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Design, manufacture, mechanical testing and numerical modelling of an asymmetric composite crossbow limb

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ABSTRACT

This paper considers the design, manufacture, mechanical testing and numerical analysis of a crossbow beam (limb). The limb should be lightweight and permit a high deflection of the beam's tip in order to achieve a good ballistic performance. Consequently, fibre-reinforced polymer matrix composites are suitable candidate materials. However, carbon fibres were considered too brittle for this application. Aramid fibres combine low density and high stiffness but are weak in compression. E-glass fibres are relatively flexible but are of high density. The optimised design developed here uses aramid fibres on the tension face with E-glass fibres on the compression side. This component was manufactured using resin infusion, modelled using a commercial finite element code (Abaqus®) and the model was validated by mechanical testing. A good correlation was found between the experimentally measured deflections and the numerical results.

1. Introduction

Polymer matrix composites are the preferred materials in applications where high-strength and high-stiffness to weight ratios are required. Composite beams are used as load-carrying elements in high-performance aerospace, marine/naval, land transport, sport, mechanical (e.g. machinery) and civil (e.g. bridges) applications. Composites are useful where energy is stored and released in a controlled manner. This includes automotive leaf [1,2] and coil springs [3] and many sports goods [4–7]. For example, a crossbow limb stores the energy required to propel the arrow [8–10]. The traditional materials for the crossbow limb are wood or spring steel. Kooi et al. [8] state that "The efficiency of the bow is affected by the relative mass of the arrow when compared to that of the limb, but for an arrow of constant mass the lighter the limb the better the efficiency". Composites offer resilience, low structural weight, long service life and are not adversely affected by the environment. Thus a lightweight composite limb should outperform limbs of other materials.

This paper reports the design, manufacture using resin infusion, mechanical testing and numerical (Abaqus® finite element code) modelling of a crossbow beam (limb). This study was undertaken in the context of an undergraduate assignment for the BEng (honours) Mechanical Engineering with Composites degree. The time constraints did not permit consideration of shear stresses and strains at the load introduction and reaction points, or of the fatigue life.

2. Preliminary design calculation

Fig. 1 shows the configuration of the key components of the crossbow. The limb deflection is a function of the draw length, *s*, limb length, *L* and the braced position, *h* [10]. A typical crossbow limb specification [11] requires that the limb must store sufficient energy to fire a bolt (arrow) of 22 g, at an exit velocity of 100 m/s with a power stroke, *d*, of 0.35 m. The limb length is usually ~0.4 m and is critical to the performance of the crossbow (Fig. 1). Composite materials have high reliability and the loading and environmental conditions for crossbows are not severe therefore the Factor of Safety (FOS) for the limb only needs to be 1.5 [12].

The kinetic energy required for a bolt (mass, m = 22 g and velocity, v = 10 m/s) is,

$$E = \frac{1}{2} m v^2 = 110\,\mathrm{J} \tag{1}$$

The work done by a force, *F*, moving a body through a distance, *d*, is given by:

$$E = Fd \tag{2}$$

The force is assumed to be a maximum at the start of the stroke and zero at the end. The requisite maximum force, F_H, can be estimated from Eqs. (1) and (2) (remembering that Fig. 1b only shows half of the system).

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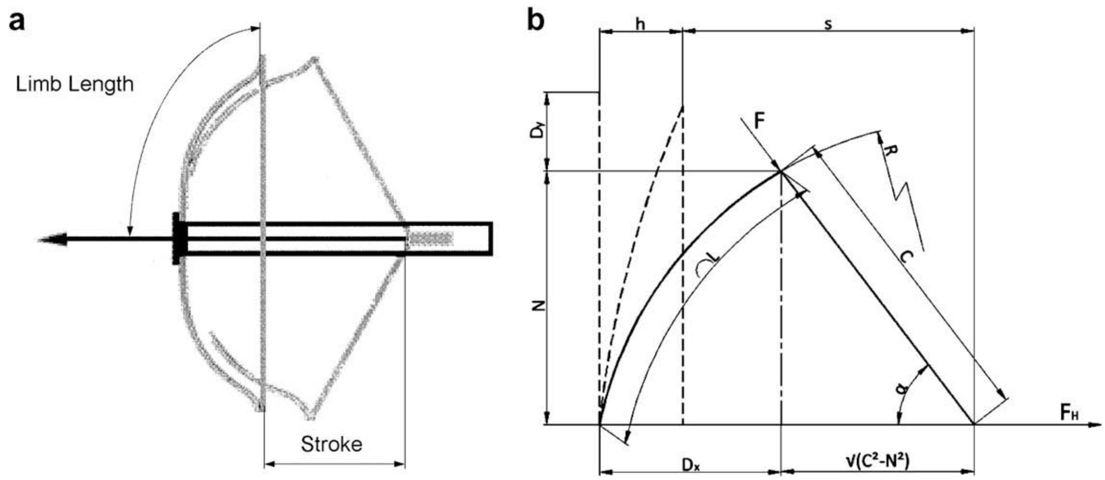

Fig. 1. The crossbow (a) and a schematic representation (b) of the crossbow at pre-firing position.

$$F_H = \frac{mv^2}{d} = 630\ \mathrm{N} \tag{3}$$

The relationship between the radius of curvature, R, and the other crossbow dimensions is given in Eq. (4), where N is half the chord length. The string is assumed to be inextensible [10] and the limb is assumed to bend in a circular arc.

$$R = \frac{h^2 + s^2 + C^2 + 2hs - 2h\sqrt{C^2 - N^2} - 2s\sqrt{C^2 - N^2}}{2\left(h + s + \sqrt{C^2 - N^2}\right)} \tag{4}$$

$$\sin\alpha = \frac{N}{C} \tag{5}$$

$$L = R\sin^{-1}\left(\frac{N}{R}\right) \tag{6}$$

$$D_x = h + s - \sqrt{C^2 - N^2} \tag{7}$$

$$D_y = L - N \tag{8}$$

The force acting on the arrow, F_H, is a function of the angle between the string and the arrow, α. At rest α is 90°, but as the string is drawn the angle decreases as shown in Fig. 2, and the deflections in the x and y directions are given by D_X and D_Y, respectively. The normalised force acting on the arrow is also shown in Fig. 2. This normalised force is a function of the end load of the beam, F, and is given by Eq. (9) [10]; the shape of the graph is similar to that given by Kooi et al. [8,10].

$$F_H = F\cos\alpha \tag{9}$$

The reinforcement options considered for the limb (Table 1) were carbon, E-glass and/or aramid fibre as monolithic or hybrid composites, or cored sandwich constructions. The limb was loaded at the end (bending load) and hence it carries a direct tensile load on the outer face and a compressive load on the inner face. Therefore unidirectional fibres oriented parallel to the beam axis will provide maximum stiffness [13]. Unidirectional (UD) carbon fibres offer highest specific modulus [13] and hence the lightest weight limb but are too brittle. E-glass fibres offer the highest strain to failure [14] which makes the limb more tolerant to higher deflection but results in the highest weight. Aramid fibres have low compression strength [14–16] although the tensile modulus of the fibre is double that of E-glass fibres [14]. Thus, a potential solution to satisfy the specification of this component is to combine the E-glass and aramid fibres to make a hybrid composite beam. The outer tension face

Table 1
Potential design options.

	Design 1	Design 2	Design 3	Design 4	Design 5
Outer (tension)	Carbon	Carbon	E-glass	Aramid	Aramid
Centre	Carbon	Core	E-glass	Core	E-glass
Inner (compression)	Carbon	Carbon	E-glass	E-glass	E-glass

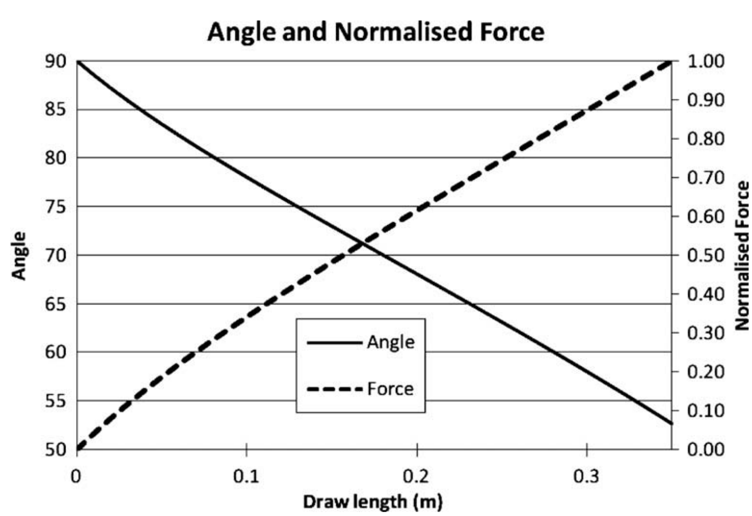

Fig. 2. Variation of force and angle between string and arrow as string is drawn.