Composites: Part A 77 (2015) 114–123

Contents lists available at ScienceDirect

Composites: Part A

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

Establishing a new Forming Limit Curve for a flax fibre reinforced polypropylene composite through stretch forming experiments

Wentian Wang *, Adrian Lowe, Seb Davey, Nima Akhavan Zanjani, Shankar Kalyanasundaram

Research School of Engineering, Australian National University, North Road, Canberra 0200, Australia

ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form 8 May 2015
Accepted 19 June 2015
Available online 28 June 2015

Keywords:
A. Polymer-matrix composites (PMCs)
C. Finite element analysis
D. Failure
E. Forming

ABSTRACT

In developing an understanding of the failure in natural fibre reinforced polymer composites, the failure limits of this class of the material system are required. It is found that the conventional Forming Limit Curve is not suitable to predict the failure initiated in the natural fibre composite as principal strains cannot differentiate the strain on the flax fibres and the polypropylene matrix. This study proposes a new Forming Limit Curve for the composite which expresses limiting fibre strain as a function of forming mode depicted by the ratio of minor strain to major strain. The new Forming Limit Curve, along with the Maximum Strain failure criterion have been successfully implemented in FEA simulations, and numerical simulations suggest that the former is more accurate. The current work provides an innovative method to predict the onset of failure in natural fibre composites, which can be applied in composite forming and structural design.

1. Introduction

Today, there is an urgent need for reducing the weight of vehicles to improve fuel efficiency, and therefore to reduce global greenhouse gas emissions. Natural fibres such as flax, hemp, jute, sisal, kenaf, bamboo and ramie have been investigated as reinforcements for fibre reinforced polymer composites, some of which seem to have the potential of being used in automobiles [1]. Natural fibres are mainly made of cellulose, hemicellulose, lignin, pectin and a small amount of extractives [2], and they can offer attractive properties including low density, low price and ease of processing [2–4]. In addition to these, the biodegradability of natural fibres allows them to be recycled and probably reused at the end-of-life. The global natural fibre composite market reached $2.1 billion in 2010 with a 15% compound annual growth rate between 2006 and 2010. The size of this market is expected to reach $3.8 billion by 2016 as a result of rising price of petroleum based products, and more importantly strong government support on eco-friendly material usage [5]. For instance, European Union and Asian countries require that 85% of the vehicle must be reused or recycled by 2015 [6].

One of challenges in widely using advanced lightweight material systems in the vehicle manufacturing is a suitable manufacturing technique. The stamp forming technique has been successfully used in rapid forming of different material systems [7–13]. Hou [14] studied a preconsolidated glass fibre reinforced polyetherimide composite. It was found that the composite can exhibit a significantly increased elongation-to-failure at 45°/45° (around 52%) compared to 0°/90° (around 0.65%) to fibre directions, which can be explained by the trellis behaviour of the woven composite. This could also effectively reduce the compressive force and prevent fibre buckling during forming. A similar finding was obtained by Wang et al. [9] indicating that matrix shear deformation can aid in superior forming behaviour of woven natural fibre composites in stamp forming. Davey et al. [7] formed a carbon fibre reinforced polyether ether ketone (PEEK) composite through stamp forming. The composite exhibited a major failure mechanism of fibre fracture due to the much lower elongation-to-failure of the carbon fibres compared to the PEEK matrix. It was also found that the variation in allowable strain of the carbon fibres affected the location where failure initiated during forming. Sexton et al. [15] investigated a fibre metal laminate based self-reinforcing polypropylene composite through stretch forming experiments. By comparing with that of the 5005 H34 aluminium, the laminate system exhibited a larger range of allowable minor strain for a given major strain and a safe forming region with higher major strain, suggesting the potential of exhibiting a superior formability.

* Corresponding author. Tel.: +61 02 6125 8546.
E-mail addresses: wentian.wang@anu.edu.au (W. Wang), adrian.lowe@anu.edu.au (A. Lowe), seb.davey@anu.edu.au (S. Davey), nima.akhavan@anu.edu.au (N. Akhavan Zanjani), shankar.kalyanasundaram@anu.edu.au (S. Kalyanasundaram).

http://dx.doi.org/10.1016/j.compositesa.2015.06.021
1359-835X/

A number of failure criteria, including non-interactive criteria and interpolation criteria, have been successfully applied to fibre reinforced composites for prediction of their failure behaviour. The Maximum Strain and the Maximum Stress belong to non-interactive failure criteria, as they limit every strain/stress component but do not account for any interactions between each component [16]. Based on the Maximum Strain failure criterion, Hart-Smith [17,18] applied modifications through a micromechanical approach and suggested a truncated failure envelope in biaxial tension as well as biaxial compression. The truncated Maximum Strain failure model predicts a more conservative failure envelope in in-plane shear where the reduction in strength is approximately 60%. The interactions between the fibres in the warp direction and the weft direction are influential for pre-consolidated woven composites, resulting in inaccuracies when applying non-interactive failure criteria to this class of the material system. Interpolation criteria consider interactions between different components of the stress/strain tensor. Tsai and Wu [19] developed tensor polynomial failure criteria, but the proposed mathematical function cannot distinguish between fibre fracture, matrix cracks or interface breakage [16]. It is important to note that most failure models are derived from unidirectional lamina or the laminates made from unidirectional lamina layers. These failure criteria do not account for weave structures, whereas the behaviour of woven composites is highly affected by the interactions between different constituents. In addition to this, failure models are developed for homogenized composites, whereas natural fibre reinforced composites usually exhibit a high level of porosity [20]. The geometric unevenness and material non-uniformity caused by this may also affect the application of these theoretical failure criteria. It can be seen that while extensive research has been conducted on establishing the failure limits of fibrous composites, little has been performed on investigating this for preconsolidated woven composites. The Forming Limit Diagram (FLD) illustrates the surface strain distributions of materials on a plot of major strain against minor strain. Materials were usually cut into different shapes (including rectangular, hourglass, etc.) with a varying middle section width (to cover a wide range of forming modes), and formed till failure occurs. The principal strains of the failure region were plotted on FLD and connected by the line referred as the Forming Limit Curve (FLC). The FLC shows clearly the limiting principal strains in each deformation mode, and the material would be considered failed if the strain deformation is beyond the FLC. A number of studies have proved that FLCs can successfully predict the failure associated with monolithic metal alloys [21,22]. Inspired from metal forming, Zanjani et al. [23] proposed a FLC for a preconsolidated woven self-reinforced polypropylene composite through experimental outcomes in stretch forming tests. The failure criterion illustrated failure limits in each forming mode of the composite, and could be easily implemented in numerical simulations to predict the onset of failure. The current study firstly examines the conventional FLD for a flax fibre reinforced polypropylene composite. A new FLD from different parameters is proposed, on which a new FLC is established through experimental outcomes in stretch forming tests. Finally, the new FLC, along with the Maximum Strain failure criterion are implemented in numerical simulations for comparison and validation.

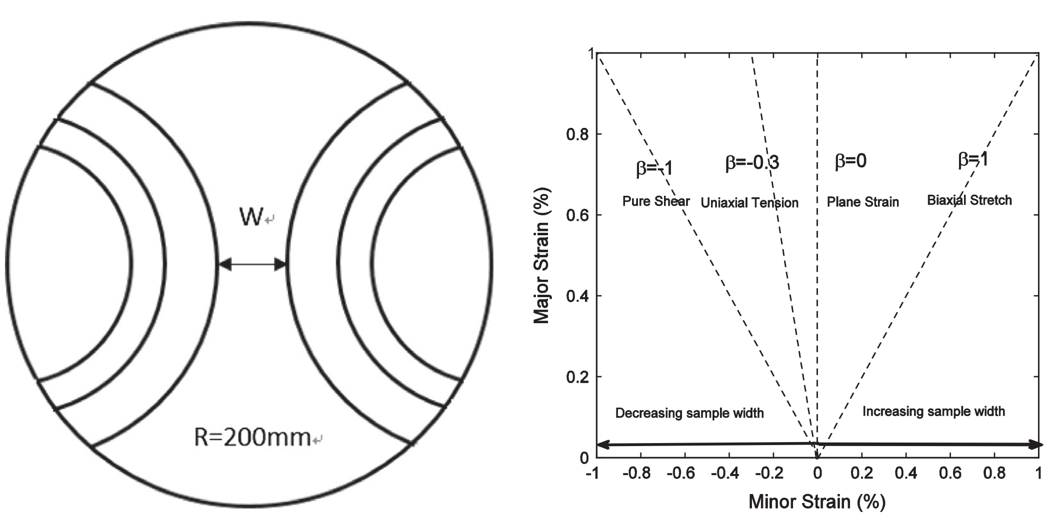
2. Material preparation and experimental setup

The fabric was manufactured by Composite Evolution, UK and then consolidated by the Xiafei factory, China. Continuous flax bundles were woven in a 2 by 2 twill structure, and the consolidated composite had a thickness of 1 mm, a fibre weight fraction of 50% and a density around 1.2 g/cm^3. It was noted that the composite exhibits a higher than expected level of porosity in the surface and through the thickness of the composite, which could be attributed to the evolution of gaseous products during the consolidation process. This results in some localised imperfections in small segments on the surface of sample. These minor imperfections do not result in mechanical properties being reduced.

Stretch forming experiments were developed to investigate failure in different forming modes in monolithic metal alloys, and this technique has also been successfully used in woven composites [23]. The current study determines the failure limits of the natural fibre composite through stretch forming experiments. By increasing the width of hourglass specimens, the composite experiences increased lateral restriction during forming, which prevents the sample from drawing into the die cavity. This results in a forming mode closer to biaxial stretch (a strain ratio closer to 1) as shown in Fig. 1. In material forming, the forming mode experienced by samples can be determined from the strain ratio between minor strain and major strain as illustrated in Eq. (1).

$$\beta = \frac{\varepsilon_{Minor}}{\varepsilon_{Major}} \tag{1}$$

where β is the strain ratio, ε_{Minor} is the minor strain, ε_{Major} is the major strain.



(a) (b)

Fig. 1. Schematic of hourglass geometries used in the tests, and the effect of sample width on the forming mode of the sample.