres are considered, twisted yarns are elaborated to increase its tensile properties. Indeed, as discussed by Goutianos *et al.* [23] sufficient tensile properties of the yarns are necessary for these ones to be considered for textile manufacturing or for processes such as pultrusion or filament winding. In this study, the flax tows used to elaborate the plain weave fabric are un-twisted and exhibit a rectangular shape. The fibres or groups of fibres are slightly entangled to provide a minimum rigidity to the tows. This geometry has been chosen as it generates low bending stiffness tows, therefore limiting the crimp effect in the fabric and therefore limiting empty zones between tows. It has also been chosen because fabric manufactured from highly twisted yarns exhibit low permeability preventing or partially preventing the use of processes from the LCM (Liquid Composite Moulding) family. Un-twisted tows have also been chosen because manufactured composites display better mechanical properties than composites made with twisted yarns [24].

At the local scale, an analysis of the shear angles [17] of the studied face shows that the values are relatively homogeneous and below the locking angle. It has also been shown that buckles defects may take place during the process [18].

An initial square specimen of the flax fabric is positioned with six blank holders placed on specific places around the tetrahedron punch. On each of them a pressure of two bar is applied. The maximum depth of the punch is 160 mm. At the end of the forming process, an epoxy resin spray is applied to the preform so that the shape is fixed in its deformed state.

An initial square specimen of the flax fabric is positioned with six blank holders placed on specific places around the tetrahedron punch. On each of them a pressure of one bar is applied. The maximum depth of the punch is 150 mm. At the end of the forming process, an epoxy resin spray is applied to the preform so that the shape is fixed in its deformed state. The preform in its final state is presented in Figure 2.a. At the scale of the preform the obtained shape is in good agreement with the expected tetrahedron punch. The fabric is not un-weaved on faces or edges. Some wrinkles appear (Fig.2.a) at the surrounding of the useful part of the preform. The position and the size of these wrinkles depend on the blank holder position and on the pressure they apply on the fabric. The process parameters (number and position of blank holders, choice of the punch, etc...) and the initial positioning of the fabric have a significant influence on the final shape. These aspects will be presented in future works. At the local scale, it is possible to analyse during the process the evolution of the shear angle between tows and the longitudinal strain along the tows. During the forming stage, the woven textile is submitted to biaxial tensile deformation, in plane shear deformation, transverse compaction and out-of-plane bending deformations. If all these components can be significant, the feasibility to obtain the expected shape is largely dependent on the in-plane shear behaviour. On the formed tetrahedron faces, values of the measured shear angle are relatively homogeneous [17]. These values do not reach the locking angle above which defects such as wrinkles appear.

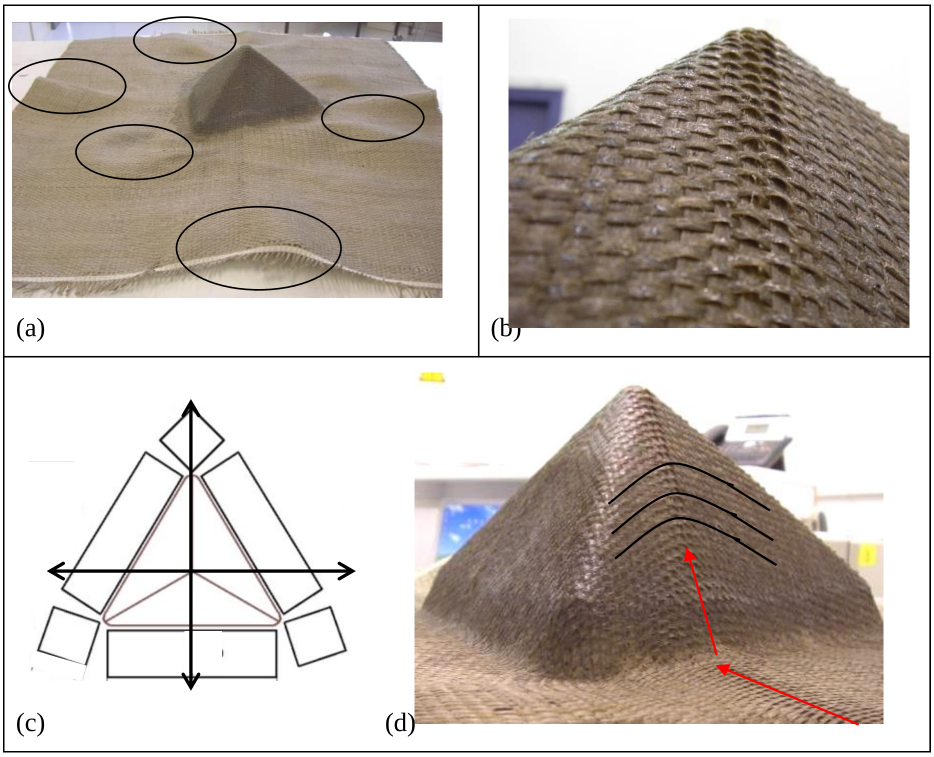
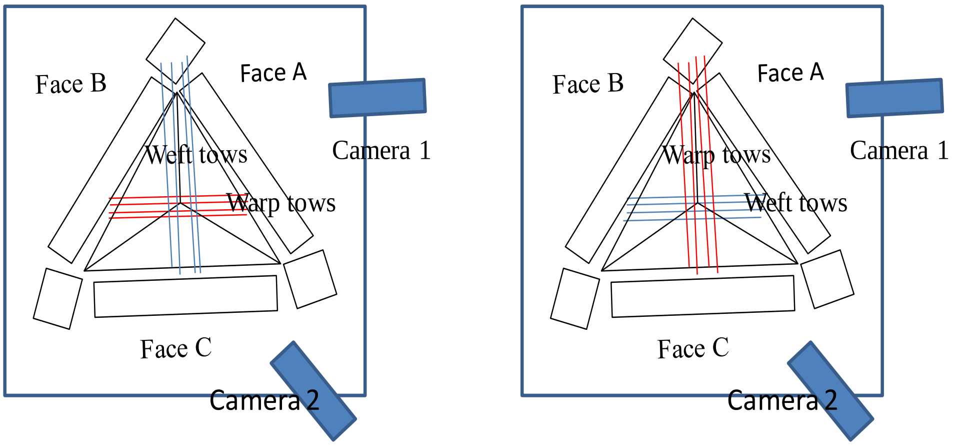


Figure 2: (a) Preform and Wrinkles. (b) Zoom on buckles. (c) Position of buckles. (d) tow orientation

3.2. Buckles defect

At the preform scale, buckles or tow buckling (Figure 2.b) appears on faces and on one edge of the formed tetrahedron shape. These buckles zones converge to the triple point (top of the tetrahedron) from the bottom of the shape (Figure 2.c) depending on the initial orientation of the fabric. Due to this defect the thickness of the preform is not homogeneous. The height of some of the buckles can reach 3 mm near the triple point. Due to this thickness in-homogeneity generated by these buckles, the preform could not be accepted for composite part manufacturing.

At the fabric scale, the buckles are the consequence of out of plane bending of the tows perpendicular to those passing by the triple point. The tows passing by the triple point (vertical ones) are relatively tight. On the contrary, the tows perpendicular to the one passing by the triple point are not tight, and the size of the buckles depends on those tows tension. In this zone, there is no homogeneity of the tensile deformation. This is illustrated by the orientation of the tows perpendicular to the one passing by the triple point on both sides of the buckle zone (drawn figure 2.d). These tows are curved instead of being straight, and this phenomenon is probably at the origin of the buckles.
To investigate the appearance of the defects, two initial positioning of the fabric have been tested as shown in Figure 3.

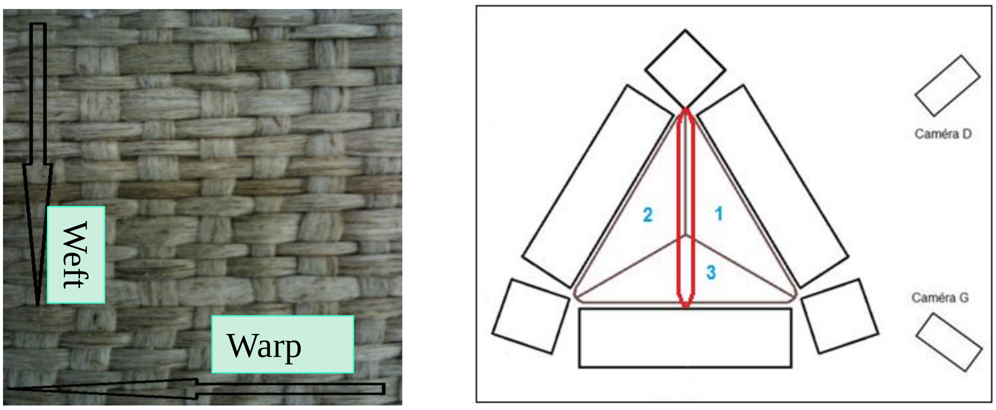


Orientation 0°: Weft tows aligned with edge 1

Orientation 90°: Warp tows aligned with edge 1

Figure 3: Initial positioning of the woven fabric

Figure 4 shows that in the case of the orientation 0°, buckles only appear on edge 1 and on the middle of face 3. No buckles are observed on faces 1 and 2.



a (initial orientation of the fabric 0°)

(b) Localisation of the buckles

Figure 4: Localisation of the buckle zone for initial fabric orientation of 0°

As the bending of the tows perpendicular to the ones passing by the triple point is the mechanisms supposed to be at the origin of the buckling defect, measurements of the bending angles on each faces has been carried out. Results are presented in Table 1:

Face number	1	2	3
Bending angle (°)	138±5	136±4	146±4

Table 1: Bending angle of the horizontal tows measured on the buckle zone orientation 0°

Table 1 shows that the bending angles are globally situated in the same range of values. The bending angles on faces 1 and 2 are slightly more pronounced than the one measured on Face 3. Similar investigations were carried out for orientation 90°. Figure 5 shows that in this case of study that the buckles can be observed in faces 1 and 2 only. For the orientation 90°, no buckles are observed on face 3 and on edge 1 as it was the case for orientation 0°.

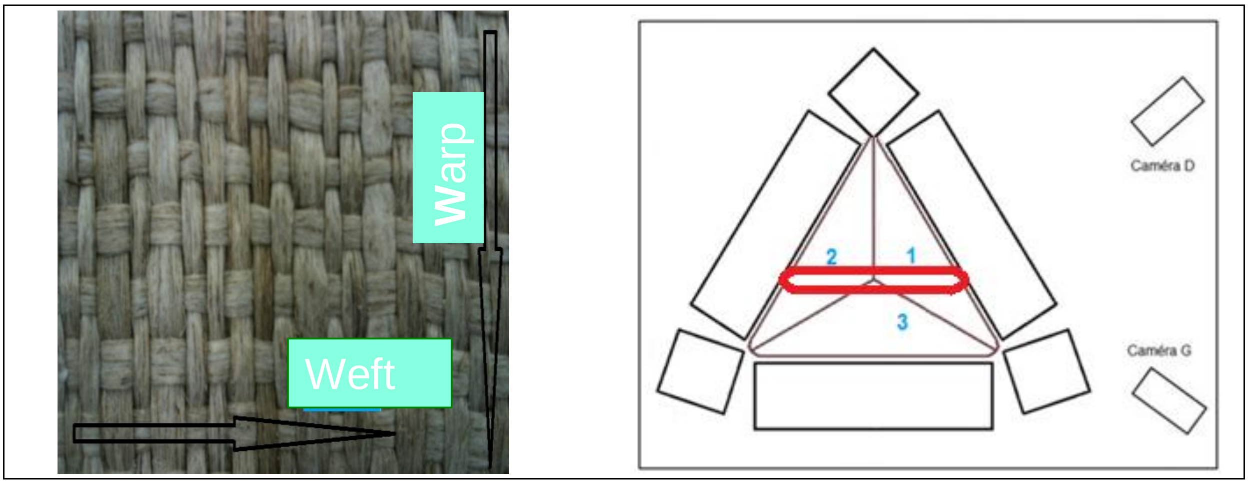


Figure 5: Localisation of the buckle zone for initial fabric orientation of 90°

The bending angles of the tows exhibiting buckling on the 3 faces of the shape were also measured. The values are reported in Table 2:

Face number	1	2	3
Bending angle (°)	138	141	143

Table 2: Bending angle of the horizontal tows measured on the buckle zone orientation 90°

For orientation 90° the measured bending angles are situated in the same range of values as the ones measured for the 3 face for orientation 0°. As a consequence, the bending of the tows (Figure 1d) is not responsible for the changes of the buckle zone location for the 2 tested orientations. The initial reinforcement orientation seems to be crucial. As a consequence, bending is not a sufficient criterion to predict the appearance of the buckles.

The reinforcement considered in this study is not balanced. The tows, used in the warp and the weft directions are similar. However, a space between the weft tows (about the width of a tow) is observed on the fabric whereas this space is not present between the warp tows. As buckles only appear on bending zones where the weft tows are vertical, (face 3 and edge 1 orientation 0° and face 1 and face 2 orientation 90°) one can conclude that the architecture of the reinforcement is a key parameter conditioning the appearance of the buckles. When the warp tows are vertical (without any space between them) the buckles do not appear even though the horizontal tows exhibit the same amount of bending. This suggests that the presence of the space between the weft tows is one of the parameter that controls the appearance of the buckles. As a consequence one can expect that a balanced woven fabric with no space between the warp and the weft tows should not show the appearance of buckles. This hypothesis was tested on a new reinforcement especially manufactured by Groupe Depestele to prevent the appearance of the buckles. This reinforcement is a balanced plain weave fabric also manufactured from flat untwisted tows. Figure 6 show that the hypothesis is verified as no buckles are observed when the tetrahedron shape is formed with the same processing conditions.

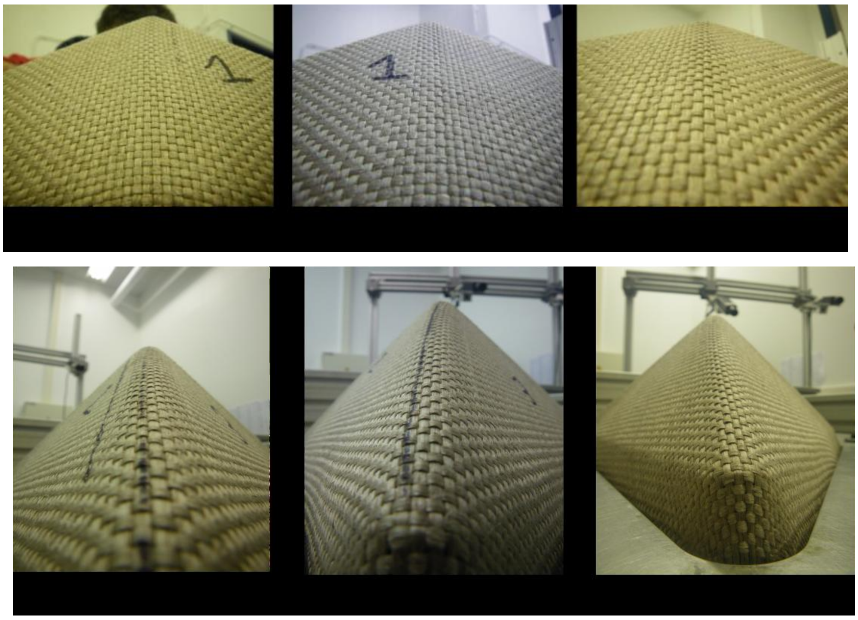


Figure 6: Forming of a balanced plain weave fabric.

4 Conclusions

A flax fibre plain weave fabric has been used to form a complex tetrahedron shape. The global shape has been obtained. Globally, the complex tetrahedron shape was obtained, but tow buckling was observed in specific zones of the shape. The main mechanism at the origin of this defect has been defined. The influence of the fabric architecture has also been discussed and a solution consisting in specifically optimising the architecture of the fabric was proposed and tested with success to prevent the appearance of the tow buckling defect.

Références

[1] La Mantia F.P., Morreale M. "Green composites: A brief review." *Composites Part A*, 42 (2011), 579-588.

[2] Satyanarayana K. G. , Arizaga G. G.C., Wypych F. "Biodegradable composites based on lignocellulosic fibers—An overview" *Progress in Polymer Science*, 34 (2009), 982–1021

[3] Biagiotti J., Puglia D., Kenny J. M. "A Review on Natural Fibre-Based Composites-Part I" *Journal of Natural Fibers*, 1: 2 (2004), 37 - 68.

[4] Puglia, D. , Biagiotti, J. and Kenny, J. M. 'A Review on Natural Fibre-Based Composites—Part II',*Journal of Natural Fibers*, 1: 3 (2005), 23 - 65.

[5] Pandey J. K., Ahn S. H., Lee C. S., Mohanty A. K., Misra M. "Recent Advances in the Application of Natural Fiber Based Composites" *Macromolecular Materials and Engineering*, 295 (2010), 975–989.

[6] Ouagne P., Bizet L., Baley C., Bréard J. "Analysis of the Film-stacking Processing Parameters for PLLA/Flax Fiber Biocomposites". *Journal of Composite Materials*, 44 (2010), 1201-1215.

[7] Baley C. "Analysis of the flax fibres tensile behaviour and analysis of the tensile increase" *Composites Part A*, 33 (2002), 2143-2145.

[8] Bodros E., Baley C. "Study of the tensile properties of stinging nettle fibres" *Materials Letter*, 62 (2008), 2143-2145.

[9] Alawar A., Hamed A.M., Al-Kaabi K.. "Characterization of treated data palm tree fiber as composite reinforcement" *Composites Part B*, 40 (2009), 601-606.

[10] Kim J.T., Netravili A.N. "Mercerization of sisal fibers: Effects of tension on mechanical properties of sisal fibers and fiber-reinforced composites" *Composite Part A,* 41 (2010), 1245-1252.
[11] Buntain M.J.,Bickerton S. "Modeling forces generated within rigid liquid composite moldings tools. Part A: Experimental study" *Composites Part A.*, 38 (2007), 1729-1741.
[12] Lekakou C, Johari B, Norman D, Bader G. "Measurement techniques and effects on in-plane permeability of woven cloths in resin transfer molding" *Composites Part A,* 27 (1996) 401-408.
[13] Ouagne P., Bréard J. "Continuous transverse permeability of fibrous media" *Composites Part A,* 41 (2010), 22-28.
[14] Hammani A., Trochu F., Gauvin R., Wirth S. "Directional permeability measurement of deformed reinforcement" *Journal of reinforced plastics and composites,* 15 (1996), 552-562.
[15] Loix F., Badel P., Orgeas L., Geindreau C. Boisse P. "Woven fabric permeability: from textile deformation to fluid flow mesoscale simulations" *Composites Science and Technology,* 68 (2008), 1624-1630.
[16] Sharma S.B., Sutcliffe M.P.F., Chang S.H.. "Characterisation of material properties for draping of dry woven composite material" *Composites Part A,* 34 (2003), 1167-1175.
[17] Ouagne P., Soulat D., Allaoui S., Hivet G. "Mechanical properties and forming possibilities of a new generation of flax woven fabrics". Proceeding of the 10th international conference on textile Composite (Texcomp). 26-28 October 2010, Lille, France.
[18] Ouagne P., Soulat D., Hivet G., Allaoui S., Duriatti D. "Analysis of defects during the preforming of a woven flax reinforcement". Advanced Composite Letters, 20 (2011) 105-108.
[19] Molnar P., Ogale A., Lahr R., Mitschang P. "Influence of drapability by using thermoforming" *Composites Science and Technology,* 67 (2007), 3386-3393.
[20] Li X., Bai S. "Sheet forming of the multy-layered biaxial weft knitted fabric reinforcement. Part 1: On hemispherical surfaces" *Composites Part A,* 40 (2009), 766-777.
[21] Vanclooster K., Lomov S.V., Verpoest I. "Experimental validation of forming simulations on fabric reinforced polymers using an unsymmetrical mould configuration. *Composites Part A,* 40 (2009), 530-539.
[22] Soulat D., Allaoui S., Chatel S. "Experimental device for the optimization step of the RTM process". *International Journal of Material Forming,* 2 (2009), 181–184.
[23] Goutianos S., Peijs T. "The optimization of flax fibre yarns for the development of high-performance natural fibre composites" *Advanced Composite Letters,* 12 (2003) 237-241.
[24] Goutianos S., Peijs T., Nystrom B. Skrifvars M. "Development of flax based textile reinforcements for composite applications" *Applied Composites Materials,* **13** (2006), 199–215.