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Numerical investigation of insect wing fracture behaviour

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ABSTRACT

The wings of insects are extremely light-weight biological composites with exceptional biomechanical properties. In the recent years, numerical simulations have become a very powerful tool to answer experimentally inaccessible questions on the biomechanics of insect flight. However, many of the presented models require a sophisticated balance of biomechanical material parameters, many of which are not yet available. In this article we show the first numerical simulations of crack propagation in insect wings. We have used a combination of the maximum-principal stress theory, the traction separation law and basic biomechanical properties of cuticle to develop simple yet accurate finite element (FE) models of locust wings. The numerical results of simulated tensile tests on wing samples are in very good qualitative, and interestingly, also in excellent quantitative agreement with previously obtained experimental data. Our study further supports the idea that the cross-veins in insect wings act as barriers against crack propagation and consequently play a dominant role in toughening the whole wing structure. The use of numerical simulations also allowed us to combine experimental data with previously inaccessible data, such as the distribution of the first principal stress through the wing membrane and the veins. A closer look at the stress-distribution within the wings might help to better understand fracture-toughening mechanisms and also to design more durable biomimetic micro-air vehicles.

1. Introduction

Insect wings appear as delicate and fragile structures, yet they are able to efficiently withstand external mechanical stress during the lifetime of an insect. During normal flight, the flapping or gliding wings of insects can experience different types of dynamic loading, they can actively or passively change their shape, and are subjected to aerodynamic forces significantly larger than the insects' weight for thousands of loading cycles (Dirks et al., 2013; Du and Sun, 2010; Ellington, 1984; Ennos, 1989; Wootton, 1992; Wootton et al., 2003).

Still many fundamental questions regarding the biomechanics of insect flight remain unanswered (Herbert et al., 2000; Sane, 2003). A common problem within the insect flight biomechanics community is that due to the small size of the specimens, and their rapid movements, often direct experimental studies of the wing dynamics and biomechanical properties are still very challenging and difficult. However, with the decreasing costs of computing power, numerical simulations have become more and more popular in studies on insect flight.

In the recent years various finite element models have been used to study the biomechanical behaviour of wings from dragonflies, locusts and other insects; this work has been reviewed and discussed in detail by Wootton et al. (Dirks et al., 2013; Du and Sun, 2010; Ellington, 1984; Ennos, 1989; Wootton, 1992; Wootton et al., 2003). So far, these numerical models have been mostly used to simulate dynamic properties of the insect wing; for example the umbrella-like unfolding in the locust hind-wing (Herbert et al., 2000; Sane, 2003), or the vibrational and deflection behaviour of wings (Darvizeh et al., 2011, 2009; Kesel et al., 1998; Rajabi et al., 2011; Vanella et al., 2008). Interestingly, for some of these cases it has been shown that a relatively sophisticated and fine-tuned model is required to replicate the behaviour of the wing; and even small changes of the parameters can easily result in notable deviations of the simulation from the model (Herbert et al., 2000). Other studies however, focusing more on static material properties of the wings, have shown that even simple numerical models can suffice to simulate natural biomechanical "behaviour"

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of the wing and simulations can be even used to supplement some otherwise difficult or even impossible mechanical experiments (Combes and Daniel, 2003a; Ganguli et al., 2009).

Here we show that a relatively simple finite element model can be devised which is capable of closely replicating the fracture behaviour of a locust hind wing. In a previous study, we examined the fracture behaviour of locust wings (Dirks and Taylor, 2012a). Our results showed that the cross veins present in the wings act as barriers to crack propagation, effectively increasing the material's toughness by a factor of 50%. The objective of the present article was to devise a way to simulate these results numerically and to use the numerical model to investigate other factors which are difficult to study experimentally.

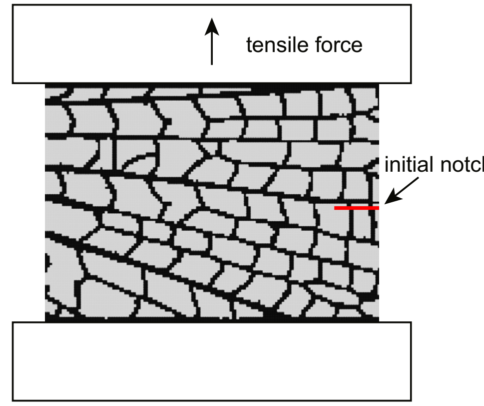

Fig. 1. Sketch of the experimental and simulated set-up for tensile tests on a locust hind wing.

2. Materials and methods

2.1. Finite element modelling using image processing technique

To create a 2D meshed model of the test samples, images were captured from video recordings of locust hind wings under tensile loading ($N=11$, adult female *Schistocerca gregaria* locusts, see Dirks and Taylor, 2012a). We chose representative recordings showing typical vein-inhibited crack growth (suppl. video 1) or recordings where the sample failed due to the development of secondary cracks (suppl. Video 2). The images were recoded into binary format, where veins and membranes are displayed by black and white colours, respectively. A custom made Matlab code (R2012a, Mathworks, Natick, MA, USA) was then used to generate a mesh from the veins and membranes. The mesh was then imported into the explicit FE solver ABAQUS/Standard Version 6.1. The wings were modelled using four-node quadrilateral shell elements of 0.121 mm in size. The models contain 13964, 12250, 11563 nodes and 13724, 12024, 11329 elements, respectively.

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2.2. Material properties and boundary conditions

Only very limited datasets are available on the mechanical properties of insect cuticle, (Dirks and Taylor, 2012b; Vincent and Wegst, 2004). In particular there are no experimental data on the wing vein strength or fracture toughness. However, previous experimental tensile tests on insect wings indicate that the deformation of cuticle usually occurs in an elastic manner (Dirks and Taylor, 2012a; Rajabi and Darvizeh, 2013; Wootton et al., 2000). Therefore, we used a linear elastic material model to describe the mechanical behaviour of the wing veins and membranes. Our earlier experiments with hind wings from *S. gregaria* locusts showed that the wing membrane has a mean tensile strength 52.21 MPa, a stiffness of 1.86 GPa and a fracture toughness of 1.04 $\text{MPa}\sqrt{\text{m}}$, which corresponds well with values published elsewhere (Dirks and Taylor, 2012a; Smith et al., 2000). As there are currently no experimental datasets available for the Young's modulus of longitudinal and cross veins in locust hind wings, we have chosen a stiffness of 3 GPa and a strength of 52.21 MPa, which corresponds the stiffness of leg cuticle and tensile strength of the membrane respectively (Dirks and Taylor, 2012b). The fracture toughness of the veins was considered to be 1.57 $\text{MPa}\sqrt{\text{m}}$ (Dirks and Taylor, 2012a).The material density and the Poisson's ratio of both veins and membrane cuticle were taken as 1200 k m^{-3} and 0.49, respectively (Combes and Daniel, 2003b; Smith et al., 2000; Vincent and Wegst, 2004).

The thickness of the membranes was assumed to be constant 1.7 μm over the entire wing structure (Smith et al., 2000). The thickness of the simulated veins (with rectangular cross sections) was adapted to equal the cross sections of the circular hollow real cross-veins.

After assigning the appropriate thickness to the models, the model was set up to simulate the fracture toughness test used in our experimental work (Dirks and Taylor, 2012a). Specifically, a rectangular sample of wing had a sharp notch induced into it from one edge; the sample was then loaded in axial tension with a crosshead speed of 0.2 mm/min with uniform displacement boundary conditions across the upper and lower edges (see Fig. 1).

2.3. Crack initiation criterion

Our previous experiments showed that locust wing behaves like a brittle material as regards its crack propagation characteristics (Dirks and Taylor, 2012a). To simulate the failure of brittle biological materials, such as bone, eggshell and mollusc shells, previous studies have successfully applied the maximum principal stress theory (Darvizeh et al., 2014, 2013; Doblaré et al., 2004; Faghih Shojaei et al., 2012; Willinger et al., 2000). We have therefore also chosen the maximum principal stress theory to simulate the crack initiation in the insect wings.

The first stage of the failure of a material is crack initiation. Crack initiation refers to the beginning of the process of degradation of an element. At the first step of crack initiation, the software checks the value of the stress at the element on the crack tip as well as the stress in all elements remote from the initial notch. When the highest principal stress in an element of the structure equals or exceeds the uniaxial ultimate tensile (S_{ut}) or compressive strength (S_{uc}) the element fails (Budynas and Nisbett, 2008). The general state of the stress at any point of the body can be defined by three principal stresses, $\sigma_1 > \sigma_2 > \sigma_3$ with failure occurring when

$$\sigma_1 \geq S_{ut}. \tag{1}$$

It is important to note that the crack initiation criterion predicts only the initial *start* of a crack. How the elements split into two parts and the magnitude of separation are governed by a traction-separation law, as described in the next section.

2.4. Traction-separation law

When a crack-like defect appears in a stressed material, a damage region may be developed due to stress concentration ahead of the crack tip. The damaged region, which is a consequence of plasticity or micro-cracking, is known as the cohesive zone (Anderson, 1991). FE modelling of crack propagation can be achieved by introducing the cohesive zone elements between all continuum elements. These cohesive elements are used to represent the cohesive forces that act against element separation (Achintha and Burgoyne, 2013). When failure takes place, these interface elements open up and the continuum elements will be separated (Brocks et al., 2003).

The fracture of a material can be characterized by traction-separation laws, i.e. they are used to describe the constitutive behaviour of a material in the cohesive zone. For our simulations, and to reduce computational complexity, we used a linear traction-separation law (Camacho and Ortiz, 1996), which is determined by the characteristic toughness and characteristic strength of the material and can be written in the following form

$$t = t_0\left(1 - \frac{\delta}{\delta_{\sigma cr}}\right). \tag{2}$$

In the above, t is the cohesive traction, t_0 is the traction at fracture, δ is the crack opening displacement and $\delta_{\sigma cr}$ is the critical opening displacement. Based on this linear softening model, the cohesive force is linearly and irreversibly decreased to zero as the crack opening displacement is increased. When the critical displacement is reached, the cohesive elements lose their stiffness and the crack growth occurs in a direction perpendicular to the maximum principal stress. In our simulations, the experimentally measured values of tensile strength and fracture toughness of the wing materials reported above are taken as the characteristic strength and characteristic toughness, respectively.

3. Results

An example of our results for the simulated crack propagation through a locust hind wing is shown in video 1 (see suppl. video 1 for the experimental test). To illustrate the results we chose representative screenshots of the simulation before the crack hits the first cross vein, at each cross vein and before complete failure of the wing (see Fig. 2). The stress-strain values from the same