Composites: Part A 42 (2011) 612–622

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Experimental and numerical analyses of textile reinforcement forming of a tetrahedral shape

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ARTICLE INFO

Article history:
Received 18 April 2010
Received in revised form 18 October 2010
Accepted 1 February 2011
Available online 25 February 2011

Keywords:
A. Fabrics/textiles
C. Finite element analysis
E. Forming
E. Preform

ABSTRACT

An experimental device for textile composite reinforcement forming is presented. A strongly double curved tetrahedral shape is formed by punch and die. This shape is those of the corner fitting parts used as corner brackets. The device shows that is possible to obtain such geometry by punch and die forming thanks to strong blank holder loads and an appropriate reinforcement. There is no wrinkle in the tetrahedral part of the formed shape but the six blank holders create wrinkles in the plane part of the preform. The shear angles reach 60° but there is no wrinkling in this zone. The presented forming process enables the experimental validation of a semi-discrete simulation approach. It is shown that shear angles and wrinkle shapes obtained by this numerical approach are in good agreement with the forming experiment. The computation of the shape of wrinkles after forming is necessary to check that these wrinkles do not expand to the useful part of the preform. This needs to take the bending stiffnesses into account. This is not the case when the simulation is based on a membrane approach.

1. Introduction

In Liquid Composite Moulding (LCM) processes, a resin is injected on a textile preform [1–3]. The shape of this preform can be complex. It can be obtained by a punch and die forming process from initially flat textile reinforcement. In case of double curved shapes, the forming process may be delicate because it needs in-plan deformations of the textile reinforcement and especially in-plane shear strains. A blank holder is then generally necessary in order to obtain a preform without defects (an especially with no wrinkles).

The experimental analysis and the numerical simulation of this forming process of the textile reinforcement are important in order to determine the conditions for a successful manufacturing of a preform (without defects). In addition they can determine the direction and the density of the fibres at any point on the preform after forming. Those directions are much depending on the forming process because shear angles between warp and weft yarns due to manufacturing can be large when the final shape is double curved. These directions condition the mechanical behaviour of the final solid composite, but also the filling of the resin in the case of a liquid moulding process [4–6].

The experimental devices for forming of textile preforms with deformation and loads measurements facilities are of main importance for the understanding of deformation modes and for the analysis of the defects that can occur during the forming. Concerning punch and die forming of textile preforms, several experimental forming system have been designed for hemispherical forming [7–15] (and extended hemispherical shape [16]). The hemispherical shape is much studied because it is rather simple, it is double curved and leads to large shear angles (about 45°). In the present paper an experimental device is presented for the forming of a tetrahedral shape which is those of corner fitting parts (or corner brackets). This shape is strongly double curved and is more difficult to form than an hemispherical part especially when the radius of curvature are small. It is shown that it is possible to manufacture this preform by punch and die forming thanks to a strong blank holder load and appropriate mechanical properties of the textile reinforcement (the thin interlock G1151® in the present work). There is no wrinkle in the tetrahedral part of the preform but many wrinkles in the plane zone due to the six blank holders. A main results given by this forming experiment concern the 'locking angle' This locking angle is commonly considered as the angle corresponding to the onset of wrinkling [17–20]. It is shown that very large shear angle are necessary for the tetrahedral forming but there is no wrinkle in this zone. Conversely there are many wrinkles in other areas where the shear angle are much smaller.

A main interest of the experimental forming device is validation of numerical forming simulations. These simulations permit to avoid the trial–error approaches for the development of forming processes and they also compute the directions and densities of

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doi:10.1016/j.compositesa.2011.02.001

the fibres before the injection stage. There are many simulation methods that are developed today based on different approaches (see Section 3) and it is important to know their abilities and their limits. The tetrahedral forming device is used to validate the semi-discrete simulation approach presented in [21]. In this approach (that is briefly described in Section 3) a finite element is made up of woven unit cells. The tensile, in-plane shear and bending internal virtual work are directly computed from the nodal displacements and from the mechanical properties obtained by experimental tests specific to textile composite reinforcements. This finite element is a shell element because bending stiffness is important for wrinkling simulations. In order to improve the numerical efficiency, a rotation-free formulation is used [22,23]. There are no rotation degrees of freedom but the curvatures are computed from the position of the neighbouring elements.

The numerical/experimental comparison concerns principally two points: the shear angles and the deformed shape, especially the shape of the wrinkles. The agreement is good. In particular, the simulation gives a realistic description of the wrinkles after forming. This is possible with the semi-discrete approach because the bending strain energy and the bending behaviour of the reinforcement (that is very specific) are considered. Some numerical analyses have been presented on onset of wrinkles [10,13], but they do not depict the shape of the wrinkles because they are based on membrane approaches and neglect the bending stiffness that conditions the wrinkle shape. However in a forming process such as the tetrahedral forming presented in this paper, it is not possible to avoid all wrinkles. The numerical simulation must check that the process conditions insure that those wrinkles do not expand in the useful part of the preform. In that goal, the computation of the shape of the wrinkles after forming, as it is performed in the present study, is important.

2. Experimental forming

2.1. Motivation

The development of one specific device able to preform woven textile reinforcement has two main objectives. First, such a device permit to experimentally analyze the possibilities to manufacture a double curved composite structure without defects in the useful part with a given textile reinforcement. The role of the blank holders, of the pretensions, of the speed of the tools…can be investigated. This is very useful because the composite forming processes do not benefit from so much experience than in the case of sheet metal forming. Furthermore the composite reinforcements are very numerous and different and it is not simple to extrapolate the results of a forming process to another one. An example corresponding to an angle bracket used in aeronautical applications is shown Fig. 1 [24,25]. The design of the part using a composite material leads to a minimum of 30% weight decrease. Nevertheless the manufacturing of this part in a composite material is difficult in particular making the preform in a RTM process with a good homogeneity of the fibre density and without defaults especially wrinkles. Other manufacturing processes are proposed for this shape for instance weaving on three-dimensional surfaces [26]. The forming process is faster.

Secondly, analyze of the state of the composite reinforcement after forming is an essential mean of validating numerical simulations. The numerical codes developed to simulate the textile reinforcement forming can significantly reduce component development time. But their validation by comparison with experimental forming processes is important for the confidence in their results. That is the purpose of the present paper. The experimental forming device described in this section permits to measure the loading parameters (loads on the tools, on the blank holders, speed of the tools …) and also to measure the geometry of the formed part. The state of the preform after forming is mainly characterised by the directions of the fibres (or in-plane shear angles) and the shape of possible wrinkles. In case of a double curved part, it is often impossible to avoid wrinkles anywhere in the woven fabric but these wrinkles must not extend to the useful part of the preform. Consequently it is important that the simulation tools forecast efficiently these wrinkles.

The comparison of the wrinkle shapes obtained by the simulation with the experimental ones is one of the objectives of this paper. This comparison needs an accurate description of the textile

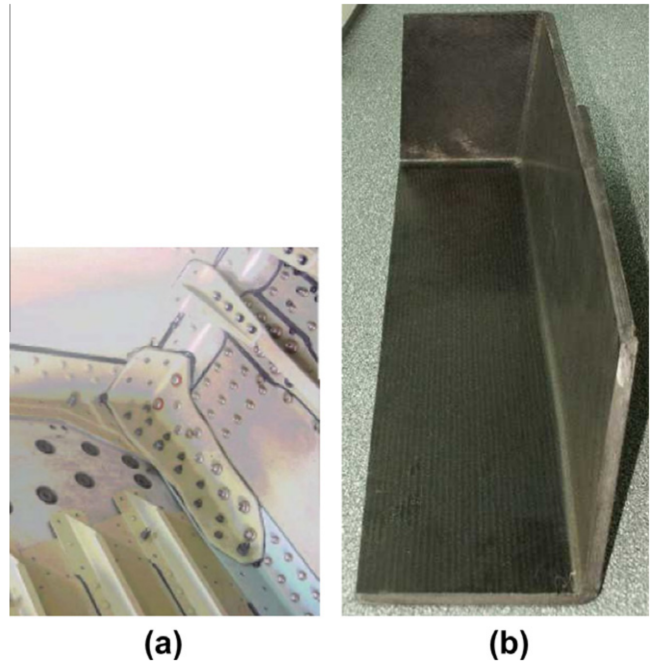

Fig. 1. Example of double curved shape for aeronautical piece. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

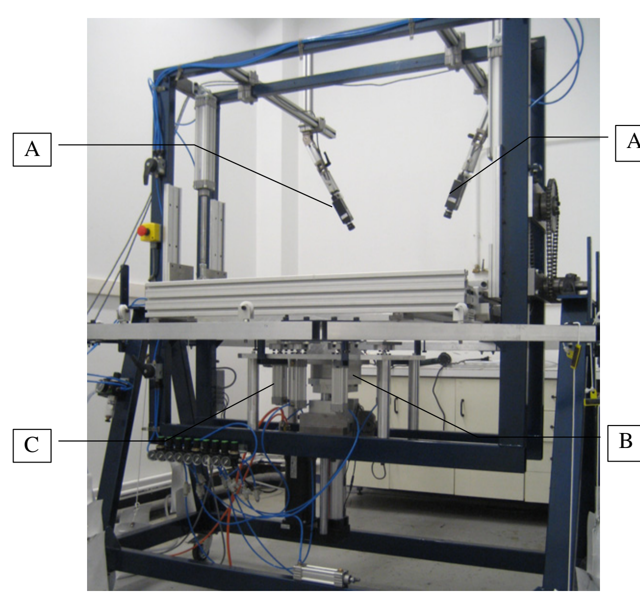

Fig. 2. The preforming device. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)