THE STATIC AND DYNAMIC BEHAVIOUR OF CARBON FIBRE COMPOSITES USED IN GOLF CLUB SHAFTS

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SUMMARY

The purpose of this research was to compare the static and dynamic behaviour of golf shafts made from carbon fibre composites. Although a strain rate dependency was found at high strain rates for flat panels replicating the lay-up of the full shafts, the effect was insignificant at strain rates representative of golf swings.

Keywords: carbon fibre composite, golf, shaft, strain rate sensitivity, structural analysis

INTRODUCTION AND AIM

A golf club is defined as consisting of a head and a shaft with a grip, and it is the shaft which was investigated in the present study. The pace of innovation in golf equipment, including shafts, is greater than at any point in the sport's long history. The role of the shaft has been debated in several seminal articles, however, the focus of this study was on both the methods used to characterise shafts and to determine the effectiveness of these methods to shaft behaviour during a golf swing. Shaft characterisation tests commonly used in the industry are static (bending) or quasi-static (fundamental frequency) [1], with loads applied at strain rates that are significantly lower than those experienced in a golf swing. Whilst the strain rate dependency of metallic alloys is limited and little difference in static and dynamic behaviour is expected over the range of deformation rates experienced during golf shots, the presence of an epoxy resin as the matrix of carbon fibre reinforced polymer (CFRP) composite shafts may introduce viscoelastic behaviour to the shaft and hence a more significant strain rate dependence.

A number of previous papers have published examples for loading patterns applied by human players [2-5], but none of these papers specifically reported typical strain rates. Using graphical data from one of these studies [3], it has been estimated that peak strain rates in human swings are approximately 0.03 s^{-1} [6]. It was further found that, within a sample of six golf shafts, the stiffness of sheet-laminated golf shafts did not change in a dynamic test with strain rates ranging from 0.03 to 0.065 s^{-1} compared to a static test [6]. However, tests were performed on full golf shafts and it was not possible to determine the Young's modulus of the tested materials. As this is required for modelling and simulating the shaft structure, it may be more beneficial to perform static and dynamic tests on representative CFRP panels rather than full golf shafts.

The properties of CFRP panels have been characterised previously using servo-hydraulic testing devices for quasi-static [7, 8] as well as moderate (1 s^{-1} [7]) strain rates. Split Hopkinson bar tests have been used extensively to generate high strain rates (> 400 s^{-1} [7]; > 250 s^{-1}, [8], >100 s^{-1} [9]). However, only one study reported results for a range of low to moderate strain rates (10^{-5} to 0.1 s^{-1} [9]) representative of those expected to occur in a golf swing. Furthermore, studies have typically focused on samples with just one fibre orientation in isolation [7-9] and not considered more complex lay-ups such as those found in golf shafts [1].

In summary, there is little information that would allow judgement as to whether viscoelastic behaviour is to be expected in CFRP composite shafts at the strain rates occurring in golf swings. This is because the typical strain rates generated by the player as well as the response of the material at these strain rates are not well documented. Therefore, the aim of this work was (i) to determine typical strain rates occurring in human swings and (ii) to evaluate whether static and quasi-static tests are appropriate to characterise the dynamic behaviour of CFRP golf shafts at these strain rates.

METHODS

Human Testing

Commercially available, sheet-laminated (SL) golf shafts served as samples for this study. Using three golf clubs with shaft-mounted strain gauges, typical strain patterns and strain rates for human golf swings were recorded. The clubs were identical in all properties apart from shaft stiffness, which covered the full range of commercially available shafts ("l", "r" and "x", with "l" being the least stiff shafts and "x" being the stiffest). Before club assembly, the fundamental frequency of each shaft was determined using a Golfsmith Frequency Analyzer and a 205 g tip mass to ensure that their stiffness covered a sufficient range (see Table 1).

Table 1: Properties of clubs used in human testing:

Club	Label	Shaft mass [g]	Rigidity[a] [Nm^2]	Frequency [Hz]	Length[b] [m]	Swing weight[b]	Mass[b] [g]
1a	l-flex	56.8	38	3.62	1.143	C9.7	306.8
2a	r-flex	57.2	48	4.07	1.142	C9.6	305.6
3a	x-flex	57.7	58	4.52	1.143	D0.0	307.7

[a]Rigidity when tested at full length (1m) with the butt end clamped.
[b]Measurements for the assembled club. Swingweight presented in lorythmic scale [10].

Each club was equipped with four foil strain gauges (2 mm, 120 Ω resistance, Kyowa, Japan). They were placed at the location where the highest amount of strain was expected during the swing, which was assumed to coincide with the location of maximum bending curvature during a static test. The strain gauges were aligned with the longitudinal axis of the shafts and placed so that one pair of strain gauges registered lead/lag deformation of the shaft and the other pair toe up and down bending, thereby forming two half-bridges (see Figure 1). Strain signals were amplified using two P-3500 analogue strain amplifiers (Vishay, USA) and recorded with a USB-2533 A/D board

(Qualisys, Sweden) at a sample rate of 960 Hz. Post-processing of the strain data was performed with user-written routines in Matlab (The MathWorks, USA).

As the contact time between clubhead and ball is only approximately 450 µs [11, 12], it is reasonable to assume that the flexible shaft will not affect the interaction between clubhead and ball during impact beyond the delivery of the clubhead to the ball. Changes in shaft loading during impact were therefore not considered in this study. Since any changes in shaft deflection after impact will have no influence on the trajectory of the ball, they also not were considered in detail in this paper.

Figure 1: Schematic drawing of instrumented test club.

Fifteen male golfers (handicap < 5) performed six swings with each of the clubs in a randomised order and single-blinded. At the end of the test, each golfer performed another six shots with whichever club they tested first. For each swing, movement of selected body segments and the club were recorded using an eight-camera motion capture system (Qualisys, Sweden; Figure 2). As this paper focuses on shaft loading patterns, analysis of the body movement was restricted to identification of key swing events (take-away, top of backswing), and no full biomechanical analysis of the swings was performed. Impact was identified using lead/lag strain data. Body movement events were identified using Visual3D software (C-Motion, USA).

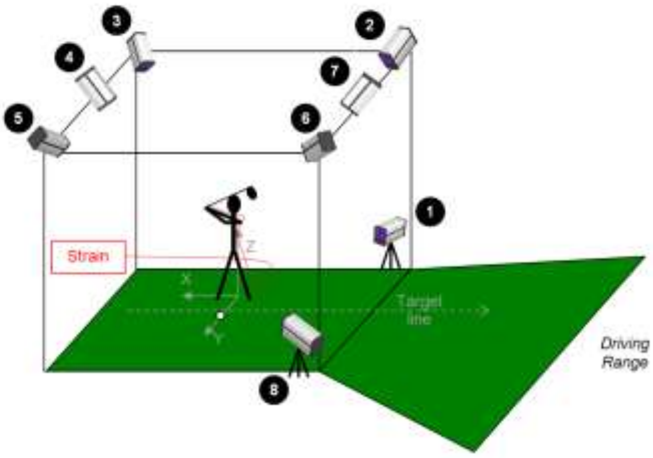

Figure 2: Test setup to determine shaft loading profiles for human players.

Structural Analysis

Three shafts of the same make and model as those used for the human tests were sectioned into 10 sections of 100 mm each. Sections from 300, 600 and 900 mm relative to the tip end were mounted in DuroFix. The samples were polished to a 1 µm diamond polish finish and observed under a Leica DMRX optical microscope using KS300 image analysis software, where the feret ratio, feret minimum, feret maximum, and area were taken of the fibres as well as the overall volume fraction and ply thickness. Fibre orientations were determined based on feret ratio, using the equation

$$\theta = \sin^{-1} \frac{l}{w},$$

where θ is the fibre orientation, and l and w are the length and width of the fibre cross-section, respectively.

Flat Panels

To isolate material properties from geometry effects in the shaft, carbon fibre/epoxy pre-pregs (T800/VTM264) with a volume fraction (V_f) of 0.55 were used to fabricate fifteen panels with different lay-ups; all panels were symmetric about the central neutral axis. The lay-ups were vacuum bagged and cured using a thermal cycle that ramped up to 125 °C at 0.5 °C min^{-1}, held for 1 hour and then cooled down at 3 °C min^{-1}. Panel testing was performed both statically, using a three-point bending test, and dynamically, using a ball cannon. For brevity, representative results for only four of the panels (Table 2) will be reported here.

Table 2: Characteristics of flat panels.

Panel	**Lay-up**	**Density (g cm^{-3})**
a	±45	1.49
b	±25 (3), ±45(16), ±25 (3)	1.49
c	0 (1), ±45 (14), 0(1)	1.45
d	0-90	1.46

The flat panels were tested statically using a three-point bending test (0.2 m span). Mass was added in 0.5 kg increments and left for 1 minute before taking the deflection reading using a Solartron C55 linear transducer. For the dynamic testing of the panels, four Kyowa uniaxial strain gauges (type KFG) were attached to the back of the panel around the centre. For slow strain rate testing, a high-quality, polyurethane-covered golf ball was dropped at varying heights (50 to 400 mm in 50 mm steps) onto the centre of the panel. A Brüel & Kjær type 4393 accelerometer was attached to the underside of the panel, beneath the impact point, so that the force of the impact could be calculated.

For the high strain rate testing, the CFRP panels were clamped vertically and an ADC Super Cannon 2000 fired golf balls (as used in drop tests above) at 6 speeds within the range of 18 to 35 ms^{-1} at each panel until at least two central impacts were achieved. Between each time a ball was fired, a 5 minute interval was imposed so that the panel could fully recover from the viscoelastic deformation. This time span was determined from repeat tests that showed good reproducibility after this period.

RESULTS

Human Full Shaft Testing

Temporal strain patterns were highly repeatable within each subject, even when comparing the stiffest to the most flexible shaft. However, the magnitude of strain appeared to change by a scaling factor depending on the stiffness of the shaft that was used. This can be observed in Figure 3 for one player, and it was confirmed by the summary statistics in Table 3 for the entire group of golfers. Highest peak strains were approximately 6200 µm/m (l-flex shaft). Maximum strain rates were 0.11 s^{-1}. These were also recorded for the l-flex shaft but generated by a different player than the one who recorded the highest strains.

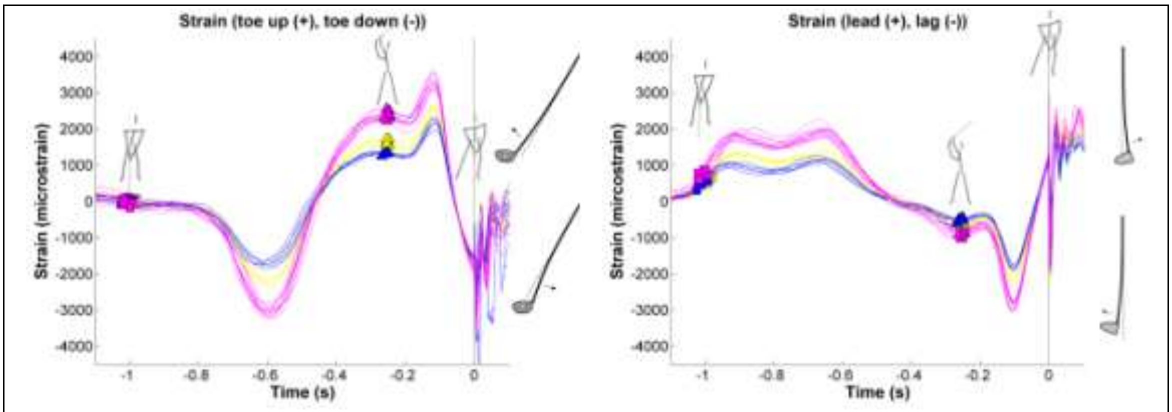

Figure 3: Typical strain pattern for one player for l-flex (magenta), r-flex (yellow) and x-flex (blue) shafts. Swing events - take-away (☐) and top of backswing(△).

Table 3: Summary statistics for human strain data

	l-flex	r-flex	x-flex
Toe strain at top of backswing (µm/m)			
Mean ± SD	3676 ± 1175	2608 ± 814	2194 ± 651
Maximum	6207	4586	3628
Strain rate before impact (s^{-1})			
Mean ± SD	0.056 ± 0.016	0.048 ± 0.016	0.043 ± 0.013
Maximum	0.11	0.10	0.10

Structural Analysis

Structural analysis of shafts of the same make and model as those used for the human tests revealed that, for each shaft, the lay-up was identical for sections taken 300, 600 and 900 mm from the tip. Each shaft consisted of eight layers, with the order of layers of different fibre orientations varying depending on the shaft type (Table 4). Fibre diameters varied between 4.7 and 7 µm, depending on the layer, and volume fraction was between 50 and 55%. The average thickness of plies was 90 µm (±10 µm), excluding a resin-rich region (RRR) between layers of 7 µm (±1 µm). This RRR was only present when the next ply was off-axis relative to the previous ply.

Table 4: Fibre orientations for shafts used in human testing.

Layer:	**← inside**							**outside →**
x-flex	±35°	±35°	±35°	±60°	0°	0°	0°	0°
r-flex	±45°	±45°	±45°	±45°	±45°	0°	0°	0°
l-flex	0°	±45°	±45°	±45°	±60°	0°	0°	0°

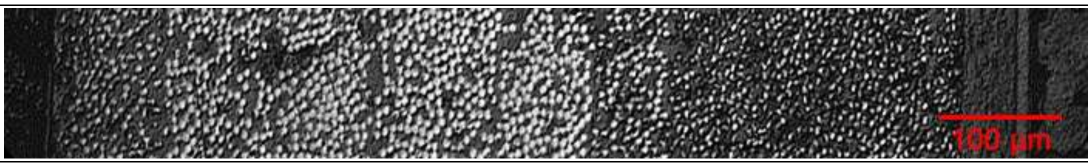

Figure 4: Example for cross-sectional image of l-flex shaft wall. The inner layer is on the left.

Flat Panel Testing

A strain of between 0.01 and 0.8 was applied in the dynamic flat panel tests at strain rates ranging from 10^{-4} to 5 s^{-1}. By comparing results from static and dynamic tests, it was found that the Young's modulus only increased significantly when strain rates exceeded 0.3 s^{-1}. There was no change in modulus when strain rates were in the range experienced in the human golf swings (< 0.11 s^{-1}). It can be seen from Figure 5 that the strain rate effects were highest for a panel composed of ±45° layers only (Panel a) and lower when six of the ±45° layers were replaced by ±25° layers (Panel b). For panels containing at least two 0° layers (Panels c, d) there was virtually no change in Young's modulus with increased strain rates.

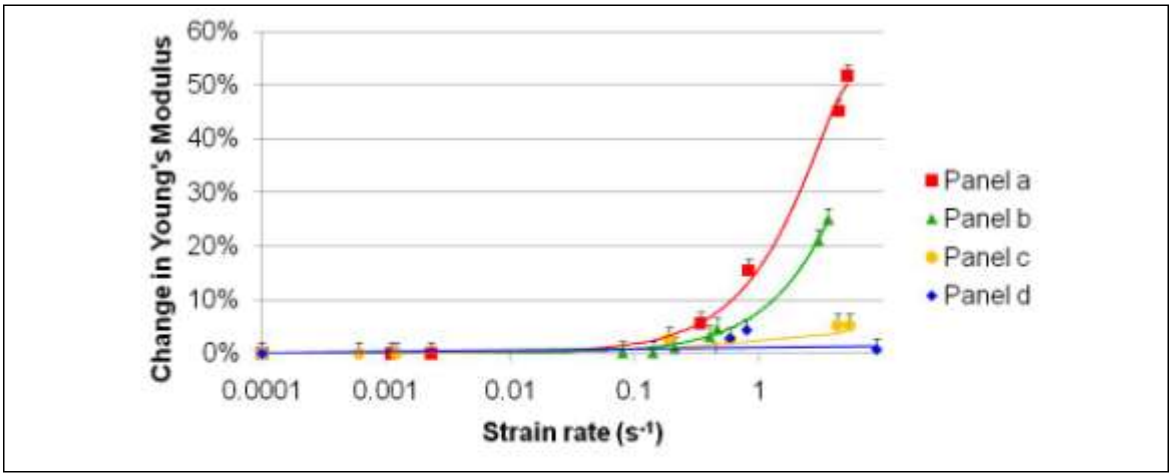

Figure 5: Strain rate response of a CFRP flat panel with the lay-up matching that of a commercial shaft.

DISCUSSION

Human Full Shaft Testing

Maximum toe-up strains recorded in the present study (6200 µm/m) were higher than those presented in previous studies (2200 µm/m) [3]. This difference may be explained by a number of factors including differences in strain gauge positions, shaft materials and player characteristics between different studies. The maximum strain rates found here (0.11 s^{-1}) were similar to those that previous authors [6] had calculated from published data [3]. It is interesting to note that both peak strain and strain rates appear to be no function of the clubhead speed generated by a given player. For instance, the highest peak strain values were recorded for a player with a mean clubhead speed of 100 mph, whilst other participants achieved mean clubhead speeds of up to 112 mph without generating the same amount of strain.

Structural Analysis

As it was not possible to identify previous research studying the lay-up of a set of golf shafts that were matched in all characteristics apart from shaft stiffness, only a limited comparison to previous work is possible. It was noted, however, that for all three shafts there are similarities in the lay-up compared to published data [13] in that the inner layers are usually oriented off-axis, followed by 0° outer layers. This design allows the outer 0° layers to carry the tensile and compression loads occurring during the swing, whilst the inner off-axis layers carry torsional loads. This would explain why the stiffest shaft had an additional outer 0° layer, whereas the least stiff shaft (l-flex) had one 0° layer as the innermost layer where it would contribute little to the bending stiffness of the shaft. One possible explanation for the presence of this layer would be the need to keep the number of layers the same for all shafts to avoid mass differences between shafts of different stiffness.

Flat Panel Testing

It was found that strain rate dependency was highest when no 0° fibres were present in the panels. This can be explained by the fact that the viscoelastic behaviour of CFRPs is mainly attributed to the resin matrix and not the carbon fibres [7, 8]. Hence, strain rate sensitivity is highest when fibres are aligned at an angle of ±45° relative to the axis of force application. This is confirmed by Panels b-d studied here as strain rate sensitivity is reduced when ±25° layers are present in place of ±45° layers (Panel b) and is almost eliminated as soon as 0° layers are introduced (Panels c and d). This finding is also in agreement with a previous study [6], which showed that a shaft with a high resin content (manufactured using the filament winding method where 0° layers could not be introduced) showed a strain rate dependency whereas five other shafts that were manufactured using the SL method did not.

CONCLUSION

This study found that, before ball impact, skilled golfers generate peak strains and strain rates of up to 6200 µm/m and 0.11 s^{-1}, respectively. Peak strains and strain rates increased with decreasing shaft stiffness but the general loading pattern remained constant. It is unlikely that the limits of linear stress-strain behaviour are exceeded during a backswing and downswing performed by a golfer, in particular if at least two of the layers of the shaft have fibres oriented parallel to the longitudinal axis of the shaft (0°). Hence, static testing appears to be sufficient to characterise the mechanical properties of a shaft in a golf swing. Further work is needed to determine how these mechanical properties relate to the actual performance of a shaft throughout the swing.

It was also found that fast oscillations occurred after impact with the ball, and it is likely that highest strain rates will occur during this phase. These oscillations were not considered here as this study was only concerned with the characterisation of the shaft's behaviour prior to impact. Further studies looking at the strains and strain rates during this phase are necessary if researchers are concerned with the stability and durability of golf shafts.

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