Investigation and Customisation of Snowboard Performance Characteristics for Different Riding Styles

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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DECLARATION

I certify that except where due acknowledgement is made, the following thesis is mine alone. It has not been submitted previously, in whole or in part, to qualify for any other academic award. The content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program. Any editorial work, paid or unpaid, carried out by a third party is acknowledged. All ethics procedures and guidelines have been followed.

Patrick Michael Clifton

April, 2011
LIST OF PUBLICATIONS

The following is a list of publications arising from this research:


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</tr>
<tr>
<td>([\bar{a}])</td>
<td>Laminate compliance matrix (in-plane) (ref. neutral plane)</td>
</tr>
<tr>
<td>([A])</td>
<td>Laminate stiffness matrix (in-plane)</td>
</tr>
<tr>
<td>([b])</td>
<td>Laminate compliance matrix (coupling)</td>
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<tr>
<td>([M])</td>
<td>Matrix of moments per unit width acting on a laminate</td>
</tr>
<tr>
<td>([M]^t)</td>
<td>Matrix of thermal moments per unit width acting on a laminate</td>
</tr>
<tr>
<td>([N])</td>
<td>Matrix of forces per unit width acting on a laminate</td>
</tr>
<tr>
<td>([N]^t)</td>
<td>Matrix of thermal forces per unit width acting on a laminate</td>
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<td>([P])</td>
<td>Snowboard stiffness matrix</td>
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<td>([Q])</td>
<td>Unidirectional composite layer 2-D plane-stress stiffness matrix</td>
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<tr>
<td>([\bar{Q}])</td>
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<td>([Q_i])</td>
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<td>Tow undulation reduced unidirectional composite layer 2-D plane-stress stiffness matrix</td>
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<td>([Q^\phi_\theta], [Q_{\phi-\theta}])</td>
<td>Reduced and transformed unidirectional composite layer 2-D plane-stress stiffness matrices</td>
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<tr>
<td>([R_k])</td>
<td>Snowboard element centroid conversion matrices</td>
</tr>
<tr>
<td>([T_\sigma], [T_\epsilon])</td>
<td>In-plane stress and strain transformation matrices</td>
</tr>
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</table>
\[ [W] \quad \text{Snowboard compliance matrix} \]
\[ [\alpha] \quad \text{Unidirectional composite layer 2-D plane-stress thermal expansion matrix} \]
\[ [\tilde{\alpha}] \quad \text{Fabric composite 2-D plane-stress thermal expansion matrix} \]
\[ [\alpha_i] \quad \text{Laminate layer 2-D plane-stress thermal expansion matrices} \]
\[ [\alpha_\theta, [\alpha_{-\theta}]] \quad \text{Transformed unidirectional composite layer 2-D plane-stress thermal expansion matrices} \]
\[ [\tilde{\alpha}_\lambda] \quad \text{Misaligned fabric composite 2-D plane-stress thermal expansion matrix} \]
\[ [\alpha'] \quad \text{Stitched unidirectional composite layer 2-D plane-stress thermal expansion matrix} \]
\[ [\alpha^\phi] \quad \text{Tow undulation reduced unidirectional composite layer 2-D plane-stress thermal expansion matrix} \]
\[ [\alpha^\phi_\theta, [\alpha^\phi_{-\theta}]] \quad \text{Reduced and transformed unidirectional composite layer 2-D plane-stress thermal expansion matrices} \]
\[ [\varepsilon^0] \quad \text{Laminate centre-line strain matrix} \]
\[ [\varepsilon^{0c}] \quad \text{Laminate centre-line thermal strain matrix} \]
\[ [\kappa] \quad \text{Laminate curvature matrix} \]
\[ [\kappa^c] \quad \text{Laminate thermal curvature matrix} \]
\[ [\omega_k] \quad \text{Snowboard element compliance matrices} \]
\[ a_{ij} \quad \text{Laminate elastic compliances (in-plane)} \]
\[ \tilde{a}_{ij} \quad \text{Laminate elastic compliances (in-plane) (ref. neutral plane)} \]
\[ (\tilde{a}_{ij})_k \quad \text{Snowboard element elastic compliances (in-plane) (ref. neutral plane)} \]
\[ a_n \quad \text{Causative performance prediction model exponents} \]
\[ (\tilde{A}_{ij})_k \quad \text{Snowboard element elastic stiffnesses} \]
\[ A^A, A^F, A^W \quad \text{Cross-sectional areas of fabric axial, fill and warp tows} \]
\[ A_c \quad \text{Snowboard accuracy} \]
\[ b_{ij} \quad \text{Laminate elastic compliances (coupling)} \]
\[ \tilde{b}_{ij} \quad \text{Laminate elastic compliances (coupling) (ref. neutral plane)} \]
\[ (\tilde{b}_{ij})_k \quad \text{Snowboard element elastic compliances (coupling) (ref. neutral plane)} \]
\[ b_n \quad \text{Causative performance prediction model exponents} \]
\[ B^F, B^W \quad \text{Fibre bundle size of fabric fill and warp tows} \]
\( c_n \) Causative performance prediction model exponents
\( c^A, c^F, c^W \) Fabric volume proportions of axial, fill and warp tows
\( C \) Snowboard self-weighted bottom camber
\( \Delta C \) Snowboard camber change
\( d^F, d^W \) Fibre diameters in fabric fill and warp tow bundles
\( d_{ij} \) Laminate elastic compliances (bending)
\( \bar{d}_{ij} \) Laminate elastic compliances (bending) (ref. neutral plane)
\( (\bar{d}_{ij})_k \) Snowboard element elastic compliances (bending) (ref. neutral plane)
\( D_m, \bar{D}_m, \bar{\bar{D}}_m \) Objective parameter values, ranks and rank means
\( D_m^{\text{input}}, D_m^{\text{max}}, D_m^{\text{min}} \) Input, maximum and minimum objective parameter values
\( (D_h)_n, (D_H)_n, (D_{HT})_n \) Causative performance model key objective parameters
\( e \) Measurement location distance from the snowboard centreline
\( E_L, E^f_L, E^m_L \) Composite, fibre and matrix longitudinal Young’s moduli
\( E^\phi_L \) Reduced composite longitudinal Young’s modulus due to tow undulation
\( E_T \) Composite transverse Young’s modulus
\( E_T^\pm \) Composite transverse Young’s modulus upper and lower bounds
\( E_{Ib}, E_{Ih}, E_{Is} \) Snowboard body, heel and shovel bending stiffness parameters
\( E_{Ib}, E_{Ih}, E_{Is} \) Snowboard body, heel and shovel material parameters
\( E_{I} \) Laminate bending stiffness
\( f \) Fabric composite fibre volume fraction
\( f^\phi \) Stitched fabric composite volume fraction of distorted fibres
\( F \) Applied load
\( Fb \) Rider feedback
\( F_g \) Snowboard forgiveness
\( G_{LT}, G_{TR} \) Composite shear moduli in the \( L - T - R \) coordinate system
\( G^f_{LT}, G^f_{TR} \) Fibre shear moduli in the \( L - T - R \) coordinate system
\( G^m_{LT}, G^m_{TR} \) Matrix shear moduli in the \( L - T - R \) coordinate system
\( G^\phi_{LT} \) Reduced composite shear modulus due to tow undulation
<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$G^+_T$, $G^-_T$</td>
<td>Composite shear modulus upper and lower bounds</td>
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<td>$G_J$</td>
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<td>$Gr$</td>
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<td>Input and datum rider height-mass products</td>
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<td>$I_{FR}, I_{FS}$</td>
<td>Freeride and freestyle importance weights</td>
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<td>$I_{ik}$</td>
<td>$2^{nd}$ order symmetric unit tensor</td>
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<td>$I_{klij}$</td>
<td>$4^{th}$ order symmetric unit tensor</td>
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<td>$k, k^f, k^m$</td>
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<td>Bending and twist moments per unit length acting on a laminate in the $x - y$ coordinate system</td>
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<tr>
<td>$M_x^<em>, M_y^</em>, M_{xy}^*$</td>
<td>Bending and twist thermal moments per unit length acting on a laminate in the $x - y$ coordinate system</td>
</tr>
</tbody>
</table>
Bending moments applied to a snowboard in the principal $y, z$ directions

$M_n$ Snowboard manoeuvrability

$n_l, n_e$ Number of layers and elements

$n^\phi$ Fabric composite fibre stitching areal density

$N_x, N_y, N_{xy}$ In-plane forces per unit length acting on a laminate in the $x - y$ coordinate system

$N_x^L, N_y^L, N_{xy}^L$ In-plane thermal forces per unit length acting on a laminate in the $x - y$ coordinate system

$\bar{N}_x$ Axial force applied to a snowboard

$o_h, o_h$ Snowboard shovel and heel asymmetrical offsets

$O_n$ Optimum performance parameter levels

$p$ Statistical significance level

$P$ Overall snowboard performance rating

$P_n$ Subjective performance parameter ratings

$P_{ij}$ Snowboard elastic stiffnesses

$r_{m,n}$ Spearman ranked correlation coefficients

$r^F, r^W$ Radii of curvature of fabric fill and warp tows

$R$ Snowboard calculated radius of curvature

$R_h, R_s, R_{sc}$ Snowboard heel, shovel and sidecut average radii of curvature

$R^2$ Coefficient of determination

$s^A, s^F, s^W$ Spacing of fabric axial, fill and warp tows

$\bar{S}$ Average snowboard stiffness parameter

$S_{ij}, S^f_{jk}, S^m_{jk}$ Composite, fibre and matrix elastic compliances

$S_{r_{si}j}, S^f_{r_{si}j}, S^m_{r_{si}j}$ Composite, fibre and matrix elastic compliances ($4^{th}$ order)

$Sp$ Snowboard speed

$St$ Snowboard stability

$t$ Fabric composite thickness

$t_k$ Snowboard element thicknesses

$t^A, t^F, t^W$ Thickness of fabric axial, fill and warp tows

$T_b, T_h, T_s$ Snowboard body, heel and shovel thickness parameters
<table>
<thead>
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<td>$\Delta T$</td>
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<td>Matrix phase thermal expansion coefficients</td>
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<td>$\alpha_L, \alpha_L^f, \alpha_L^m$</td>
<td>Composite, fibre and matrix longitudinal thermal expansion coefficients</td>
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<td>$\alpha_T, \alpha_T^f, \alpha_T^m$</td>
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<td>$\beta_f, \beta^m$</td>
<td>Fibre and matrix Hashin parameters</td>
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<td>Hashin parameter</td>
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<td>Laminate centre-line shear strain in the principal $x$ - $y$ plane</td>
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<tr>
<td>$\gamma_{xy}^{\text{tr}}$</td>
<td>Laminate centre-line thermal shear strain in the principal $x$ - $y$ plane</td>
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<tr>
<td>$\delta$</td>
<td>Measured snowboard deflection/displacement</td>
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<tr>
<td>$\varepsilon_{xy}^0$, $\varepsilon_{y}^0$</td>
<td>Laminate centre-line normal strains in the principal $x$, $y$ directions</td>
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<td>$\varepsilon_{xy}^{\text{tr}}$, $\varepsilon_{y}^{\text{tr}}$</td>
<td>Laminate centre-line thermal normal strains in the principal $x$, $y$ directions</td>
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<tr>
<td>$\eta$</td>
<td>Hashin parameter</td>
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<td>$\theta$</td>
<td>Composite tow orientation in the $x$ - $y$ plane</td>
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<tr>
<td>$\theta_x$</td>
<td>Rate of twist about the longitudinal $x$ axis</td>
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<tr>
<td>$\kappa$</td>
<td>Cohen’s Kappa coefficient</td>
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<td>$\kappa$</td>
<td>Fibre packing factor</td>
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<td>$\kappa_x, \kappa_y, \kappa_{xy}$</td>
<td>Curvatures of the reference surface in the $x$ - $y$ coordinate system</td>
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<tr>
<td>$\kappa_x^T, \kappa_y^T, \kappa_{xy}^T$</td>
<td>Thermal curvatures of the reference surface in the $x$ - $y$ coordinate system</td>
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<td>Curvature of the reference surface about the through-thickness $z$ axis</td>
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<td>Snowboard average longitudinal thermal curvature</td>
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<td>Fabric composite layer alignment angle</td>
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<td>Composite Poisson’s ratios the $L$ - $T$ - $R$ coordinate system</td>
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ABSTRACT

The major aim of the research is to fully characterise the design of modern snowboards in terms of feel through identification and customisation of their on-snow performance characteristics. A comprehensive set of subjective performance parameters is formulated through a series of online surveys and interviews, which cover all facets of riding. The relative importance and optimal level of each of the parameters are determined for both freeride and freestyle snowboards. Nine expert snowboarders are used in this investigation to provide systematic on-snow ratings of the subjective parameters for three high-quality test snowboards that span these major riding styles.

The Quality Function Deployment method is utilised to link these subjective performance characteristics to 31 objective design parameters that completely define modern snowboards. Relevant data is obtained from the user surveys, interviews and on-snow tests, and the bending stiffness is identified as the most important objective parameter. An associated Market Opportunity Map is used to determine an innovation opportunity existing within the snowboard marketplace for a versatile model that performs well in both major riding styles. A versatility value is formulated in the research, indicating which design parameters are both crucial to the feel of snowboards and change markedly between freeride and freestyle designs. The results demonstrate that together with bending stiffness, torsional stiffness and camber also strongly affect the feel and performance between the major riding styles.

To enable the customisation of snowboard designs to fulfil any performance requirements, a general parametric model is developed. The model uses a discrete set of objective parameters together with user characteristics to predict the on-snow performance of the design. Two different performance prediction measures are implemented in the model. The first is a correlation based measure, which utilises individual Spearman ranked correlations between the objective design parameters and subjective performance parameters determined during the research. Conversely, the second is an exponent based performance measure that uses three key objective design attributes to estimate each subjective performance parameter. These performance measures are validated against the existing subjective and objective datasets, with a coefficient of determination generated for each
expression. The parametric model is shown to predict the performance of any snowboard within the major riding styles to an acceptable level of accuracy.

An applied code is developed to predict the bending and torsional stiffness properties for any snowboard sandwich composite structure that utilises common fabric configurations. The model also provides an estimation of the total mass, as well as the camber change for a discrete temperature differential. A simple but effective validation of the code is undertaken through the manufacture and static testing of three sandwich composite samples of different structure and geometry. The model is proven to accurately predict the thermal and mechanical response of the samples within reasonable error bounds.

Utilising the snowboard performance prediction model, an optimal feel design is generated in each of the major riding styles. The software package Esteco ModeFrontier is employed to determine the optimal design solutions, where the performance targets are derived from the expert rider survey/interview/test process. The predicted feel of the optimised designs shows good agreement with the prescribed parameter levels. Also, it reinforces the fact that in any snowboard design, the overall on-snow performance is a balance between mutually exclusive facets. In other words, desired levels of the subjective performance parameters may not all be attainable simultaneously.

The final outcome of the investigation is the generation of guidelines for the customised design, manufacture and testing of modern snowboards. A table is developed which summarises this process, including the specification of all required inputs from the rider, together with the methods, analyses and information drawn from the current research. Use of this procedure in industry could alleviate the current trial and error approach plaguing snowboard design, leading to considerable cost and time savings. Furthermore, the widespread introduction of customised snowboard designs could potentially increase user satisfaction across the product market and improve on-snow rider performance.
1. INTRODUCTION

1.1 Background

Snowboarding is one of the fastest growing sports in the world today, with an estimated five to six million boarders on the slopes annually [1]. As a result, the snowboard equipment market is expanding at a phenomenal rate, with total industry sales in excess of $280 million dollars per annum in the US alone [2]. Unit sales of snowboards also rose by 23% in US chain stores between 2005 and 2006 [2].

Initially prohibited from ski resorts, snowboarding was only gradually accepted as an alternative to skiing between its inception in the 1970’s and the mid 1990’s. However due to its rapid increase in popularity over the last decade, the number of skiers has declined by 25%, and furthermore it has been predicted that by 2015 the number of snowboarders will eclipse that of skiers [3].

Given the relatively short history of the sport and the extent of the recent expansion within the snowboard market, there exists significant scope for potentially lucrative technological development and innovation, which to date has been primarily conducted on a trial and error basis by hobbyists and enthusiasts [4].

The modern snowboard is fundamentally a composite sandwich structure, consisting of composite reinforcing layers (generally one to two layers of glass fibres embedded in a resin matrix though some also possess carbon or Kevlar stringers) either side of a core (usually wood stringers, aluminium honeycomb or PVC\(^1\) foam), enclosed by a topsheet (generally ABS\(^2\)), base layer (extruded or sintered UHMWPE\(^3\)) and sidewall (usually ABS or UHMWPE). Steel edges are added to the lower corners of the structure to provide the necessary grip on the snow surface during turns. This basic structure (sidewall and edges not shown) of the majority of snowboards currently on the market is displayed pictorially in Figure 1.

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\(^1\) Poly-vinyl-chloride.
\(^2\) Poly-acrylonitrile-butadiene-styrene.
\(^3\) Ultra-high molecular weight polyethylene.
Modern snowboard design is dictated predominantly by the desired application or style of the ride, with boards generally falling under one of two headers; freestyle (park and trick based) or freeride (all-mountain). Freestyle boards have developed under the direct influence of skateboarding. As a result, freestyle boards tend to be shorter and lighter, possessing more ‘pop’ or spring than their counterparts. They are also usually symmetrical about their transverse axis, allowing equally weighted riding both forwards and backwards. Freeride boards on the other hand are less-specific in their application, and are designed for all-mountain riding under any snow conditions. They tend to be longer, stiffer and directional in their shape. Certain boards are also considered ‘versatile’ (do not fall under either major style heading), and are designed to bridge the gap between the two major styles. A third less popular race specific category also exists, that of freecarving or alpine. Freecarve boards are centred solely on speed and turning grip, and as a result are generally stiffer, longer and narrower than other boards on the market.

There is considerable anecdotal evidence that suggests riders relate a snowboard’s on-snow performance to its perceived ‘feel’, or the physical and psychological feedback given to the rider whilst snowboarding. Such feedback may be visual, aural, kinaesthetic or

*Figure 1: General snowboard structure [5]*
vibrational [6], all having an effect on the muscular inputs applied to the board by the rider and the resultant movement and control achieved on the slope.

Manufacturers currently spend significant time and money trialling new designs, relying heavily on the feedback of professional riders to design-in the ‘feel’ and optimise the performance of the board [7] - [10]. A systematic user-centred design procedure could provide the intelligence required to alleviate the trial and error approach, resulting in higher customer satisfaction as well as cost and time savings.
1.2 Literature Review

User-centred or feel based approaches are becoming more commonplace in sports technology design and development, with the ‘actuation’ of sportsmen in design recognised recently by Rossel and Stricker [11]. Whilst such subjective evaluation methods have been employed for skis [9], [12] - [17], golf clubs [6] and motor vehicles [18], [19] there have been only limited attempts to implement a similar approach to the analysis and design of snowboards.

Brennan [7] formulated a multi-faceted model to calculate the basic mechanical properties of any snowboard design, together with a prediction of its speed through a predetermined slalom course. Inputs to the model are the snowboard geometry, construction layup and layer material characteristics. The key mechanical properties of bending and torsional stiffness are evaluated using the classic laminate thin beam theory, whilst the flex and twist are determined using a finite element (FE) method utilising beam elements. Conversely, the prediction of speed is calculated through a dynamic force analysis on the snowboard, including the effects of the snow (elastic foundation) and specific rider characteristics. The two facets of the model were validated using laboratory testing of several snowboard structures and on-snow field tests with a combined camera/GPS system, respectively. As rider characteristics such as height, weight and ability were incorporated into the model, a limited user-centred performance evaluation of any snowboard design is possible.

Buckingham and Blackford [8] collected basic technical attributes (mass and geometry) and sampled the stiffness of four snowboards in the laboratory. They loosely correlated this data to qualitative on-slope performance evaluations of general feel (on a scale from 1 - 10), as well as perceived overall and torsional stiffness (stiff, medium or soft). Piezoelectric sensors were also utilised to compare on-slope vibrational outputs of different riders during basic turns. The authors determined positive correlations between the on-slope subjective assessments and static testing results. Furthermore, they found links between frequency spectra voltage outputs during turns and the ability of the various riders, where beginners have higher low-frequency voltages than intermediate and advanced riders. The suitability of the analysis to the advancement of snowboard training and coaching techniques was described.

Buffinton et al. [20] measured the geometric and mechanical characteristics of eight snowboards in the laboratory, including stiffness properties, damping ratios and natural
frequencies. The data collected was then correlated to vague subjective manufacturer descriptions (soft, stiff or high quality) of each snowboard. The authors also constructed simplified (non-layered) FE models of five snowboards and compared the results of a FE analysis to the experimental data. The models created were used to determine the effects of design changes on natural frequencies and allow the visualisation of mode shapes. On-snow field tests were also conducted using several snowboards fitted with strain gauges to establish a database of strain and acceleration information that quantifies typical snowboard manoeuvres. Links were determined between the type of manoeuvre (turn, jump etc.) and resulting stresses and vibrations imparted on the snowboards.

**Darques et al.** [9] describe a Quality Function Deployment (QFD) method for the design of skis and snowboards which is comparable to that conducted in the present research. Key objective geometric and mechanical attributes such as length, edge radius, stiffness and damping ratio were linked to eight subjective performance parameters for giant slalom skis using a QFD matrix of statistical correlations and user requirements. The overall impact of the key objective parameters on the various facets of ski performance was then able to be determined by the authors. It is noted that the methodology was not specifically applied to snowboards, only pinpointed as a suitable design process.

The remaining published literature to date in relation to snowboards has focussed primarily on the formulation of predictive and analytical models (particularly FE) for key snowboard attributes, together with the testing and comparison of the mechanical properties of different snowboard structures.

**Biancolini et al.** [21] created a FE model to analyse the static and dynamic characteristics of a typical snowboard. Bending and torsional stiffness distributions, along with the natural frequencies of the board were evaluated and loosely validated against published experimental data. A trend of increasing stiffness towards the centre of the snowboard was noted. The authors also incorporated the effects of the rider and snow into their analysis through the variation of applied loads and the introduction of an elastic foundation, respectively. The FE model was then employed to calculate the stability of the snowboard at different tilt angles, using a derived index based on the second-order moment of force distribution between the snowboard and snow surface.

**Borsellino et al.** [22] focussed on the effects of different core materials and polymeric base surfaces on resulting snowboard properties. They undertook wear, wettability and adhesion
tests for several polymeric base materials, which define the ability of the surface to adsorb and retain wax, crucial to the speed of the snowboard. It was determined that UHMWPE exhibits the best overall mechanical performance. The study also investigated the effect of using wood, PVC and polymer foam cores on the bending and torsional flexural properties of the sandwich composite structure. From analysis of the experimental data, they determined that in wood core structures, the core plays a large role in the properties of the final composite. Conversely, they found that a low density polymer foam core merely acts as a support for the fibreglass layers and to separate them from the neutral axis. This information was utilised by the authors as inputs for a predictive FE model that replicated a snowboard sandwich structure.

Grewal et al. [23] investigated the effect of different snowboard constructions on stiffness, strength and work energy to failure. Seven snowboards constructed with either wood, foam or composite cores were evaluated. The study determined that stiffness and strength were more strongly influenced by the core wrap thickness and not the core material, whereas stored work energy was more closely related to the core material and construction method.

Snowboard vibration characteristics have proven to be a key sub-area of research, as the natural frequencies and damping ratios of any snowboard strongly affect its on-snow feel and performance [10], [20]. K2 Corporation developed an active vibration controlled snowboard using piezo-ceramic dampers which reportedly reduces selective vibration frequencies by up to 80% [24]. Foss and Glenne [10], [25] investigated the factors that reduce noise and damp vibrations for skis and snowboards on hard snow. They firstly tested several skis and snowboards on-snow, taking measurements using mounted accelerometers and were able to identify bending and torsional vibration characteristics in the range of 0 – 200 Hz. In the later study, the authors conducted laboratory experiments that attempted to replicate the on-snow conditions of the earlier tests. Modal analysis and compliance mapping (to show the spatial distribution of structural dynamic characteristics) both utilising a matrix of mounted accelerometers were undertaken for several skis and snowboards. The full dynamic system of ski/snowboard, boot, binding and rider (represented by a static load) was replicated for each test conducted. A comparison of the results was made to the construction and expert performance reviews of several pairs of skis, where it was confirmed that skis containing a thin layer of aluminium or a viscoelastic standoff damper are more stable and quiet than regular fibreglass skis. This was reportedly a result of a diminished torsional mode.
Three numerical models estimating the on-snow dynamic response of snowboards have been created by Sakata and Kawai [26] - [28]. In the studies, experimental results were compared to the outputs of the proposed numerical models. A urethane sheet was utilised to represent the snow surface (elastic foundation) throughout the experiments. In the first study, an analysis of the dynamic bending deformation of a snowboard under purely vertical loads or a combination of vertical loads and bending moments was undertaken. The authors were able to provide an estimation of the reaction force acting on the snowboard by the snow surface. Conversely, the purpose of the second study was to show that the natural frequencies in the free vibration (coupled bending and torsion) of a snowboard can be estimated using the numerical approach for an inhomogeneous plate. Results were obtained both with and without an elastic foundation included in the dynamic system, and it was concluded that the numerical model predicted the natural frequencies of the snowboard tested within reasonable error bounds. The numerical results also showed that lower natural frequencies were far more strongly affected by the elastic foundation than higher natural frequencies. Finally, the third study evaluated forces applied to the board by a rider during standard snowboarding manoeuvres. It was established that the proposed numerical model accurately predicted the forces applied to the snowboard for a variety of loading situations.

There has only been one snowboarding standard published to date, entitled ASTM F1107-04: Standard Terminology Relating to Snowboarding [29], which covers terms used to describe the geometry of snowboards and associated hardware. Several skiing standards were also utilised as reference points for the current research [16], [30] - [34].

Thus, throughout the reported literature there has been only limited user-centred and feel based research into snowboard design and technology. Given the potential cost and time benefits for the industry, the aim of this thesis is to fully investigate the feel and performance of snowboards across the major riding styles, and incorporate this knowledge into a new user-centred snowboard design process. Not only would this research minimise the trial and error approach that currently plagues snowboard design, but also allow tailored snowboard designs to any performance requirements. The research would also facilitate the evaluation of new technological innovations prior to manufacture.
1.3 Research Questions

This thesis aims to address the following key research questions:

- How can feel in snowboarding be characterised and correlated to snowboard design?
- What are the key design parameters with respect to feel for the major riding styles?
- Can a user-centred design process be devised to customise snowboard design with respect to the desired performance and feel in the major riding styles?
- What is the optimised combination of design parameters for each riding style?

The knowledge-base developed will provide a technological platform for design customisation of modern snowboards with respect to desired feel over the major riding styles. This information would allow the design and manufacture of snowboards that meet specific user requirements, resulting in increased customer satisfaction. The research will also determine whether an optimal snowboard design exists for each major riding style.
1.4 Methodology

In order to fully characterise the feel of modern snowboards, the identification of objective snowboard design parameters and subjective user requirements for each of the major riding styles is undertaken. The objective attributes are obtained through a combination of existing snowsports standards, together with available technical articles. Conversely, the feel based subjective performance parameters are defined primarily using comparable research already completed for skis, however other user-centred design approaches are also consulted.

To obtain subjective data for the major riding styles, a range of online surveys, focus group interviews (in consultation with industry) and on-snow tests are conducted. The online surveys and focus group interviews allow user profiling, style requirements and popularity data, as well as board performance reviews to be collected. Conversely, the on-snow tests involve the collection of qualitative performance reviews (conducted by experts) for a sample of snowboards spanning the major riding styles. Objective technical data is also obtained for the selected snowboard models through a variety of laboratory tests or from published data sheets, and consists of geometric, stiffness and material properties. The information collected is then processed in a benchmarking or Quality Function Deployment (QFD) analysis to pinpoint the key objective snowboard design parameters for each major riding style. Market Opportunity Mapping (MoM) is also utilised to identify design innovation opportunities for the snowboard equipment market.

From the results of the QFD and MoM, a deeper investigation into the key objective design attributes of bending/torsional stiffness and camber is undertaken. This consists of firstly a more detailed correlation analysis between the key objective parameters and subjective performance parameters. Secondly, an investigation into the effect of on-snow temperature on these attributes is conducted.

All of the information collected is then utilised in the formulation of a general parametric design model for modern snowboards. The model allows the input of any discrete set of objective snowboard design parameters together with individual user characteristics, and outputs a prediction of the on-snow feel of the design through the determination of subjective performance parameter values. The key objective attributes of bending/torsional stiffness, mass and camber are considered in a sub-model, allowing their calculation from
the input of fundamental layup construction data, along with material, geometric and thermal properties.

The general parametric design model is validated against the existing subjective and objective datasets, with an overall coefficient of determination generated. Validation of the stiffness, mass and camber portion of the model is achieved through the manufacture and static laboratory testing of three composite samples of varying layer structure and geometry. The validated snowboard prediction model together with the determined optimal performance targets are utilised to generate an optimal feel design for each major riding style.

The developed prototype prediction model forms the basis of a new cost and time effective design method for snowboards, centred on the characterisation of feel and correlation to key snowboard technical parameters. A table is developed which summarises the overall design process, including the specification of all required inputs from the rider, together with the methods, analyses and information drawn from the current research.
1.5 Overview of Thesis

The main aim of the present research is to fully characterise the feel of modern snowboards through the identification and investigation of on-snow performance characteristics. This knowledge forms the basis of a design customisation platform for the desired feel and performance of both freeride and freestyle snowboards.

Chapter 2 of the thesis describes the identification of snowboard design parameters and innovation opportunities. This includes both qualitative and quantitative analyses, as well as a benchmarking process centred on Quality Function Deployment. For the qualitative analysis, after extensive surveys, interviews and consultation of comparable research in similar fields, nine subjective performance parameters are defined. The importance and ideal level of each parameter are assessed for both major riding styles during this survey process, allowing the relevant user requirements for freeride and freestyle snowboards to be determined. It is established that stability, manoeuvrability and accuracy are the paramount considerations for freeride models, whilst forgiveness, manoeuvrability and board liveliness are the key user rated considerations for freestyle snowboards. To finalise the qualitative analysis, on-snow tests are conducted with nine expert riders, who assess three high-quality test snowboards under the prescribed subjective performance headers. The three test boards are selected to span the freeride-freestyle snowboard spectrum, and assessed on-snow using a systematic method. After testing all facets of the board, each expert rider is questioned as to the levels of each subjective parameter present. The performance is rated from 1 - 10, where 1 represents low levels of the particular parameter and 10 the opposite. The importance and ideal level ratings collected during the survey process also employ this 1 - 10 scale. From the results of the qualitative analysis, it is determined that the stability, accuracy and edge grip are linked for both freeride and freestyle snowboards, whilst feedback possesses the highest degree of subjectivity.

A Quality Function Deployment method is utilised to link these subjective performance characteristics to 31 objective design parameters that completely define modern snowboards within the major riding styles. The subjective data is obtained from the user surveys, interviews and on-snow tests, whereas relevant objective data is collected from laboratory measurements or published data sheets. From the QFD analysis, the body bending stiffness is identified as the most important snowboard design parameter. The results also show that the self-weighted camber is considerably more important to freestyle
designs than freeride designs, whilst conversely, the major length parameters are more important to freeride models than their freestyle counterparts. The associated Market Opportunity Map (which compares performance reviews of snowboard models and their specified riding style) shows that there are practically no high performing versatile boards on the market. This result is at odds with the desires of modern snowboarders identified through the various surveys and interviews, and confirms that a gap in the snowboard marketplace exists for snowboards that perform well in both major riding styles.

To conclude Chapter 2, a versatility value is formulated indicating which design parameters are both crucial to the feel of the snowboard and change markedly between freeride and freestyle models. It is calculated for each objective design parameter using the product of the average relative importance value from the QFD and the normalised range of the test snowboard objective data. The results demonstrate that along with bending stiffness, torsional stiffness and camber also strongly affect the feel and performance between the major riding styles.

In Chapter 3, the identified key snowboard design parameters are given an in-depth analysis. An experimental investigation of the test snowboards reveals that all three possess similar bending stiffness profiles, comprising a steep rise in stiffness from the tip and tail towards the centre, and a substantial trough in the centre of the board. Neglecting the trough in the curve, the bending stiffness profiles are highly representative of each snowboard’s thickness distribution. Hence, it is postulated that the thickness of a snowboard at any location along its chord will drive its resulting bending stiffness. It is noted however that width, layer orientations and materials will also factor into the final bending stiffness profile. The torsional stiffness curves display a similar shaped profile, however the large differences in stiffness magnitudes exhibited by the test boards imply that the materials and/or fibre orientations are likely the driving force behind the torsional stiffness curves. A camber properties analysis of the three test snowboards reveals that the freeride and freestyle models possess similar camber levels, and the versatile snowboard the least camber. Yet despite the similarity in camber levels between the freeride and freestyle snowboards, the freestyle board is rated as significantly more lively. It is postulated that the high levels of bending stiffness present in the body section of the freeride model may hinder its perception as a lively snowboard, as the rider must exert greater effort to depress the cambered section of the board into the snow. The low levels of
Camber exhibited by the versatile test board correlate directly to its rating as the least lively test snowboard.

A comprehensive Spearman ranked correlation analysis between the key design parameters and the subjective performance parameters is consequently undertaken. All of the performance parameters except forgiveness show positive associations to the body bending/torsional stiffness and camber, with manoeuvrability exhibiting the strongest correlations. The forgiveness shows the exact opposite trend, implying that higher levels of flex and less camber promotes a forgiving snowboard.

The influence of temperature on the key properties of bending/torsional stiffness and camber is also examined. This investigation is undertaken due to the large gulf between usual laboratory and on-snow temperatures, and furthermore the common fluctuations in temperature present during snowboarding. All of the key objective attributes increase with a reduction in temperature for the snowboards tested. However between 4°C and -17°C, the parameters remain essentially constant. The changes in stiffness are also different for each type of composite structure. Given the almost constant response of the test snowboards between 4°C and -17°C, the on-snow performance of all three test boards would not be greatly affected by the usual temperature fluctuations present during snowboarding. Instead, the effect of the stiffness/camber changes on the laboratory results and analysis has to be considered. Whilst the stiffness ranked correlations are unchanged, the camber correlations are modified and consequently the analysis is reassessed. On the basis of the new correlations, all of the performance attributes except for the manoeuvrability, feedback and liveliness show weak negative associations with camber. The manoeuvrability displays a weak positive association with camber, whilst the feedback and liveliness show strong positive associations. The low-temperature camber levels also provide a better rationale for the relatively high liveliness performance reviews of the freestyle test board compared to the freeride test board. Finally, the revised stiffness and camber results also have an effect on the determined versatility values, with new values considerably lower than previously calculated.

In Chapter 4, a general parametric model is developed to allow the customisation of snowboard designs to fulfil user performance requirements. The model uses any discrete set of objective design parameters together with rider characteristics to predict the on-snow performance of the design. Two different performance prediction measures are implemented in the model. The first is a correlation based measure, which utilises
individual Spearman ranked correlations between the objective design parameters and subjective performance parameters determined during the research. Conversely, the second exponent based performance measure uses three key objective design attributes to estimate each subjective performance parameter.

As a result of the determined importance of sandwich composite architecture on the bending and torsional stiffness distributions of modern snowboards, an applied prediction code is developed to predict these properties for any sandwich composite that utilises common fabric configurations. The model also calculates the total snowboard mass, and provides an estimation of the camber change for any temperature differential. A geometric unit-cell approach is employed to predict the overall fibre volume fraction, average tow undulation and areal weight for the fabric layers, which are crucial properties to the strength and stiffness of any manufactured composite part. Effective elastic properties are calculated using a modified Hashin’s cylinder model to incorporate the effects of tow undulation or stitching, together with common coordinate transformations and volumetric averaging methods. Laminate beam theory is applied to calculate the bending and torsional stiffness, mass and thermal properties along the chord for the full snowboard composite sandwich, including consideration of the topsheet, base layer, sidewall and edges. These key objective properties are then used as inputs for the general parametric design model.

Chapter 5 describes the validation process for the parametric snowboard model. The performance prediction component is validated against the existing subjective and objective datasets, with a coefficient of determination generated for each individual expression. An overall coefficient of determination for the entire predictive model is also calculated. The parametric model is shown to have an average of 91% predictive capability for the performance of any snowboard within the major riding styles. Conversely, the stiffness, mass and camber prediction model is validated through the manufacture and static testing of three sandwich composite samples of different structure and geometry. The model is shown to predict within 3.5% and 5%, the stiffness and camber of the samples, respectively. Therefore, it provides an alternative to more complex and time consuming CAD/FEA models for the analysis of snowboard sandwich composites.

In Chapter 6, the procedure for the generation of an optimal feel design in each of the major riding styles is described. The software package Esteco ModeFrontier is utilised to determine the design solutions, where the performance targets are derived from the expert rider survey/interview process. To minimise the time of the optimisation, the objective
design parameter list is firstly collapsed by deriving several parameters using simple assumptions. The simulated annealing scheduler within ModeFrontier is employed to generate the designs, by minimising the weighted sum of the difference between the predicted and desired performance parameter values. The resulting predicted performance of the optimal feel designs shows good agreement with the desired parameter levels, but reinforces the fact that in any snowboard design, the overall on-snow performance will be a balance between mutually exclusive facets. In other words, desired levels of the subjective performance parameters may not all be able to be attained simultaneously.

Finally, in Chapter 7 the new knowledge generated and specific outcomes of the research are summarised. General guidelines are presented for the design, manufacture and testing of feel and performance customised snowboards within the major riding styles. The table developed includes the specification of rider inputs, together with methods, analyses and information drawn from the current research. Whilst the described design process is multi-faceted, time and resource requirements are considerably reduced compared to existing design approaches, which are highly experimental and possess significant trial and error. The information, methodologies and analytical tools generated in this research would hence be highly useful for modern snowboard manufacturers. Furthermore, the customised snowboard designs made possible using this process could potentially increase user satisfaction across the product market and improve on-snow rider performance.
2. IDENTIFICATION OF SNOWBOARD DESIGN PARAMETERS AND INNOVATION OPPORTUNITIES

2.1 Qualitative Analysis

Extensive qualitative data in relation to snowboard feel and performance is collected through a range of surveys and interviews, conducted online and in person (on-snow). Participants in an initial mass circulated survey (115 completed responses) are asked to identify, rate and analyse their current board against the set criteria. A secondary follow up survey with a smaller focus group (nine experts) allows more specific questions concerning snowboard feel and performance to be posed and discussed.

Use of surveys within product research and development is well established and can greatly enhance the commercial success of products in any market sector [35]. The first survey is conducted online and mass circulated for maximum respondents. In order to achieve a wide spectrum of participants across the various riding styles, the survey is disseminated throughout worldwide snowboarding institutions, including professional associations, clubs and resorts. The survey software includes a central online database for simple entry and analysis of the results, thus eliminating the need for a lengthy collation process. When the survey is closed, 115 complete responses have been received. The survey questions in their entirety are contained in Appendix A.

The first key element of survey one is rider profiling, which consists of personal characteristics (sex, weight, height and experience) and riding preferences (current and desired snowboard make, model and bindings, along with preferred riding style(s), purchase reasoning and history). Respondents are also asked general, open ended questions regarding their definition of ‘feel’ and ‘performance’ in relation to snowboarding. These initial questions are primarily used for data filtering to highlight subsequent performance reviews by participants with insufficient knowledge or experience.

The rider profiling identifies that 82% of respondents that complete the survey are male. This male/female breakdown is of the order of the published snowboard participation data available, which for 2005 is approximately 74%/26% [36]. Hence, despite the 8% difference, it is assumed the survey results are sufficiently representative on this basis.

Figure 2 displays the breakdown of participants’ snowboarding experience. It is noted that the ‘11+ years’ response is the most common and the ‘0 - 1 years’ non-existent, which
shows the success of the targeted circulation despite its breadth. A closer examination of the entire results set reveals that there are a small number of participants in the latter experience range, none of which are willing or able to complete the survey. The results of riders in the 2 - 3 and 4 - 7 years experience ranges (approximately 6% and 23% of respondents, respectively) are analysed carefully for indicators that the data is not of sufficient standing, given the high probability that under seven years experience is insufficient for the depth of analysis required. As a result, during data filtering, the number of boards owned by the participant and all open-ended comments assume particular importance to gauge the validity of the results.

![Pie chart showing experience breakdown](image)

**Figure 2:** Respondent experience breakdown

The respondent weight and height distributions are shown in Figures 3 and 4, respectively. The breakdowns are essentially normal according to the Shapiro-Wilk test [37], where for weight the test statistic is 0.94 (significance level: p = 0.0001), whilst for height the test statistic is 0.87 (p < 0.0001). Therefore, the ‘average’ snowboarder possesses a mass of 70 - 79 kg and height 170 - 179 cm.
Regarding respondent style preferences, the survey identifies that freestyle (FS) and freeride (FR) snowboards are the most popular, with 55% and 70% of respondents riding in each style, respectively (noting that participants could select more than one style in their answer). Furthermore, freeriding and freestyling interest is linked in 45% of total responses, with a Cohen’s Kappa coefficient (κ) [38] of 0.31 (mild agreement), which is significant (p < 0.0004). Conversely, freecarving is only highlighted in 31% of responses, and is mutually exclusive to the other two styles (Freestyle: κ = -0.39, p < 0.0001;
Freeride: $\kappa = -0.28, p < 0.0001$). Note that for all statistical tests performed, the significance level is set at $p < 0.05$. The associated comments tend to show that modern snowboarders are searching for boards that are able to both handle variable terrain and perform tricks successfully. In other words, the distinction between freestyle and freeride boards has become blurred, and versatility of snowboards within the two main riding styles is now desired by the users.

From the user definitions of ‘feel’ provided in the survey responses, a clear trend emerges that feel is strongly connected to the ‘flex pattern’ and ‘response’ of a snowboard. The term ‘flex pattern’ refers to the bending and torsional stiffness distributions (objective properties) of a board, whilst ‘response’ is a subjective performance term (not unlike feel). To a lesser extent, the terms ‘comfort’, ‘feedback’ and ‘pop’ are also used to describe snowboard feel, which are again all subjective performance attributes. ‘Comfort’ and ‘feedback’ relate to stresses and vibration levels imparted on the rider during snowboarding, whilst ‘pop’ refers to the perceived assistance given to the rider by the board for a manoeuvre. Conversely, the user definitions of ‘performance’ provide more varied responses, implying that it is a wider term than feel in relation to snowboarding. However, many respondents again refer to ‘flex pattern’ and ‘response’, along with ‘pop’ and ‘edge grip’. Thus from the user responses it is concluded that snowboard feel and performance are both intertwined and highly subjective.

In the second major element of survey one, participants are also asked to rate their current snowboard using a comprehensive list of qualitative performance parameters. These dynamic performance attributes are formulated by consulting published snowboard reviews together with comparable research for skis [9], [12] - [17], and are initially classified into straight line boarding, turns and tricks. However, feedback from respondents in an initial pilot survey indicates that subjectively analysing their board under such specific categorical headers is too difficult, and as a result the parameter list is collapsed. Definitions and scope of the parameters are also altered and refined from the pilot survey participants’ comments, resulting in the comprehensive list of subjective feel based performance parameters shown in Table 1.
Table 1: Subjective performance parameter list

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>How stable the rider feels on the board</td>
</tr>
<tr>
<td>Feedback</td>
<td>The amount of stress felt on the rider's body including the effects of board chatter</td>
</tr>
<tr>
<td>Speed</td>
<td>The gliding speed of the board compared to other boards of similar length</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The precision of board movement in response to rider input</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>The tolerance of the board to errors from the rider.</td>
</tr>
<tr>
<td>Edge grip</td>
<td>The level of grip exhibited during turns</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>How easily the board responds to rider inputs</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>How easily the board flows from edge to edge</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>The level of ‘pop’ or spring in the board when performing a jump</td>
</tr>
</tbody>
</table>

The rating system utilised in the subjective analysis is based on the approach formulated by the BMW Group and the University of Bath whilst investigating steering feel for BMW vehicles [18]. This method is selected for several reasons. Firstly, it provides a highly structured, systematic way of linking subjective and objective attributes. Secondly, unlike other comparable studies (Buckingham and Blackford [8], Darques et al. [9], Dore et al. [13], Federolf et al. [14] and Fischer et al. [15]), the BMW/Bath method considers not only sensory quantification but also importance and optimality of the subjective attributes. Finally, despite the wealth of feel and performance information collected from the participants, the approach is relatively simple and easy to understand.

In the selected method, each performance parameter is subjectively rated between 1 and 10, with a rating of 1 representing minimal levels of the parameter (and 10 the opposite). Furthermore, a secondary rating between 1 and 10 of the user’s perceived ideal level of the parameter is given, to allow determination of whether the board exhibits too little, too much or the correct amount of each parameter, and if applicable, the margin by which the board is sub-optimal. An importance rating between 1 and 10 is also sought for each parameter to give them a relative weighting.

The 115 performance reviews in the first online survey span 35 different brands and 67 different models. Unfortunately the lack of any significant grouping prevents a strong statistical basis for individual board model ratings. However, the data is useful to indicate
the varying levels of importance and subjectivity of each parameter, any connections between parameters, and the overall popularity and performance of individual brands.

Firstly, it is noted that stability, edge grip and accuracy all possess highly similar results. The proportion of ‘Too Low’ ratings is approximately 15 - 20% in all cases, whilst conversely only 5 - 6% of respondents assessed the parameters as ‘Too High’. Using the Friedman test for non-parametric measures [39], the differences between the mean ranks for these parameters is highly insignificant (p = 0.73). Furthermore, the average assessment indices (across all styles) are between 7.9 and 8.2 (p = 0.33: Insignificant difference using a one-way repeated measures ANOVA test [40]), with standard deviations between 1.5 and 1.9 rating points. Also, the average importance values are all between 8.5 and 8.8 (p = 0.38), with standard deviations between 1.4 and 1.8.

The results for speed indicate that if considered sub-optimal by the rider (approximately 20% of responses), the snowboard is rated as too slow in almost all cases. Thus the average assessment index is relatively low as a consequence, at 7.5. The low speed ratings are also not confined to any particular style. Forgiveness and feedback show the highest level of variation in the assessment indices (and are also the least important), with dataset standard deviations of 2.0 and 2.1 respectively, implying that these parameters possess the highest levels of subjectivity. The associated ratings are also well spread between ‘Too Low’ and ‘Too High’ (an approximate 50/50 split), providing a further indication of their subjective nature. Edge grip, manoeuvrability and board liveliness all show similarly high levels of low ratings (of the order of 24%), and thus are identified as areas of potential improvement. Finally, the transition smoothness parameter is regarded as optimal in the overwhelming majority of board ratings (92%). It is thus assumed that either participants found it difficult to apply a critical viewpoint to this parameter, or the parameter is rarely sub-optimal in modern snowboard design. The latter proposition is supported by transition smoothness possessing the highest overall average assessment index (8.3).

In terms of relative parameter importance, stability, manoeuvrability and edge grip are rated the highest by respondents, with average weights between 8.7 and 8.8. Accuracy and board liveliness are the next most important, with 8.4 and 8.3 average weights respectively. Transition smoothness has an average importance weight of 7.9, compared to 7.5 for speed and feedback, with forgiveness possessing an average value of 7.1.
Regarding preferred snowboard make/model of the survey respondents, the top seven brands with their relative sample share are displayed in Table 2. It is noted that the top seven brands comprise 61% of the total responses, with Burton clearly the most popular at 29%. The next six most popular brands all possess a comparable proportion of the total number of snowboards analysed, at 5% - 6%. Due to the small number of respondents per brand (aside from Burton), drawing statistically significant brand trends is not possible. However, the feedback, manoeuvrability and board liveliness ratings for Burton snowboards are notably different from the remaining brands. The feedback has a 1 point lower average mean and 1.1 points lower average standard deviation which is significant (p = 0.036 using an independent t-test). The manoeuvrability ratings for Burton snowboards possess a 1.1 points higher average and a 0.4 points lower standard deviation which is highly significant (p = 0.008). Finally, the Burton board liveliness ratings are 0.7 points higher on average than the remaining brands (with standard deviation 1 point lower), however the result is not statistically significant (p = 0.114).

Table 2: First survey snowboard brand distribution

<table>
<thead>
<tr>
<th>Brand</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burton</td>
<td>29</td>
</tr>
<tr>
<td>Nitro</td>
<td>6</td>
</tr>
<tr>
<td>Ride</td>
<td>6</td>
</tr>
<tr>
<td>Rome</td>
<td>5</td>
</tr>
<tr>
<td>Rossignol</td>
<td>5</td>
</tr>
<tr>
<td>K2</td>
<td>5</td>
</tr>
<tr>
<td>Salomon</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>61</td>
</tr>
</tbody>
</table>

Finally, considering the bindings owned by the first survey respondents, the top six brands with their relative sample share are shown in Table 3. As per the snowboard brand distribution, Burton is again the most popular make, with approximately half of all respondents owning Burton bindings. The next five most popular brands each comprise between 4% and 7% of the total sample. Whilst the proportions of Ride, Rossignol and Salomon binding owners approximately match the associated snowboard brand data, a
significant proportion of respondents (21%) who do not utilise Burton boards prefer Burton bindings. It is noted that the binding data is only utilised as a selection basis for the on-snow tests (see below), and is not given further consideration. Whilst it is recognised that bindings are an integral component of the total snowboard system and may significantly alter the resulting feel and performance of any board if incorrectly sized or fitted to the rider’s boot, they are not within the scope of the present research. It is hence assumed that for all survey and focus group responses, the participants’ bindings are correctly sized and fitted, and only provide the force transfer link between the rider and snowboard (no further impact on feel and performance).

Table 3: First survey binding brand distribution

<table>
<thead>
<tr>
<th>Brand</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burton</td>
<td>50</td>
</tr>
<tr>
<td>Flux</td>
<td>7</td>
</tr>
<tr>
<td>Ride</td>
<td>6</td>
</tr>
<tr>
<td>Rossignol</td>
<td>5</td>
</tr>
<tr>
<td>Flow</td>
<td>4</td>
</tr>
<tr>
<td>Salomon</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>76</td>
</tr>
</tbody>
</table>

The secondary follow up survey, whilst again conducted online, is undertaken only by an invited group of nine expert respondents (focus group), which includes a senior member of the Canadian Snowboard Federation. They are questioned in relation to feel, performance and design features of snowboards within each major riding style, and are asked to pinpoint the ideal levels and relative importance of the subjective parameters. Respondents are specifically requested to apply a highly critical analysis to the subjective parameter ratings to ensure a sufficient spread in the results, which is lacking in the first mass circulated survey. Freecarving is excluded from the research at this point due to lack of riders interested in the style, along with its determined exclusivity to the other major riding styles. The survey results are displayed in Figures 5 and 6 as well as Tables 4(a) and (b) for freeride and freestyle snowboards, respectively, whilst the questions in their entirety are contained in Appendix B.
Figure 5: Focus group analysis: Freeride snowboards

Figure 6: Focus group analysis: Freestyle snowboards
For freeride snowboards, the desired performance features vary amongst the responses, with eight out of the nine subjective parameters appearing throughout (feedback is not mentioned). This implies that an ideal freeride board possesses a balanced blend of all performance facets in order to achieve rider satisfaction. Overall however, manoeuvrability is the most commonly desired performance feature, appearing in 57% of responses. Manoeuvrability, forgiveness and correct stiffness levels are the factors most frequently identified as missing amongst the freeride snowboards currently on the market (29% of responses in each case). Stability and stiffness levels are the parameters providing the highest satisfaction levels in the respondents’ current freeride snowboard (43% and 29% of responses, respectively), whereas forgiveness and liveliness are identified as the worst features (also 43% and 29% of responses, respectively). Whilst strongly desired by riders, it appears that optimal manoeuvrability is often not attained in modern snowboard models. Furthermore, the presence of stiffness in both mutually exclusive categories indicates that the optimal level is highly user dependent, but nonetheless crucial to the overall snowboard design.

For freestyle snowboards, the responses exhibit significantly different trends. The most commonly desired parameter is liveliness (for trick performance), appearing in 86% of responses. Manoeuvrability, forgiveness and stiffness are also mentioned in 57%, 43% and 29% of answers, respectively. The remaining subjective parameters are almost non-existent in the responses, implying that (unlike freeride models) freestyle boards need to have certain specific performance attributes fulfilled to satisfy the rider, which can be at the expense of other performance areas. Stability, forgiveness and stiffness are most commonly pinpointed as the best feature of the respondents’ freestyle snowboard (29% of responses in each case), whilst the stiffness levels, speed, edge grip, stability and durability are identified as the worst features (29% of responses for stiffness levels and 14% for each of the remaining parameters). It is noted that the stability and stiffness are common amongst mutually exclusive categories, implying that the optimal levels of these parameters are highly subjective for freestyle snowboards.

Tables 4(a) and (b) display the importance and ideal levels (mean ± standard deviation) of each subjective parameter for the major riding styles. Both scales are again from 1 to 10, with 10 representing high levels or high importance of each parameter and 1 the opposite.
The Kano model of customer requirements [41] is utilised to identify the desired performance attributes for modern snowboards. Developed in the 1980’s by Professor Noriaki Kano, the product development model assesses customer satisfaction through classification of user preferences. It aims to assist development teams in the product specification process by providing a deeper understanding of the item. The Kano model is selected over alternative methods such as Dual Importance Mapping, Penalty Reward Contrast Analysis or Correspondence Analysis [42] due to its strong historical links to product development and direct importance weights determination (unlike the latter two methods). Dual Importance Mapping is not considered due to the requirement of correlation information between attribute performance and overall customer satisfaction which has not been generated.

The sorting of customer requirements using the Kano model is undertaken with respect to ‘essential’, ‘functional’ and ‘excitement’ attributes. From the importance ratings contained in Tables 4(a) and (b), stability, manoeuvrability and accuracy are classified as ‘essential’ for freeride boards, where if not fulfilled, will cause high levels of dissatisfaction to the customer. Edge grip, speed and feedback represent the ‘functional’ requirements, whilst forgiveness, liveliness and transition smoothness are considered ‘excitement’ features, where non-fulfilment does not result in customer dissatisfaction, but achieving the optimal levels of these parameters will add value to the product. It is noted an even split between

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Importance</th>
<th>User Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>6.7 ± 2.7</td>
<td>8.8 ± 0.9</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>6.3 ± 2.6</td>
<td>8.8 ± 1.1</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5.7 ± 3.1</td>
<td>8.5 ± 1.4</td>
</tr>
<tr>
<td>Edge grip</td>
<td>5.4 ± 2.1</td>
<td>8.1 ± 2.1</td>
</tr>
<tr>
<td>Speed</td>
<td>4.6 ± 3.6</td>
<td>8.5 ± 1.5</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.4 ± 2.1</td>
<td>6.4 ± 2.7</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>4.4 ± 1.6</td>
<td>7.1 ± 1.1</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>4.0 ± 2.9</td>
<td>7.5 ± 2.1</td>
</tr>
<tr>
<td>Transition</td>
<td>3.4 ± 1.6</td>
<td>7.4 ± 1.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Importance</th>
<th>User Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board liveliness</td>
<td>7.6 ± 1.9</td>
<td>8.6 ± 1.0</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>7.0 ± 1.4</td>
<td>8.5 ± 1.8</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>7.0 ± 1.7</td>
<td>7.8 ± 1.2</td>
</tr>
<tr>
<td>Stability</td>
<td>5.4 ± 3.0</td>
<td>7.3 ± 2.0</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5.3 ± 2.3</td>
<td>7.8 ± 1.5</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.9 ± 1.6</td>
<td>5.1 ± 2.5</td>
</tr>
<tr>
<td>Edge grip</td>
<td>3.1 ± 1.9</td>
<td>6.6 ± 1.6</td>
</tr>
<tr>
<td>Speed</td>
<td>2.4 ± 1.3</td>
<td>6.5 ± 1.7</td>
</tr>
<tr>
<td>Transition</td>
<td>2.3 ± 1.3</td>
<td>7.0 ± 1.9</td>
</tr>
</tbody>
</table>
attribute categories is chosen for the division instead of using an importance level cut-off basis.

An identical analysis is applied to the freestyle results, where the range in importance values (5.3) is significantly greater than the corresponding freeride range (3.3). Furthermore, the three groups of requirements are highly distinct for freestyle snowboards, possessing large differences in average values between groups (minimum 2.0 points difference between successive group means), but small data ranges within each group (all within 0.5 to 0.8). This contrasts to the freeride parameters where the decrease in importance ratings between groups is more gradual (all groups with 1 point data ranges and maximum 1.3 points difference between means of successive groups). These trends reinforce the previous results where surveyed users require specific attributes for freestyle snowboards, as opposed to the balanced blend of all performance parameters required for freeride boards.

Considering the ideal levels results, all performance parameters across both styles are rated between 5.1 and 8.8, implying mid to high levels of each attribute is desired regardless of the riding style in question. The data ranges are also far smaller than the corresponding importance value ranges (FR: 2.4, FS: 3.5), and possess lower average standard deviations (FR: 0.9 points difference, FS: 1.1 points difference). Both riding styles display comparable ideal levels maxima and minima (FR max: 8.8, FR min: 6.4, FS max: 8.6, FS min: 5.1). Furthermore, the ideal level maximum for both riding styles is also the most important parameter (FR: Stability/manoeuvrability, FS: Board liveliness), and feedback is the ideal level minimum in both cases (but not the least important parameter). There is also a general trend of increasing ideal levels with importance across both riding styles.

From the obtained results, it is noted that freeriders desire a board which is manoeuvrable and stable (as well as accurate), parameters that on face value are polar opposites. Thus an optimal freeride board would be based on a compromise between manoeuvrability and stability, with a slight leaning towards ensuring the ideal level of stability is attained. Conversely, the essential user requirements for freestyle snowboards of board liveliness, manoeuvrability and forgiveness appear less mutually exclusive than the aforementioned essential freeride requirements.

Comparing the results of the first survey to the second, again the results for stability, accuracy and edge grip show no significant differences in means using a one-way repeated
measures ANOVA test (FR importance: \( p = 0.72 \), FR ideal levels: \( p = 0.48 \), FS importance: \( p = 0.27 \), FS ideal levels \( p = 0.35 \)). Additionally, the ideal level results for feedback across both styles possess the largest standard deviations (refer to Tables 4(a) and (b)), matching the result from the first survey and further indicating high subjectivity levels for the parameter. The corresponding result for forgiveness is not displayed in the results of the second survey. Regarding overall importance levels, the results of the two surveys are difficult to compare due to the style breakdown in the second survey. However, there are common trends, with stability and manoeuvrability possessing high importance values (across both riding styles), and conversely speed and feedback relatively low importance values. An anomalous result is also noted where transition smoothness is rated least important across both riding styles in the second survey, yet possesses only the third lowest importance ranking in the first survey.

To finalise the qualitative analysis, on-snow testing and interviews using a range of high quality test boards are conducted to obtain subjective ratings with a strong statistical basis, and further investigate the interrelationships between each of the qualitative parameters. Nine experienced testers (snowboarding instructors) of similar mass and height (Average mass: 76.9 ± 8.0 kg; Average height: 177.5 ± 7.2 cm) are employed to ride and rate three best-in-class new snowboards that spanned the freeride-freestyle board spectrum. One highly freeride oriented and one specialist freestyle board are chosen to represent the end points of the spectrum, and a third versatile (VE) board is selected mid-way. The board selection process is two-fold. Using published market share data [2], the snowboard brands holding the greatest market share (most popular) in the US are first identified. This shortlist is then compared to data from the first survey, where the most popular and highly rated recent models are pinpointed. However to ensure that the boards selected are placed at the desired locations within the freeride-freestyle board spectrum, published information on the models is sought in combination with interviews of experienced snowboarders.

For the on-snow tests, a course is custom-designed to examine all facets of snowboard performance. It consists of four turns of different radii (between 5 m and 20 m), a rail for presses or board slides (approximately 2.5 m long), and a jump for the performance of tricks (approximately 2 m high). Each rider completes three runs of the course, and is then immediately interviewed to provide performance ratings for the subjective parameters and general comments linking these performance facets to the design of the snowboard (refer to Section 2.3). To reduce variables present in the testing, all riders use the same make,
model and size binding (Burton Custom 2008), which requires at least a size 9 (US) foot. This also ensures variance in rider mass is minimised. The tests are undertaken over a two day period at Mt Buller, Victoria, where the temperature fluctuates between -1°C and 3°C. A schematic of the course is shown in Figure 7 (not to scale), whilst the performance ratings for each test board (mean ± standard deviation) are shown in Tables 5(a) - (c). The freeride and freestyle test snowboard ratings are also compared to the respective ideal parameter levels in Tables 6(a) and (b).

![Figure 7: On-snow tests course schematic](image)

**Table 5(a):** Freeride test board performance ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge grip</td>
<td>9.5 ± 0.5</td>
</tr>
<tr>
<td>Stability</td>
<td>9.0 ± 0.7</td>
</tr>
<tr>
<td>Accuracy</td>
<td>8.9 ± 0.7</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>8.8 ± 0.8</td>
</tr>
<tr>
<td>Speed</td>
<td>8.5 ± 0.7</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>8.0 ± 1.6</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>6.7 ± 1.9</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>5.4 ± 1.5</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.4 ± 3.0</td>
</tr>
</tbody>
</table>

**Table 5(b):** Versatile test board performance ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition smoothness</td>
<td>8.7 ± 0.5</td>
</tr>
<tr>
<td>Speed</td>
<td>8.1 ± 1.3</td>
</tr>
<tr>
<td>Accuracy</td>
<td>7.8 ± 1.1</td>
</tr>
<tr>
<td>Edge grip</td>
<td>7.3 ± 2.2</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>7.2 ± 2.0</td>
</tr>
<tr>
<td>Stability</td>
<td>7.0 ± 0.9</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6.8 ± 1.9</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>6.6 ± 1.2</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.3 ± 2.6</td>
</tr>
</tbody>
</table>

**Table 5(c):** Freestyle test board performance ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board liveliness</td>
<td>7.9 ± 1.5</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>7.8 ± 1.4</td>
</tr>
<tr>
<td>Accuracy</td>
<td>7.1 ± 1.4</td>
</tr>
<tr>
<td>Edge grip</td>
<td>6.9 ± 1.2</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>6.5 ± 1.5</td>
</tr>
<tr>
<td>Stability</td>
<td>6.2 ± 0.7</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>6.0 ± 1.3</td>
</tr>
<tr>
<td>Speed</td>
<td>5.1 ± 1.6</td>
</tr>
<tr>
<td>Feedback</td>
<td>5.1 ± 2.4</td>
</tr>
</tbody>
</table>
Considering the test board ratings in Tables 5(a) - (c), all parameters are rated (average) between 4.3 and 9.5, which is a range from low-mid to very high levels of the performance attributes. The individual data ranges decrease from freeride to freestyle (FR: 5.1, VE: 4.4, FS: 2.7), where the freestyle range is approximately half the corresponding freeride range. The overall maximum across the datasets is the freeride edge grip parameter (9.5), whilst the minimum is the versatile feedback parameter (4.3). The spread in the ratings is also comparable for all three test snowboards, with no significant difference between average standard deviations (p = 0.38). Finally, the ratings for stability, accuracy and edge grip are again linked, with no significant differences between the datasets (FR: p = 0.18, VE: p = 0.55, FS: p = 0.23).

As per the previous results, the feedback parameter displays the highest level of subjectivity, possessing the largest standard deviation for all three test boards. The continuing trend of high subjectivity is likely due to the different possible parameter interpretations, where feedback can be considered as both a positive and negative influence on snowboard performance. Some users dislike high stress and vibrations imparted on them during riding due to a perceived lack of control and increased body fatigue rate. Conversely, others may prefer strong levels of feedback to obtain maximum information from the snowboard and terrain, thus allowing riding style and dynamics to be continually fine-tuned. These different possible interpretations are the likely cause of the large spread of ideal feedback levels displayed in Tables 4(a) and (b). Furthermore, difficulty of resolving the positive and negative facets could be the source of the large standard deviation of feedback test board ratings shown in Tables 5(a) – (c). The different personal characteristics (ie height, mass) of the test riders would also have been another factor in the spread of feedback perceptions. This overall variance in interpretation contrasts with the remaining subjective parameters, which are generally considered positive facets of performance.
Table 6(a): Freeride test board optimality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Importance</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>6.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>6.3</td>
<td>-0.8</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Edge grip</td>
<td>5.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Speed</td>
<td>4.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.4</td>
<td>-2.4</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>4.4</td>
<td>-1.7</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>4.0</td>
<td>-0.8</td>
</tr>
<tr>
<td>Transition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>smoothness</td>
<td>3.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 6(b): Freestyle test board optimality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Importance</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board liveliness</td>
<td>7.6</td>
<td>-0.7</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>7.0</td>
<td>-0.7</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>7.0</td>
<td>-1.3</td>
</tr>
<tr>
<td>Stability</td>
<td>5.4</td>
<td>-1.1</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5.3</td>
<td>-0.7</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Edge grip</td>
<td>3.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Speed</td>
<td>2.4</td>
<td>-1.4</td>
</tr>
<tr>
<td>Transition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>smoothness</td>
<td>2.3</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

Tables 6(a) and (b) show the difference between the freeride and freestyle test board ratings and ideal parameter levels, and are hence a measure of test board optimality. It is noted that aside from the freeride feedback, all observed differences are less than 2 rating points or 20% of the overall scale. However given the determined subjectivity of feedback ratings and ideal levels, little can be drawn from this relatively large discrepancy. The freeride results display equal number of parameters that have positive and negative differences (the speed is optimal), where the key linked attributes of stability, accuracy and edge grip are all rated as too high. Conversely, the essential attributes for freestyle snowboards (forgiveness, liveliness and manoeuvrability), are rated as too low for both test boards. Furthermore, only the edge grip is rated as too high for the freestyle test board (only 0.3 points), whilst the remaining parameters are either too low or optimal (feedback). The forgiveness parameter displays the largest total sub-optimal result, with a net difference of -3.0 rating points, and hence is pinpointed as a key improvement area.
2.2 Quantitative Analysis

The quantitative parameters used in the research are based primarily on the ASTM Standard *F1107-1995 – Standard Terminology Relating to Snowboarding* [29], although several other objectively measurable parameters relating to material properties are introduced to cover all relevant aspects of any snowboard design. They are defined and grouped as follows:

**Major Lengths**

- **Chord length** ($L_{ch}$): The straight-line distance between the tip and tail with the snowboard pressed flat to a plane surface to take out the camber (Figure 8(a)).
- **Contact length** ($L_{co}$): The difference between the projected length ($L_p$) and the sum of the heel and shovel lengths ($L_h + L_s$) (Figure 8(b)).
- **Projected length** ($L_p$): The length of the projection of the snowboard, measured between the tip and tail with the snowboard unweighted on a plane surface (Figure 8(b)).

**Shovel**

- **Shovel length** ($L_s$): The projected length of the forward turn-up, measured from the tip to the contact point where a 0.1 mm feeler gage intersects the running surface with the snowboard unweighted on a plane surface (Figure 8(b)).
- **Shovel radius** ($R_s$): The average radius of the circular line or lines that describe the curved portion of the snowboard contour at the shovel (Figure 8(c)).
- **Tip height** ($H_t$): The height of the underside of the tip from a plane surface with the snowboard unweighted (Figure 8(b)).
- **Shovel width** ($W_s$): The horizontal perpendicular distance between two vertical planes placed on either edge of the shovel, parallel to the longitudinal centreline of the snowboard (Figure 8(c)).

**Heel**

- **Heel length** ($L_h$): The projected length of the rear turn-up, measured from the tail to the contact point where a 0.1 mm feeler gage intersects the running surface with the snowboard unweighted on a plane surface (Figure 8(b)).
• Heel radius ($R_h$): The average radius of the circular line or lines that describe the curved portion of the snowboard contour at the heel (Figure 8(c)).

• Tail height ($H_h$): The height of the underside of the tail from a plane surface with the snowboard unweighted (Figure 8(b)).

• Heel width ($W_h$): The horizontal perpendicular distance between two vertical planes placed on either edge of the heel, parallel to the longitudinal centreline of the snowboard (Figure 8(c)).

**Body**

• Waist width ($W_w$): The width at the narrowest point of the snowboard, measured perpendicular to the longitudinal centreline (Figure 8(c)).

• Sidecut radius ($R_{sc}$): The average radius of the circular line or lines that describe the curved portion of the snowboard contour between the lines denoting the shovel and heel width dimensions (Figure 8(c)).

• Self-weighted bottom camber ($C$): The maximum height of the running surface measured from the ground plane with the snowboard unweighted (Figure 8(d)).

**Thickness (Researcher Defined)**

• Body thickness ($T_b$): The average distance between two parallel planes placed tangentially to the upper and lower snowboard surfaces, within the dimension $L_{co}$ (Figure 8(e)).

• Shovel thickness ($T_s$): The average distance between two parallel planes placed tangentially to the upper and lower snowboard surfaces, within the dimension $L_s$ (Figure 8(e)).

• Heel thickness ($T_h$): The average distance between two parallel planes placed tangentially to the upper and lower snowboard surfaces, within the dimension $L_h$ (Figure 8(e)).

**Edges (Researcher Defined)**

• Edge sharpness – Body ($\xi_b$): The average angle of the edge that cuts into the snow during a turn, within the dimension $L_{co}$ (Figure 8(f)).

---

4 Some snowboard models feature reverse camber or ‘rocker’ technology, where the running surface possesses a U or V shaped profile instead of the traditional curvature. This type of camber profile is not considered in the present research.
• Edges sharpness - Shovel ($\xi_s$): The average angle of the edge that cuts into the snow during a turn, within the dimension $L_s$ (if present).
• Edges sharpness - Heel ($\xi_h$): The average angle of the edge that cuts into the snow during a turn, within the dimension $L_h$ (if present).

**Stiffness (Researcher Defined)**

• Body bending stiffness ($EI_b$): The average bending stiffness of the snowboard within the dimension $L_{co}$.
• Shovel bending stiffness ($EI_s$): The average bending stiffness of the snowboard within the dimension $L_s$.
• Heel bending stiffness ($EI_h$): The average bending stiffness of the snowboard within the dimension $L_h$.
• Body torsional stiffness ($GJ_b$): The average torsional stiffness of the snowboard within the dimension $L_{co}$.

**Miscellaneous**

• Asymmetrical offset ($\alpha_s, \alpha_h$): The distance along the longitudinal axis that each side of an asymmetrical snowboard is offset from the other side. Offset may be different at the shovel and heel (Figure 8(g)).
• Mass ($M$): The total mass of the snowboard.

**Materials (Researcher Defined)**

• Edge material ($\frac{H_B}{\rho}$): The Brinell hardness to density ratio of the edges.
• Body material ($\frac{EI_b}{\rho}$): The body bending stiffness to weight ratio of the snowboard.
• Shovel material ($\frac{EI_s}{\rho}$): The shovel bending stiffness to weight ratio of the snowboard.
• Heel material ($\frac{EI_h}{\rho}$): The heel bending stiffness to weight ratio of the snowboard.
• Base material ($\frac{\xi}{\rho}$): The wax absorption to density ratio of the base.

All of the above parameters are measured in the laboratory (refer also to Chapter 3) or obtained from published data sheets for each of the test boards purchased. The quantitative dataset for each test snowboard is shown in Table 7. Note that edge sharpness data is displayed as a range due to the ability of the rider to modify the edge angle at any time.
through tuning and detuning. Displayed measurement uncertainties are dependent on the quantity considered, where the lengths, widths, heights and asymmetrical offset all possess an error range estimated at ± 0.5 mm, driven by the human resolution limit when using a ruler. The uncertainties in the nose, tail and sidecut radii refer to the standard deviation in the radius of curvature values calculated for each profile, averaged over the three test snowboards. For the nose and tail radii, this value is approximately 40% of the average radius of curvature for each test board, whereas the sidecut radius error is less than 1% of the measured values. This shows the high variance in curvature radius throughout the nose and tail profiles of modern snowboards, compared to the more constant sidecut radius. For the thickness and camber parameters, the use of callipers and comparators allowed a measurement resolution up to 0.01 mm, but the textured nature of the test snowboard topsheets means that uncertainty is estimated at 0.1 mm (slight change in measurement location alters reading considerably). The error in edge sharpness parameters is set at the nominal value of 1°, again driven by the human resolution limit. Calculations of average uncertainty in the bending and torsional stiffness parameters are considered in detail in Chapter 3. The error in mass measurements is estimated at 0.01 kg based on digital scale fluctuations. Finally, for the derived material parameters, overall errors are determined using published material data ranges and the method of combined uncertainties for algebraic expressions [43].
Figure 8(a): Chord length

Figure 8(b): Self-weighted geometry

Figure 8(c): Top view (symmetric snowboard)

Figure 8(d): Self-weighted camber

Figure 8(e): Thickness geometry

Figure 8(f): Edge sharpness angle

Figure 8(g): Top view (asymmetric snowboard)
Table 7: Quantitative snowboard data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Error</th>
<th>Freeride</th>
<th>Versatile</th>
<th>Freestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major lengths</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chord length</td>
<td>mm</td>
<td>± 0.5</td>
<td>1569.5</td>
<td>1552.5</td>
<td>1515.5</td>
</tr>
<tr>
<td>Contact length</td>
<td>mm</td>
<td>± 0.5</td>
<td>1199.5</td>
<td>1195</td>
<td>1149.5</td>
</tr>
<tr>
<td>Projected length</td>
<td>mm</td>
<td>± 0.5</td>
<td>1571.5</td>
<td>1551.5</td>
<td>1512.5</td>
</tr>
<tr>
<td><strong>Shovel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shovel length</td>
<td>mm</td>
<td>± 0.5</td>
<td>193.5</td>
<td>179</td>
<td>181.5</td>
</tr>
<tr>
<td>Shovel radius (avg)</td>
<td>mm</td>
<td>± 82</td>
<td>183</td>
<td>210</td>
<td>189</td>
</tr>
<tr>
<td>Tip height</td>
<td>mm</td>
<td>± 0.5</td>
<td>56</td>
<td>47</td>
<td>54.5</td>
</tr>
<tr>
<td>Shovel width</td>
<td>mm</td>
<td>± 0.5</td>
<td>291</td>
<td>294</td>
<td>299</td>
</tr>
<tr>
<td><strong>Heel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heel length</td>
<td>mm</td>
<td>± 0.5</td>
<td>178.5</td>
<td>177.5</td>
<td>181.5</td>
</tr>
<tr>
<td>Heel radius (avg)</td>
<td>mm</td>
<td>± 77</td>
<td>188</td>
<td>187</td>
<td>189</td>
</tr>
<tr>
<td>Tail height</td>
<td>mm</td>
<td>± 0.5</td>
<td>55</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td>Heel width</td>
<td>mm</td>
<td>± 0.5</td>
<td>291</td>
<td>294</td>
<td>299</td>
</tr>
<tr>
<td><strong>Waist</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waist width</td>
<td>mm</td>
<td>± 0.5</td>
<td>246</td>
<td>250</td>
<td>253.5</td>
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<tr>
<td><strong>Sidecut</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sidecut radius (avg)</td>
<td>m</td>
<td>± 0.04</td>
<td>8.36</td>
<td>8.42</td>
<td>7.17</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body thickness (avg)</td>
<td>mm</td>
<td>± 0.1</td>
<td>10.0</td>
<td>9.1</td>
<td>9.0</td>
</tr>
<tr>
<td>Shovel thickness (avg)</td>
<td>mm</td>
<td>± 0.1</td>
<td>5.2</td>
<td>4.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Heel thickness (avg)</td>
<td>mm</td>
<td>± 0.1</td>
<td>5.0</td>
<td>4.5</td>
<td>5.3</td>
</tr>
<tr>
<td><strong>Camber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camber</td>
<td>mm</td>
<td>± 0.1</td>
<td>8.1</td>
<td>4.4</td>
<td>7.9</td>
</tr>
<tr>
<td><strong>Edges</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body edge sharpness</td>
<td>deg</td>
<td>± 1</td>
<td>86 - 94</td>
<td>86 - 94</td>
<td>86 - 94</td>
</tr>
<tr>
<td>Shovel edge sharpness</td>
<td>deg</td>
<td>± 1</td>
<td>86 - 94</td>
<td>86 - 94</td>
<td>86 - 94</td>
</tr>
<tr>
<td>Heel edge sharpness</td>
<td>deg</td>
<td>± 1</td>
<td>86 - 94</td>
<td>86 - 94</td>
<td>86 - 94</td>
</tr>
<tr>
<td><strong>Stiffness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shovel bending stiffness (avg)</td>
<td>N.m²</td>
<td>± 10.3</td>
<td>30.5</td>
<td>27.3</td>
<td>32.0</td>
</tr>
<tr>
<td>Body bending stiffness (avg)</td>
<td>N.m²</td>
<td>± 10.3</td>
<td>234.3</td>
<td>196.5</td>
<td>200.5</td>
</tr>
<tr>
<td>Heel bending stiffness (avg)</td>
<td>N.m²</td>
<td>± 10.3</td>
<td>28.9</td>
<td>27.0</td>
<td>32.7</td>
</tr>
<tr>
<td>Body torsional stiffness (avg)</td>
<td>N.m²</td>
<td>± 16.0</td>
<td>266.0</td>
<td>160.3</td>
<td>172.6</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asymmetrical offset</td>
<td>mm</td>
<td>± 0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mass</td>
<td>kg</td>
<td>± 0.01</td>
<td>2.87</td>
<td>3.01</td>
<td>3.02</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge material</td>
<td>m³/kg</td>
<td>± 0.05</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Shovel material (avg)</td>
<td>N.m²/kg</td>
<td>± 3.4</td>
<td>10.6</td>
<td>9.1</td>
<td>10.6</td>
</tr>
<tr>
<td>Body material (avg)</td>
<td>N.m²/kg</td>
<td>± 3.4</td>
<td>81.6</td>
<td>65.3</td>
<td>66.3</td>
</tr>
<tr>
<td>Heel material (avg)</td>
<td>N.m²/kg</td>
<td>± 3.4</td>
<td>10.1</td>
<td>9.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Base material</td>
<td>mm</td>
<td>± 0.003</td>
<td>0.027</td>
<td>0.027</td>
<td>0.020</td>
</tr>
</tbody>
</table>
2.3 Benchmarking Analysis Using the Quality Function Deployment Method

In order to pinpoint the key design parameters for each riding style with respect to fulfilling the identified customer requirements, a Quality Function Deployment (QFD) method is used to process the information collected. QFD methodology is intrinsically linked to the previously employed Kano model, and utilises known relationships between the customer requirements and design parameters to determine the relative importance of the latter [41], [44], [45].

The QFD analysis is undertaken by synthesising all the information collected during the initial qualitative and quantitative phases of the research, including the online surveys/interviews, on-snow testing and objective data collection. Matrices of Spearman ranked correlations assessing links between the subjective and objective parameters (see Appendix C), as well as between individual subjective performance parameters (see Appendix D) are also generated to assist in the analysis. Individual relationships are determined through examination and critical assessment of the entire knowledgebase for each parameter. For the relationships involving subjective parameters, this involves resolving expert comments and responses to open ended questioning with relevant Spearman ranked correlations and fundamental logical reasoning [46]. Where minimal information is available or the information is inconclusive, a weak correlation is assumed. Conversely, for the purely objective relationships, a logical assessment of the influence of the design parameters on each other (relative design freedom) is utilised as the basis of the correlation, where if the first design parameter can be freely varied without any influence on the second, zero correlation is assumed.

The following data is presented in the QFD charts:

1. *Objective-subjective parameter relationships* (central matrix): Relationships between all objective and subjective feel based parameters, determined via the online survey/interview process, on-snow tests, Spearman ranked correlations between the datasets (see Appendix C) and logical reasoning.

2. *Customer importance*: Importance weights (from 1 - 10) of the subjective parameters obtained via the on-line surveys/interviews.

3. *Objective parameter correlations* (top roof): Relationships between the objective technical attributes of the snowboard, determined through relations analysis and logical reasoning.
4. **Subjective parameter correlations** (left side roof): Relationships between the subjective feel based parameters, determined using Spearman ranked correlations between the results of the on-snow tests (see Appendix D) and logical reasoning.

5. **Direction of improvement**: Direction of the required variation (if any) to improve each objective parameter.

6. **Technical assessment**: Numerical value range for each objective parameter obtained via the static lab tests/measurements and published data sheets.

7. **Units**: The relevant unit of measurement for each objective parameter.

8. **Customer assessment**: A comparison between user test board ratings and perceived ideal levels for each style.

9. **Weighted importance**: The overall importance results for the objective parameters obtained after QFD processing.

10. **Relative importance**: A relative comparison between overall importance results.

For the correlations between the parameters, six different relationships are defined, denoted by the symbols and correlation weights (in brackets) displayed in Figure 9. The resulting QFD charts for both freeride and freestyle snowboards are shown in Figures 10 and 11, respectively.

![QFD symbols](image)

**Figure 9**: QFD symbols

- Strong positive (+9)
- Medium positive (+3)
- Weak positive (+1)
- Weak negative (-1)
- Medium negative (-3)
- Strong negative (-9)
Figure 10: Freeride QFD results
Figure 11: Freestyle QFD results
Examining the relationships shown in the QFD charts, it is firstly noted that the average bending stiffness of the snowboard body (and consequently the associated material parameter) has the most strong correlations and thus highest relative importance for both major riding styles. This is due primarily to its strong impact on overall performance determined from the initial on-line surveys. The major lengths of projected, chord and contact length (all interdependent) also possess high weighted importance as a result of several strong correlations, being crucial to the stability, manoeuvrability, accuracy, edge grip, speed and feedback of modern snowboards. These relationships are identified predominantly from the results of the on-snow tests (together with logical reasoning), where several strong Spearman ranked correlations between performance ratings and objective data sets are present (see Appendix C). It is noted however that statistical correlations do not equate to causation, and thus the prior knowledge of a strong connection between stability, accuracy and edge grip is also factored into the final QFD correlations. The torsional stiffness, mass and major widths also display several strong correlations to various facets of snowboard performance (due to the results of the initial surveys, Spearman correlations and logical reasoning), and consequently display medium-high weighted importance values.

Conversely, the heel/shovel lengths, heights and radii, average thicknesses and asymmetrical offset possess no strong correlations. Furthermore, the heel and shovel thickness parameters exhibit the lowest overall weighted importance. None of these parameters are mentioned by any respondents throughout the survey/interview process, hence driving the weak and medium correlations determined. It is noted however that despite the low direct impact on performance, the thickness distribution of a snowboard affects the bending and torsional stiffness distributions (flex pattern), which are strongly connected to on-snow performance.

Considering the weighted importance outputs of the QFD analysis, any variation between freeride and freestyle snowboards is due solely to differing rider importance weights for the subjective performance parameters (refer to Tables 4(a) and (b)). To directly compare the results for each style, individual weighted importance values are normalised using the weighted importance sum from each QFD chart. The graph shown in Figure 12 compares relative importance values between the two major riding styles.
It is noted that the body stiffness and body material parameters are at least 1.2% more important to both styles than any other parameter, implying that the bending stiffness distribution and mass of the main body section are crucial in any optimal feel design. The major lengths, widths, sidecut radius, mass and torsional stiffness also display high relative importance (approximately 5%) for both freeride and freestyle snowboards. Furthermore, the major lengths and camber display the largest difference in relative importance between the major riding styles. The camber is 0.66% more important to freestyle designs due to its importance to liveliness and forgiveness, which drive trick performance and landing. Conversely, the major lengths are 0.44% more important to freeride designs, with the focus of the style on stability, accuracy and edge grip.
2.4 Snowboard Design Innovation Opportunities

A comprehensive gap analysis [47], [48] is undertaken to identify possible design innovation and product development opportunities for modern snowboards. Using the subjective ratings from the first survey of board models manufactured between 2004 and 2007 (40 out of the 67 total different models), the snowboards’ cumulative performance under the prescribed qualitative headers is plotted against their published style, within a range between pure freeride and pure freestyle. The performance measure for each model is calculated using a weighted average of ratings, compared to the ideal levels of each subjective parameter within the prescribed style, as follows:

\[
P = \frac{1}{\sum_{n=1}^{9} (I_n \times |\chi_n - O_n|)}
\]

Where \( P \) is the overall snowboard performance rating, \( I_n \) is the parameter importance, \( \chi_n \) is the average parameter rating, \( O_n \) is the parameter optimal level, and the subscript \( n \) refers to each subjective parameter (1 - 9). The averages are reciprocated to give low ratings for high average differences from the ideal levels, and the results normalised to fit a scale between +5 and -5. Considering that the ideal levels for both styles are unique, for snowboard models located between the pure freeride and pure freestyle endpoints of the spectrum, a cumulative weighted difference is used to compare ratings to both sets of ideal levels. Similarly, a weighted average of importance levels is also implemented. The resulting Market Opportunity Map (MoM) [47], [48] shown in Figure 13, aims to identify gaps in the overall snowboard market with respect to the freeride-freestyle riding style domains.

The MoM shows that the performance levels of snowboard models manufactured between 2004 and 2007 are highly variable across the entire spectrum, involving both low and high performing pure freeride and freestyle models. It is noted that there are practically no high performing versatile boards using the applied test. This result appears at odds with the desires of modern snowboarders identified through the various surveys and interviews, and specifically the noted overlap in style interest. It is readily apparent that riders desire versatile boards that exhibit high level performance within both styles. This confirms that a gap in the snowboard marketplace exists, which provides potential design innovation opportunities for high performing, versatile snowboards.
In order to realise the identified design innovation opportunity, it is important to pinpoint the objective design parameters that affect the versatility of snowboards. This is achieved using a combination of existing qualitative and quantitative data. A ‘versatility value’ is formulated as a measure of the extent variation in an objective design parameter drives the feel and performance from freestyle to freeride or vice versa. It is calculated for each objective parameter using the following expression:

$$VV_m = \frac{I_{FS} + I_{FR}}{2} \times \frac{D^\text{max}_m - D^\text{min}_m}{D^\text{max}_m}$$  \hspace{1cm} (2)$$

Where $VV_m$ is the versatility value, $I_{FS}$ is the freestyle importance weight, $I_{FR}$ the freeride importance weight, $D^\text{max}_m$ is the maximum objective design parameter value, $D^\text{min}_m$ the minimum objective design parameter value and $m = 1, 2, ..., 31$. Thus the versatility value results highlight those factors which vary significantly along the style spectrum and strongly alter the feel and performance of any snowboard.

Whilst it was expected that the limits of the objective parameter range would originate from the freestyle and freeride labelled test boards, several of the maxima and minima are derived from the test board classified as versatile, illustrating that there is no logical
progression for technical parameters along the style spectrum, and instead the amalgamation of all parameters results in a certain style and feel. It also reinforces the assertion that the overlap between freeride and freestyle boards is relatively pronounced.

![Versatility Design Drivers](image)

**Figure 14:** Versatility values

The graph displayed in Figure 14 shows how the versatility values vary with each objective parameter. It is noted that several features appear to be crucial to the versatility of modern snowboards. The self-weighted camber, bending/torsional stiffness in the body and the body stiffness/weight ratio all possess values at least double that of the remaining objective parameters. However the low value of the mass parameter indicates that stiffness is of key concern as the mass does not vary to any significant extent between the test boards. Furthermore, the source of the high values differs between the three design features. The body bending stiffness and stiffness/weight ratio versatility values are primarily the result of very high importance weights from the QFD charts, indicating their importance to the overall feel for both styles. The normalised ranges are only of the order of 16% - 20%, implying that small changes in stiffness result in strong feel and performance variation. The camber and torsional stiffness show the opposite trend, where
between the test boards, the normalised ranges are approximately 46% and 40% respectively, and the importance weights values are notably lower.

Overall, varying the bending and torsional stiffness distributions and the camber appears to be the key approach to altering the feel and performance of a snowboard across the major riding styles.
3. SNOWBOARD STIFFNESS AND CAMBER CHARACTERISTICS

3.1 Experimental Investigation

The bending/torsional stiffness distributions and camber properties have been determined to be crucial to the feel and performance of modern snowboards. The bending stiffness distribution was identified as the most important design parameter, whilst the torsional stiffness distribution and camber characteristics were pinpointed as key parameters driving a change in the identified riding style.

A thorough investigation into the bending, torsional and camber characteristics of the three test boards is therefore undertaken. The procedures for the stiffness tests are based primarily on ISO Standard 5902: Alpine skis - Determination of the elastic properties [31], as no equivalent standard exists for snowboards. Several modifications are made to the specified procedures to allow their application to the present research. These modifications are a result of differing geometry between snowboards and skis, requiring alternate testing dimensions as well as the application of greater forces and moments on the test boards to generate the requisite levels of bending and torsion. Furthermore, the standard only contains procedures for calculating spring constants (with units of N/mm and N.m/deg for bending and torsion respectively), so further transformation of the data is required to allow the calculation of relevant stiffness values [9].

*Bending Stiffness*

The bending stiffness of the three test boards is calculated using the following standard beam equation [49]:

\[ EI = \frac{\bar{M}_y}{\kappa_y} \]  

(3)

Where \( EI \) is the bending stiffness (N.m²), \( \bar{M}_y \) is the applied bending moment about the transverse \( y \) axis (N.m) and \( \kappa_y \) is the longitudinal curvature (about the transverse \( y \) axis) of the snowboard (m⁻¹). The apparatus designed for the tests based on the descriptions given in the standard is pictorially shown in Figures 15 - 17 below. The test rig displayed in Figure 15(a) comprises a 1500 mm long C-channel base, two adjustable supports with 20 mm diameter rollers (capable of supporting the entire width of all three snowboards from tip to tail), and finally a load (F) application device consisting of two 20 mm diameter...
rollers supporting two variable masses via hooks (between 32 kg and 50 kg of mass applied). This particular setup allows the calculation of the bending stiffness in the body section of the test boards. To determine the bending stiffness at the heel and shovel of the snowboards a different setup is required, as shown in Figure 15(b). For these particular tests the forebody or aftbody of each snowboard is clamped using sets of 40 mm wide metal plates, and the boards are deflected using 22 kg of total mass 100 mm from the tip/tail.

Figure 15(a): Bending stiffness test rig - body

Figure 15(b): Bending stiffness test rig - heel/shovel

Figure 16 shows the apparatus used to calculate the curvature of the test snowboards, consisting of a 20 mm comparator positioned centrally in a 200 mm C-section. The device allows accurate measurement (0.01 mm resolution) of the localised relative deflection at 50 mm intervals along the chord, and thus calculation of the curvature using the following simple geometry (shown in Figure 17):
Using Pythagoras theorem,

\[ R^2 = \left(\frac{L}{2}\right)^2 + (R - \delta)^2 \]  \hspace{1cm} (4)

When \( R \gg \delta \),

\[ R \approx \frac{L^2}{8\delta} \]  \hspace{1cm} (5)

Where \( R \) is the calculated radius of curvature, \( L \) is the measurement length (200 mm) and \( \delta \) is the measured deflection. Thus, the longitudinal curvature \( 1/R \) can easily be determined. The combined results of the bending tests on all three test boards are shown graphically in Figure 18. Regarding accuracy of the bending stiffness calculations, overall error is comprised of uncertainty in the measurement of distance and mass, along with the error associated with the simplification of the radius of curvature expression. As per previous, uncertainty in the measurement of length (using a ruler) and mass (using a digital scale) is estimated at ± 0.5 mm and ± 0.01 kg, respectively. Also, despite the 0.01 mm resolution for comparator readings, uncertainty in the measurement of localised relative deflection is set at ± 0.1 mm, again due to the textured nature of the test snowboard topsheets. The method of combined uncertainties described in Dieck [43] is utilised to determine the average overall error in bending stiffness for each test snowboard, the components of which are shown in Table 8.
Figure 18: Bending stiffness distributions

Table 8: Bending stiffness uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Freeride</th>
<th>Versatile</th>
<th>Freestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature assumption (avg)</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Curvature experimental (avg)</td>
<td>5.0%</td>
<td>4.8%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Moment experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>5.4%</td>
<td>5.2%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>11.6</td>
<td>9.6</td>
<td>9.6</td>
</tr>
</tbody>
</table>
**Torsional Stiffness**

The torsional stiffness profiles of the test snowboards are obtained using the following standard beam formula [49]:

\[
GJ = \frac{T_x L}{\theta_x}
\]  

(6)

Where \(GJ\) represents the torsional stiffness (N.m²), \(T_x\) is the applied torque about the longitudinal \(x\) axis (N.m), \(\theta_x\) is the resulting angular deformation (rad) and \(L\) is the measurement length (m). Given that snowboard structures are non-homogeneous, the measurements are made utilising 200 mm sections of each test snowboard. Although the measurement length should be as small as possible (giving an instantaneous rate of change in angular deformation), 200 mm is chosen on the assumption that utilising an average angular deformation rate will produce a smaller overall error than angular measurement inaccuracy. Figure 19 displays the sectioning of the snowboard for the torsional tests.

Using the same rig as per the forebody and aftbody bending tests to clamp the board, the portion under consideration is twisted using a dual system, comprising a hanging mass on one side of the snowboard, and a mass pulling the board upward via a pulley and flagstaff on the opposing side. This setup is shown in Figure 20. Note that the masses applied to each test board varied between 11 kg and 23 kg, to ensure adequate angular displacement without straying into the plastic deformation zone (0.2% offset elastic limit assumed [50]).

The test boards are clamped in four separate configurations during the tests. Firstly, the basic forebody/aftbody tests are conducted, where each board is clamped along the centreline, and the rollers positioned 170 mm from the tip/tail (as per Figure 20). Secondly, in order to simulate the twist generated on the body section of each snowboard by the rider, the boards are clamped at the forward binding location, with the rollers positioned on the aft binding inserts. This test is repeated with the opposing setup, with both tests utilising a test section of the stance width plus 100 mm.
To calculate the resulting angular deformation along each test section (at 50 mm intervals), again a comparator (on a guided rail) is utilised to measure the vertical displacement of locations adjacent to the snowboard edge, which are then converted into angles using the following simple geometry (shown in Figure 21):

Angular deformation:

$$\theta_x = \tan^{-1}\left(\frac{\delta}{e}\right)$$  \hspace{1cm} (7)

Where $e$ is the distance from the centreline of the board to the measurement location, and $\delta$ is the measured vertical displacement. The resulting torsional stiffness profiles for the
three test boards are displayed in Figure 22. Note that unlike the bending profiles (which are calculated from tip to tail), the difficulty in undertaking the torsional measurements on the curved heel and shovel sections means that these areas of the boards are neglected. However considering that torsional stress on the board is imparted almost solely by the riders’ feet, the torsional stiffness in the body of the snowboard is of paramount importance.

Regarding accuracy of the torsional stiffness calculations, overall error is again comprised of uncertainty in the measurement of distance and mass, along with the error associated with taking an average angular deformation rate (over 200 mm sections) instead of an instantaneous rate. Unfortunately, the effect of the latter simplification cannot be quantified. Uncertainty in the measurement of length (± 0.5 mm) and mass (± 0.01 kg) is as previously described. The error in comparator displacement readings is estimated at ± 0.5 mm due to the visible variance of measurement position on the highly textured upper snowboard surfaces (refer to Figure 21) as torque is applied. This is five times the estimated displacement uncertainty from the bending stiffness calculations, where measurement positional changes are negligible. As per previous, the method of combined uncertainties described in Dieck [43] is utilised to determine the average overall error in torsional stiffness for each test snowboard, the components of which are displayed in Table 9.
Table 9: Torsional stiffness uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Freeride</th>
<th>Versatile</th>
<th>Freestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular deformation experimental (avg)</td>
<td>6.6%</td>
<td>9.5%</td>
<td>7.1%</td>
</tr>
<tr>
<td>Torque experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Measurement length experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>7.2%</td>
<td>10.1%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>19.4</td>
<td>16.1</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Camber Properties

The camber of each test board is determined using a simple setup consisting of a comparator on a stand. It is calculated along the centrelines of the snowboards, by comparing readings with the boards pressed flat and when resting under only their own weight. Five measurements are taken and the results averaged. The camber properties are shown within the objective data table (Table 7), where the approximate error in the
measurements is of the order of ± 0.1 mm. This uncertainty is determined using the same reasoning as per the localised relative displacement readings for the bending stiffness calculations.

Discussion of Results

The bending stiffness profiles in Figure 18 show a number of trends across the style spectrum. All three test snowboards possess similar bending profiles, comprising a steep rise in stiffness from the tip and tail towards the centre, and a substantial trough in the centre of the board. The bending stiffness distributions correlate strongly to the respective thickness distributions of the test boards, shown in Figure 23. These distributions are generated using callipers, with measurement uncertainty again estimated at ± 0.1 mm. It is hence postulated that the thickness profile of a snowboard will be one of the primary drivers of its resulting bending stiffness characteristic (as per simple beam theory). The combination of the sidecut and slightly smaller thickness (particularly for the versatile board) in the centre of each test snowboard appears to cause the trough in the bending profiles. Hence, the width distribution is also pinpointed as an important factor to bending stiffness. Furthermore, whilst not considered at this stage, it is noted that composite layer architecture will strongly affect the final bending stiffness profile. The steel binding inserts would also have provided additional bending resistance near the locations of the peaks.

The freeride test board possesses the greatest levels of bending stiffness, with its entire bending characteristic above the profiles of the remaining two test snowboards. It is also noted that the freeride profile is not centred due to its transverse asymmetry (longer shovel than heel). The versatile test board profile displays higher peaks than the freestyle curve, yet a lower trough. It is postulated that this variation in bending stiffness is an indicator of its versatility, representing a combination of the stiffness profiles of the remaining two test snowboards. The freestyle bending characteristic has considerably less stiffness fluctuation compared other two test snowboards. It is assumed that bending stiffness profiles of this nature provide a consistent response during riding, desired for trick performance.
Regarding the bending stiffness uncertainties displayed in Table 8, it is noted that the average experimental error associated with the calculation of the snowboard curvature is the largest contributor to average overall relative error, regardless of the test snowboard under consideration. This error source is approximately 50 times the average error associated with the assumption in the calculation of the radius of curvature 4.8 - 5.0% compared to 0.1% for each test snowboard), and approximately 17 times the average experimental error associated with the applied moment (0.3% for each test snowboard). Whilst the average overall relative error in the calculation of bending stiffness for each test snowboard is comparable (between 5.2% and 5.4%), the freeride test snowboard possesses the greatest average overall absolute error (11.6 N.m$^2$ compared to 9.6 N.m$^2$ for the versatile/freestyle snowboards). This is a result of the higher overall bending stiffness of the freeride test snowboard compared to the versatile and freestyle test snowboards (refer to Table 7). The average overall absolute uncertainty in the calculation of bending stiffness for each snowboard is pictorially represented by the error bars in Figure 18.
The torsional stiffness profiles shown in Figure 22 possess similar trends to the preceding bending stiffness curves, with the characteristic wave profile apparent for all three test boards. Again, the freeride test snowboard displays the greatest torsional stiffness, but in this case by a significant margin (average of $266.0 \pm 19.4$ N.m$^2$ compared to $172.6 \pm 13.2$ N.m$^2$ and $160.3 \pm 16.1$ N.m$^2$ for the freestyle and versatile test snowboards, respectively) unlike the previous bending curves. Considering that the geometry of the three test boards is not overly dissimilar (less than 10% difference between most parameters; refer to Table 7), and thus highly unlikely to cause such a large torsional stiffness range, the materials and/or fibre orientation are assumed to be the primary drivers of the torsional stiffness curves. The torsional profiles for the versatile and freestyle curves are highly similar, with the freestyle test board possessing a slightly greater torsional stiffness throughout the body (average of $172.6 \pm 13.2$ N.m$^2$ compared to $160.3 \pm 16.1$ N.m$^2$). This is most likely a result of the larger width parameters (refer again to Table 7) for the freestyle snowboard.

Regarding the calculated torsional stiffness uncertainties displayed in Table 9, similar trends are noted to the bending stiffness data, where the average angular deformation experimental error (corresponds to the average curvature experimental error) is the largest contributor to the average overall relative error for each test snowboard (6.6% – 9.5% contributions to totals of 7.2% – 10.1%). The average experimental uncertainties associated with the applied torque and measurement section length only contribute 0.3% each to the overall error values. Despite possessing the lowest average overall relative error, the freeride test snowboard has the largest average overall absolute error in the torsional stiffness calculations (19.4 N.m$^2$ compared to 16.1 N.m$^2$ and 13.2 N.m$^2$ for the versatile and freestyle test snowboards, respectively). This is again a result of the higher overall stiffness of the freeride test snowboard compared to the versatile/freestyle test snowboards (refer to Table 7). The average overall absolute uncertainty in the calculation of torsional stiffness for each snowboard is pictorially represented by the error bars in Figure 22.

The freeride test board also possesses the highest levels of camber (8.1 ± 0.1 mm; refer to Table 7), 0.2 ± 0.2 mm more than the freestyle board and 3.7 ± 0.2 mm more than the versatile board. Given the trick based nature of the style, it was expected that the freestyle test board would have been the most highly cambered. However, considering the estimated margin of error in the measurements (± 0.1 mm), the maximum camber heights of the freeride and freestyle test snowboards are very similar. Assessing the liveliness ratings for
these two test boards, despite the similarity in camber levels, the freestyle board is rated as significantly more lively (7.9 ± 1.5 compared to 6.7 ± 1.9; refer to Tables 5(a) and (c)). It is postulated that the high levels of bending stiffness present in the body section of the freeride board may hinder its perception as a lively snowboard, as greater effort by the rider is required to depress the cambered section of the board into the snow. The low levels of camber exhibited by the versatile test board (4.4 ± 0.1 mm; refer to Table 7) also correlate directly to its rating as the least lively test snowboard (average liveliness rating of 6.6 ± 1.2; refer to Table 5(b)).

Whilst not examined in this research, the stiffness and camber properties of modern snowboards vary over time through consistent on-snow usage or mechanical laboratory testing. It is well established from rider feedback that snowboards have a performance fatigue life, where after a certain amount of use boards lose their ‘pop’ or liveliness. This is a result of diminishing stiffness and camber levels, with lifespan dependent on construction architecture, manufacturing process and quality of materials utilised, frequency and modes of use, operating temperature and initial design levels [51]. The fatigue life can be as low as one season if the snowboard is consistently subjected to high-stress use, such as the performance of large jumps and rails. Fatigue of the snowboard sandwich structure is a complex process, generally driven by failure (shear cracking) of the polymer matrix in the fabric composite layers, but can also be caused by delamination and buckling of the embedded fibres [51]. The stiffness and camber testing described in this section was conducted on the test snowboards after the on-snow testing at Mt Buller, and thus it is possible that the results may have been slightly different had the laboratory tests been performed when the snowboards were brand new. However, given the on-snow tests only consisted of limited, low impact runs over a two day period, it is likely that any fatigue effects are insignificant in the overall stiffness and camber analysis.
3.2 Correlation Analysis

A statistical correlation analysis is conducted between the key objective parameters and subjective performance ratings of the three test snowboards. It aims to provide further insight into the relationships between snowboard stiffness and camber characteristics and on-snow performance. Since the stiffness data is in the form of continuous curves, for the correlation, integrated average values are calculated for each major portion of the test snowboards, and are as shown in Table 7. Table 10 displays the resulting Spearman correlation coefficients for each relationship, on scale between +1 (increasing linear) and -1 (decreasing linear). These values are obtained by firstly converting each data set to ranks, then applying the following standard formula [52]:

$$r_{m,n} = \frac{\Sigma (\bar{D}_m - \bar{D}_m)(\bar{X}_n - \bar{X}_n)}{\sqrt{\Sigma (\bar{D}_m - \bar{D}_m)^2(\bar{X}_n - \bar{X}_n)^2}}$$  (8)

Where $r_{m,n}$ is the relevant correlation coefficient, $\bar{D}_m$ is the objective parameter rank, $\bar{X}_n$ is the subjective parameter rank, $\bar{D}_m$ and $\bar{X}_n$ are the respective sample rank means, whilst $m = 17,21,22,23,24$ (camber and stiffness parameters only) and $n = 1,2,...,9$. Given the limited nature of the data (3 points for each set), only a 1 or -1 correlation result indicates a statistically significant association ($p < 0.05$).

| Table 10: Subjective-objective parameter correlations |
|---------------------------------|-----|-----|-----|-----|
| Camber | Bending Stiffness (avg) | Body Torsional Stiffness (avg) |
|        | Shovel | Body | Heel |        |
| Stability | 0.50 | -0.50 | 0.50 | -0.50 | 0.50 |
| Manoeuvrability | 1.00 | 0.50 | 1.00 | 0.50 | 1.00 |
| Accuracy | 0.50 | -0.50 | 0.50 | -0.50 | 0.50 |
| Edge grip | 0.50 | -0.50 | 0.50 | -0.50 | 0.50 |
| Feedback | 0.50 | 1.00 | 0.50 | 1.00 | 0.50 |
| Forgiveness | -1.00 | -0.50 | -1.00 | -0.50 | -1.00 |
| Speed | 0.50 | -0.50 | 0.50 | -0.50 | 0.50 |
| Board liveliness | 0.50 | 1.00 | 0.50 | 1.00 | 0.50 |
| Transition smoothness | 0.50 | -0.50 | 0.50 | -0.50 | 0.50 |
Discussion of Results

Stability, accuracy, edge grip, speed and transition smoothness all possess the same correlations with the key objective parameters. Whilst none of the relationships are strong or statistically significant, the values indicate that for a snowboard with high levels of these performance parameters, high bending/torsional stiffness in the body and camber is required. The correlations also reinforce the previously identified links between stability, accuracy and edge grip. It is thus postulated that high overall stiffness promotes a strong, stable and fast snowboard for the rider, as well as ensuring the board does not undergo drastic flex during turns, diminishing the grip. Furthermore, the correlations suggest that certain levels of these objective parameters are required for a smooth transition between edges, to avoid the snowboard feeling limp and unresponsive, and the transition forced. Little bearing is placed on the medium negative correlations between heel/shovel stiffness and these five performance parameters, as the heel and shovel of the board are not in contact with the snow surface during carve turns.

Whilst stability and manoeuvrability are polar opposites by definition, both body stiffness parameters (and the heel and shovel to a lesser extent) show strong positive correlations with the manoeuvrability of the test snowboards. It was expected that softness in the centre of the board would allow independent foot movement increasing rider control, yet the correlations suggest this assertion is incorrect. It is hence postulated that as the stiffness in the snowboard increases, the response to rider inputs is quicker, increasing the overall manoeuvrability. The camber also shows a strong linear positive correlation to the manoeuvrability, which in combination with the previous results suggests that a stiff, highly cambered body section will allow the rider to swiftly generate turns by aggressively pushing the body of the snowboard into the snow (flattening the camber). These same properties would also allow a quick exit from a turn as the camber returns to its natural level.

The correlations for feedback (despite its determined subjectivity) are essentially as expected, with increased camber and stiffness along the chord implying greater feedback to the rider. The heel and shovel stiffness display the strongest positive associations with feedback, potentially caused by increasing vibration magnitudes of these sections with stiffness due to the cantilever beam effect.
The forgiveness shows medium to strong negative correlations with camber and stiffness, indicating that a stiffer and more highly cambered board, whilst stable and accurate, would tend to punish any mistakes by the rider. Unlike the feedback results however, the body section possesses a stronger correlation with forgiveness than the heel and shovel regions. This result is justifiable given the heel and shovel sections rarely contact the snow during general riding, thus have a minimal effect on forgiveness.

All objective parameter correlations with liveliness are positive, implying that increased stiffness and camber will promote a lively board. It is noted however that the response will strongly depend on the mass and strength of the rider, as a heavier person may find a softer board less lively if the camber is too easily pressed, and consequently a stiffer board more suitable. Thus stiffness and camber levels must be tailored to individual riders in order to achieve an optimal response. The strong positive correlations between heel/shovel stiffness and liveliness indicate that relatively stiff nose and tail sections are required for satisfactory performance of tricks (presses and board slides).
3.3 Temperature Effects

The on-snow temperature in snowboarding is highly variable and dependent on factors such as geographical location, elevation, time of year, humidity, wind speed, cloud cover and even time of day. For example, at the height of winter in Canada, riders may be exposed to on-snow temperatures in the order of -20°C [53]. Conversely, as the ski season draws to a close in Australia, the snow will be softened by ambient temperatures well above 0°C [54].

To date there have been no published attempts to fully evaluate the effects of such a temperature differential on snowboard properties. This phenomenon should not only be taken into consideration in the overall snowboard design process, but also any post-manufacture laboratory or on-snow analysis. Therefore, the effect of temperature variation on stiffness and camber properties of the three test snowboards is investigated. The test boards are subjected to the elastic bending and torsional deflection tests described previously at three different temperatures, 22°C, 4°C and -17°C. Measurements of the self-weighted camber are also taken at each temperature. Table 11 summarises the testing conditions for each set of experiments.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>22°C</th>
<th>4°C</th>
<th>-17°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
<td>± 2°C</td>
<td>± 0.5°C</td>
<td>± 2°C</td>
</tr>
<tr>
<td>Location</td>
<td>Laboratory</td>
<td>Industrial fridge</td>
<td>Industrial freezer</td>
</tr>
</tbody>
</table>

Any changes in the stiffness and camber properties of the test snowboards are correlated to the temperature dependent properties of the materials used in their construction. The three snowboards possess significantly different composite constructions, varying with core material, layer composition and base material. Table 12 shows detailed specifications of the test boards, whilst Figures 24(a) and (b) display schematically the two types of fibreglass fabric. The results of the static bending and torsional deflection tests for each snowboard are shown in Figures 25 - 27 and 28 - 30 respectively, with integrated average stiffness values displayed in Table 13 and components of uncertainty shown in Tables 14 and 15. A comparison of camber properties (plus uncertainties) is contained in Table 16.
Table 12: Test snowboard specifications

<table>
<thead>
<tr>
<th></th>
<th>Freeride Test Board</th>
<th>Versatile Test Board</th>
<th>Freestyle Test Board</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>159 cm</td>
<td>157 cm</td>
<td>154 cm</td>
</tr>
<tr>
<td><strong>Core material</strong></td>
<td>Aluminium honeycomb</td>
<td>Wood</td>
<td>Wood</td>
</tr>
<tr>
<td><strong>Layer composition</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper and lower single tri-axial fibreglass layers</td>
<td>• Upper single bi-axial fibreglass layer</td>
<td>• Upper and lower single tri-axial fibreglass layers</td>
<td></td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>• Epoxy resin</td>
<td></td>
<td>• Epoxy resin</td>
</tr>
<tr>
<td>• Carbon reinforcing strips</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Base material</strong></td>
<td>Sintered UHMWPE</td>
<td>Sintered UHMWPE</td>
<td>Extruded UHMWPE</td>
</tr>
<tr>
<td><strong>Topsheet</strong></td>
<td>ABS</td>
<td>ABS</td>
<td>ABS</td>
</tr>
</tbody>
</table>
Figure 25: Freeride test snowboard bending stiffness comparison

Figure 26: Versatile test snowboard bending stiffness comparison
Figure 27: Freestyle test snowboard bending stiffness comparison

Figure 28: Freeride test snowboard torsional stiffness comparison
Figure 29: Versatile test snowboard torsional stiffness comparison

Figure 30: Freestyle test snowboard torsional stiffness comparison
### Table 13: Average stiffness comparison (N.m²)

<table>
<thead>
<tr>
<th></th>
<th>Freeride Test Board</th>
<th>Versatile Test Board</th>
<th>Freestyle Test Board</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Bending</strong></td>
<td><strong>Torsion</strong></td>
<td><strong>Bending</strong></td>
</tr>
<tr>
<td><strong>22°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shovel</td>
<td>30.5</td>
<td>27.3</td>
<td>32.0</td>
</tr>
<tr>
<td>Body</td>
<td>234.3</td>
<td>266.0</td>
<td>196.5</td>
</tr>
<tr>
<td>Heel</td>
<td>28.9</td>
<td>27.0</td>
<td>32.7</td>
</tr>
<tr>
<td>Full chord</td>
<td>186.3</td>
<td>157.5</td>
<td>161.2</td>
</tr>
<tr>
<td><strong>4°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shovel</td>
<td>37.3</td>
<td>36.9</td>
<td>50.4</td>
</tr>
<tr>
<td>Body</td>
<td>246.6</td>
<td>281.8</td>
<td>214.2</td>
</tr>
<tr>
<td>Heel</td>
<td>36.2</td>
<td>37.1</td>
<td>49.6</td>
</tr>
<tr>
<td>Full chord</td>
<td>197.3</td>
<td>174.0</td>
<td>184.1</td>
</tr>
<tr>
<td><strong>-17°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shovel</td>
<td>39.6</td>
<td>37.7</td>
<td>50.8</td>
</tr>
<tr>
<td>Body</td>
<td>249.9</td>
<td>283.3</td>
<td>216.4</td>
</tr>
<tr>
<td>Heel</td>
<td>38.7</td>
<td>37.4</td>
<td>49.8</td>
</tr>
<tr>
<td>Full chord</td>
<td>200.5</td>
<td>175.9</td>
<td>184.9</td>
</tr>
</tbody>
</table>

### Table 14: Bending stiffness uncertainty comparison

<table>
<thead>
<tr>
<th></th>
<th>Freeride</th>
<th>Versatile</th>
<th>Freestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature assumption (avg)</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Curvature experimental (avg)</td>
<td>5.0%</td>
<td>4.8%</td>
<td>5.0%</td>
</tr>
<tr>
<td><strong>22°C</strong></td>
<td>Moment experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>5.4%</td>
<td>5.2%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>11.6</td>
<td>9.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Curvature assumption (avg)</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Curvature experimental (avg)</td>
<td>5.0%</td>
<td>5.5%</td>
<td>6.0%</td>
</tr>
<tr>
<td><strong>4°C</strong></td>
<td>Moment experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>5.4%</td>
<td>5.9%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>12.5</td>
<td>11.4</td>
<td>12.5</td>
</tr>
<tr>
<td>Curvature assumption (avg)</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Curvature experimental (avg)</td>
<td>5.1%</td>
<td>5.6%</td>
<td>6.1%</td>
</tr>
<tr>
<td><strong>-17°C</strong></td>
<td>Moment experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>5.5%</td>
<td>6.0%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>12.8</td>
<td>11.6</td>
<td>12.6</td>
</tr>
</tbody>
</table>
Table 15: Torsional stiffness uncertainty comparison

<table>
<thead>
<tr>
<th></th>
<th>Freeride</th>
<th>Versatile</th>
<th>Freestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>22°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular deformation experimental (avg)</td>
<td>6.6%</td>
<td>9.5%</td>
<td>7.1%</td>
</tr>
<tr>
<td>Torque experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Measurement length experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>7.2%</td>
<td>10.1%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>19.4</td>
<td>16.1</td>
<td>13.2</td>
</tr>
<tr>
<td><strong>4°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular deformation experimental (avg)</td>
<td>6.8%</td>
<td>10.0%</td>
<td>7.4%</td>
</tr>
<tr>
<td>Torque experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Measurement length experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>7.4%</td>
<td>10.6%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>21.0</td>
<td>20.1</td>
<td>16.1</td>
</tr>
<tr>
<td><strong>-17°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular deformation experimental (avg)</td>
<td>6.8%</td>
<td>10.0%</td>
<td>7.4%</td>
</tr>
<tr>
<td>Torque experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Measurement length experimental (avg)</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>7.4%</td>
<td>10.6%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Overall absolute (avg) (N.m²)</td>
<td>21.2</td>
<td>20.4</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Table 16: Camber comparison (mm)

<table>
<thead>
<tr>
<th></th>
<th>Freeride</th>
<th>Versatile</th>
<th>Freestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>22°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.1 ± 0.1</td>
<td>4.4 ± 0.1</td>
<td>7.9 ± 0.1</td>
<td></td>
</tr>
<tr>
<td><strong>4°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.3 ± 0.1</td>
<td>7.6 ± 0.1</td>
<td>11.2 ± 0.1</td>
<td></td>
</tr>
<tr>
<td><strong>-17°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.5 ± 0.1</td>
<td>7.7 ± 0.1</td>
<td>11.5 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>

Discussion of Results

The main trend identified from the bending and torsional stiffness profiles is an increase in overall stiffness with a decrease in temperature. Most of the stiffness gain occurs when the temperature is reduced from 22°C to 4°C; there is negligible stiffening between 4°C and -17°C for all three test boards. Despite the heterogeneous layered construction of the snowboards, the overall shape of each stiffness profile is not affected by temperature variation.
Each test snowboard exhibits different variations in stiffness. The freeride test board shows the smallest variation over the total temperature range in both bending and torsion, with a total increase in integrated average stiffness of 7.6% ± 13.6% and 6.5% ± 15.7% respectively. However only 1.7% ± 13.7% and 0.6% ± 15.9% of these respective gains occur when the temperature falls from 4°C to -17°C. The freestyle test board displays average stiffness gains in bending and torsion of 14.7% ± 14.6% and 17.1% ± 18.3% respectively, yet again only minor changes between 4°C and -17°C (0.5% ± 15.6% and 0.6% ± 18.8% respectively). The versatile board shows the most interesting results, with a total observed average bending stiffness increase of 11.7% ± 14.2% (1.2% ± 14.7% between 4°C and -17°C), but a total increase in average torsional stiffness of 22.4% ± 25.0% (1.9% ± 25.5% between 4°C and -17°C).

Regarding uncertainties in the stiffness calculations and related percentage increases, all values are determined using the aforementioned method for combined uncertainties [43]. The individual component error sources associated with measurement of displacement, length and mass are all independent of the testing location and temperature (values as per previous).

Considering firstly the bending stiffness uncertainties, it is noted that the magnitudes of relative and overall error have a comparable relationship with temperature as the baseline stiffness data. The freestyle test snowboard possesses the largest increase in relative and absolute error with decreasing temperature (1.1% relative error and 3.0 N.m² absolute error increase from 22°C to -17°C), whereas the freeride test snowboard possesses the smallest variations over the tested temperature range (0.1% relative error and 1.2 N.m² absolute error increase from 22°C to -17°C). This trend correlates directly to the relative gains (listed above) in baseline stiffness data of the three test snowboards with decreasing temperature.

Regarding the bending stiffness uncertainty components, it is noted that the error associated with the measurement of curvature is the primary driver of increasing error magnitudes with decreasing temperature; the error associated with the curvature assumption and applied moment possesses negligible variation over the different testing conditions. These gains in curvature measurement uncertainty are directly attributable to the respective stiffness increases of the test snowboards with decreasing temperature, where smaller curvatures (and greater relative error) resulted as the applied loads did not vary with testing location.
Considering uncertainty in the torsional stiffness calculations, the same trends as per the bending stiffness data are noted, where the relative increases in test snowboard torsional stiffness correlates to the respective gains in overall absolute and relative uncertainty. The versatile test snowboard which exhibits the greatest increase in torsional stiffness between 22°C and -17°C (22.4% ± 25.0%) also possesses the largest overall relative and absolute error increase (0.5% and 4.3 N.m², respectively). Conversely, the freeride test snowboard which exhibits the smallest increase in torsional stiffness over the tested temperature range (6.5% ± 15.7%), also possesses the smallest variation in overall relative and absolute error (0.2% and 1.8 N.m², respectively).

The changes in torsional stiffness uncertainty components also mirror that of bending stiffness, with negligible variance in measurement length and applied torque experimental errors over the temperature dependence tests. The experimental error associated with the measurement of angular deformation is the primary source of increasing overall relative and absolute error in torsional stiffness between 22°C and -17°C. As per previous reasoning, these gains in experimental angular deformation error are directly attributable to the respective stiffness increases of the test snowboards with decreasing temperature, where smaller angular deformations (and greater relative error) resulted as the applied torques did not vary with testing location.

It is also noted that due to the scale of the overall relative errors compared to the gains in stiffness with decreasing temperature, the listed uncertainties in percentage stiffness increases (above) are in all cases comparable to or greater than the associated baseline data. Hence confidence cannot be placed in the actual magnitude of the relative gains in both bending and torsional stiffness of the three test snowboards, but overall trends can nonetheless be examined.

The camber measurements presented in Table 16 show exactly the same trends as the bending and torsional stiffness data, whereby camber levels are significantly greater at the lower temperatures for all three test boards. Furthermore, the results are essentially constant between 4°C and -17°C, with a maximum difference of 0.3 mm between the three snowboards, which is comparable to the estimated measurement uncertainty of 0.1 mm. However, the percentage increases in camber levels of the test boards with decreasing temperature are considerably larger than the corresponding increases in average bending and torsional stiffness. This is the case particularly for the highly flexible versatile test board, which exhibits a 75.0% ± 6.3% increase in maximum camber height, though only
2.3\% \pm 2.7\% \text{ between } 4^\circ\text{C and } -17^\circ\text{C}. The highly stiff freeride board experiences a 17.3\% \pm 2.7\% increase in camber over the total temperature range (2.5\% \pm 2.2\% between 4^\circ\text{C and } -17^\circ\text{C}), whilst the freestyle test board exhibits a 45.6\% \pm 3.1\% change (3.8\% \pm 1.8\% between 4^\circ\text{C and } -17^\circ\text{C}). The uncertainty for all camber measurements is independent of the testing location and temperature, and is as previously described (0.1 mm).

As the overall geometry of each snowboard remains constant during the temperature dependent tests (aside from some thermal contraction/expansion), the different stiffness gains of the three snowboards are attributed to their different composite sandwich construction. The freeride test board, constructed with an aluminium honeycomb core and two tri-axial layers of fibreglass, exhibits the most constant stiffness response over the temperature range. Conversely, aside from the very large increase in torsional stiffness displayed by the versatile test board, the freestyle test board made with a wooden core and bi-axial fibreglass layers shows the highest temperature dependence.

Overall, the versatile and freestyle test snowboards constructed with a wooden core and bi-axial fibreglass skins show larger stiffness increases than the freeride board made using aluminium honeycomb and tri-axial fibreglass skins. The differences in the stiffness-temperature responses of the boards are partly due to differences in the temperature dependent elastic properties of the fibreglass skins and core materials. The stiffness of the bi-axial fibreglass skins has a greater dependency on the elastic properties of the epoxy matrix than the tri-axial fibreglass skins. This is because bi-axial skins only have glass fibres in two reinforcement directions (normally 45°/-45° though other angles are possible), whereas tri-axial skins have three reinforcement directions (0°/45°/-45°). Thus depending on the fibre angles utilised in the fabric, either the bending stiffness (governed by longitudinal or 0° stiffness) or torsional stiffness (governed by shear or 45°/-45° stiffness) of bi-axial fibreglass skins are influenced more strongly by matrix properties than fibre properties [55], [56]. Conversely, the stiffness of the tri-axial fibreglass skins is less dependent on the matrix properties. The stiffness of glass fibres is insensitive to changes in temperature over the range studied (-17°C to 22°C), whereas the elastic modulus of the epoxy matrix increases as the temperature decreases [57], [58]. This stiffness gain is a result of decreased mobility of the polymer network structure, which slows the movement of the chains under an external applied load resulting in higher rigidity [59]. Therefore, the overall stiffness of the bi-axial fibreglass skins shows a larger increase than the tri-axial skins when the temperature is reduced.
Another factor influencing the bending and torsional stiffness properties of the snowboards is the temperature dependent elastic modulus of the core materials. The stiffness of polymer encased wood (restricting moisture changes) increases significantly as the temperature is reduced (at least 20% between 22°C and -17°C) [60], whereas the elastic modulus of aluminium honeycomb exhibits far smaller changes over the tested temperature range (less than 5%) [61], [62].

The elastic properties of the UHMWPE base layer and ABS topsheet present on all three test boards are also temperature dependent. Again, this is a result of reduced molecular mobility, whereby the molecules do not move as easily under an externally applied stress when the temperature drops [59]. The outermost layers of each snowboard, despite their relatively small thickness, have a significant influence on the bulk stiffness-temperature properties due to their elastic modulus increasing significantly with decreasing temperature and their distance from the neutral bending axis. Decreasing the temperature from 22°C to -17°C will increase the elastic modulus of the UHMWPE and ABS layers by about 70% and 200% - 300%, respectively (the exact response of ABS in the tested temperature range is unknown) [63], [64]. Implementing these stiffness gains in an elastic stress-strain analysis of a laminated snowboard, the resulting increase in bulk bending and torsional stiffness is approximately 4.5% and 7.5% respectively. Therefore, the stiffness gains of the snowboards with decreasing temperature is due to increases in the elastic properties of the fibreglass skins, wood and aluminium honeycomb cores, UHMWPE base layer and ABS topsheet.

Despite the large percentage changes in camber exhibited by the test snowboards, examining the actual increases in total camber (in millimetres), trends similar to those noted for the bending and torsional stiffness data are apparent. Again the stiffest freeride board shows the most constant response over the temperature range (1.4 mm camber gain), whilst the freeride and versatile test boards both exhibit a camber increase of about 3.5 mm. It is postulated that the camber changes for all three test boards are caused by the differences in thermal expansion coefficients of the constituent layers (Table 17). Upon cooling, the UHMWPE base layer contracts to a far greater extent (at least 200%) than the other layers in the composite sandwich. This contraction rate differential causes a thermal curvature and the snowboard to bend upwards, increasing the camber.
Table 17: Thermal expansion coefficients [65]

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha \left(10^{-6}/^\circ C\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (spruce) (parallel to grain)</td>
<td>3.4 - 6.1</td>
</tr>
<tr>
<td>Aluminium honeycomb</td>
<td>21.5 - 23.6</td>
</tr>
<tr>
<td>Fibreglass (parallel to fibres)</td>
<td>5.0</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>81 – 117</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>234 - 360</td>
</tr>
<tr>
<td>ABS</td>
<td>65 - 95</td>
</tr>
</tbody>
</table>

The different camber changes between the test boards are rationalised in a similar manner. Compared to the aluminium honeycomb core snowboard, the wooden core snowboards possess a significantly larger contraction rate differential between the UHMWPE base layer and core material (by a factor of four). This provides an explanation for the far larger camber gains exhibited by the freestyle and versatile test boards. The small gains in the 4°C to -17°C temperature range are more difficult to justify, however studies have shown that epoxy resin and UHMWPE exhibit significant reductions in their thermal expansion coefficient with temperature [66] - [68], as opposed to wood and aluminium which have essentially constant coefficients [67], [69]. Thus the thermal expansion differentials between the layers of each test snowboard reduce significantly with temperature, providing a rational explanation for the camber results.

Given the almost constant response of the test snowboards between 4°C and -17°C, the on-snow performance of all three test boards would not be greatly affected by the usual temperature fluctuations present during snowboarding. Instead, the stiffening effect should be considered when undertaking various laboratory tests at room temperature, such as during vibrational analysis where calculated natural frequencies may be considerably different at on-snow temperatures. Any results would have to be scaled to incorporate the temperature effects, particularly when boards with different composite structures are being compared as even a relative comparison may be inaccurate.
**Scaling of Results**

Analyses utilising laboratory data at 22°C are revisited using results at -17°C in order to assess the effect of on-snow temperatures on any conclusions drawn. Figure 31 displays the results of the scaling on calculated versatility values. It is noted that compared to the initial versatility values chart (Figure 14), the values for camber and body bending/torsional stiffness are significantly reduced. This is a result of reduced normalised ranges (-13% for camber, -3% for bending stiffness and -10% for torsional stiffness) for these parameters. Conversely, the values for shovel and heel bending stiffness increase as a result of larger normalised ranges (11% for the heel and 21% for the shovel). The stiffness to mass ratios for all four stiffness parameters also change as a consequence of the modified data ranges.

**Figure 31:** Revised versatility values

Despite the noted variation in calculated versatility values, the overall conclusions drawn are only slightly affected. The camber and bending/torsional stiffness in the body are still pinpointed as key parameters to the overall feel and performance of modern snowboards. However on the basis of the temperature scaled data, the entire bending stiffness...
distribution and associated material parameters appear to be crucial to feel and performance (particularly the heel portion). Furthermore, the sidecut radius assumes greater importance to the versatility of snowboards using the revised data, primarily as a result of reduced values for the key objective parameters. It is also noted that only the camber and stiffness are considered at -17°C; the effect of temperature on the remaining objective parameters is negligible. Thermal expansion/contraction has only a nominal effect on geometric parameters such as lengths, radii and thicknesses, whilst the measured changes in heel and shovel heights produce only minor changes in the calculated versatility values.

The correlation analysis is also revisited to assess the effect of temperature on indicated associations between objective and subjective parameters. The stiffness increases for all three test boards have no effect on the ranks for each objective parameter (average stiffness), and thus the Spearman ranked correlations are unchanged. Conversely, the camber ranks are varied as a result of the large camber increase for the freestyle test snowboard, producing different correlations to those contained in Table 10. The revised subjective-objective parameter correlations are displayed in Table 18.

Table 18: Revised subjective-objective parameter correlations

<table>
<thead>
<tr>
<th></th>
<th>Camber</th>
<th>Shovel bending stiffness (avg)</th>
<th>Body bending stiffness (avg)</th>
<th>Heel bending stiffness (avg)</th>
<th>Body torsional stiffness (avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>-0.50</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>0.50</td>
<td>0.50</td>
<td>1.00</td>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>Accuracy</td>
<td>-0.50</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Edge grip</td>
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<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Feedback</td>
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<td>1.00</td>
<td>0.50</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>-0.50</td>
<td>-0.50</td>
<td>-1.00</td>
<td>-0.50</td>
<td>-1.00</td>
</tr>
<tr>
<td>Speed</td>
<td>-0.50</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>1.00</td>
<td>1.00</td>
<td>0.50</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>-0.50</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Stability, accuracy and edge grip are still linked, however display a medium negative correlation with camber. This result is more logical than the previous medium positive association, implying that increased camber decreases the smoothness of the pressure distribution on the snow, thus decreasing stability, accuracy and grip. The manoeuvrability-camber association decreases in strength, but still implies that increased camber assists in turn generation.

Feedback and liveliness retain their positive associations with camber (increase in strength), whilst forgiveness retains its negative association (decreases in strength). However the same reasoning is still applicable for these relationships. Conversely, the speed and transition smoothness associations change from medium positive to medium negative using the revised camber data. The new relationship between camber and speed is logical, using the previous reasoning of decreased pressure distribution smoothness and hence speed of the snowboard base over the snow. The revised transition smoothness-camber association however is more difficult to rationalise, but it is postulated that lower camber levels are easier to control when transitioning between turns, thus increasing the transition smoothness.

Overall, given the noted variation in several of the parametric correlations compared to those contained in Table 10, only the associations that retain the same overall relationship (either positive or negative) are taken as indicating a potential relationship.
4. STRUCTURAL MODEL FOR SNOWBOARD PERFORMANCE PREDICTION

4.1 Performance Prediction

To achieve the main objective of developing a new method for the user-centred and feel based design of modern snowboards, a general parametric model is developed. The snowboard model uses any discrete set of objective design parameters together with user characteristics (sex, mass, height and foot size), to predict the on-snow performance of the design through output values of the nine subjective performance parameters. Using this model, new snowboard designs within the major riding styles could be evaluated prior to manufacture, and furthermore prototype boards could be custom produced to satisfy any specific set of performance requirements.

There are several well-established and popular multi-variable modelling approaches which could be utilised as the basis of the snowboard performance prediction model [70], [71]. Linear least squares regression is the most commonly employed method for model building due to its effectiveness, simplicity and applicability to small data sets (such as in the present application) [71]. However it cannot model declining rates as the explanatory variables approach their extreme values. Conversely, non-linear least squares regression permits the use of any closed form function, allowing the implementation of asymptotic relationships not possible in linear regression. This method can also efficiently produce good estimates of unknown variables using small data sets [71]. Weighted regression is an extension of both linear and non-linear least squares regression, where varying importance is placed on different data points due to differences in measurement precision. Finally, LOESS is a modern modelling method which employs point-by-point fitting of polynomials to localised subsets of the entire dataset [72]. It eliminates the requirement of specifying a global function to fit the data (a prerequisite for non-linear regression). However, LOESS requires large datasets with high density sampling to produce accurate models, and furthermore the models are not easily transferrable (due to the lack of a global function) [71]. This modelling approach is hence unsuitable for the present application.

Due to the limited number of datasets accessible (three) for the snowboard performance prediction model, two different performance measures are formulated to improve the predictive capability and statistical basis of the model. The first is a linear regression and
weighted correlation based measure, which utilizes the individual Spearman ranked correlations between 31 objective design parameters and the nine subjective performance parameters determined during the research. The output for each subjective performance parameter is calculated using the following expression:

\[ P_n = \sum_{m=1}^{31} (Z_m \times r_{m,n}) \quad (9) \]

Where \( P_n \) is the \( n \)th parameter performance rating (\( n = 1, 2, ..., 9 \)), \( Z_m \) is a relative scaling factor that normalizes each objective design parameter, and \( r_{m,n} \) is the relevant correlation coefficient (refer to Equation 8). The relative scaling factor for each objective parameter is calculated using a similar expression to the versatility value:

\[ Z_m = \left( \frac{l_{FR} + l_{FS}}{2} \right) \times \frac{D_m^{input}}{D_m^{max}} \quad (10) \]

Where \( l_{FR} \) is the freeride QFD importance weight, \( l_{FS} \) the freestyle QFD importance weight, \( D_m^{input} \) is the input design value for the relevant objective parameter and \( D_m^{max} \) the maximum objective parameter value from the test snowboard data. It is noted that stiffness and camber values of \( D_m^{max} \) (and resulting Spearman ranked correlations) are taken from the -17°C objective data set, to ensure the performance prediction is centred on parameters sampled at on-snow temperatures.

The summated product of the relative scaling factor and correlation coefficient is also normalized against the existing test snowboard objective and subjective data to ensure performance ratings fit a scale between 1 and 10. Figures 32(a) – (i) display the linear normalising scale plots for each subjective parameter. In all plots, the \( x \) axis is the summated product of relative scaling factors and correlation coefficients (as per Equation 9), whilst the \( y \) axis displays the performance parameter output.
Figures 32(a) - (i): Linear performance modelling scale plots
The $R^2$ values (coefficient of determination) shown in the plots provide a direct indication of the success of the linear correlation performance prediction model. The average coefficient is 0.84, implying that the average predictive capability of the linear model is 84%. Thus an average of 16% of performance variation in the test snowboards cannot be explained by the model. This level of accuracy is acceptable according to the approximate target range of 0.7 – 0.8 provided by NASA [73]. It is also noted that four out of nine subjective performance parameters have coefficients over 0.9, with only two lower than 0.7. The feedback and liveliness parameters which possess the lowest $R^2$ values also displayed relatively high levels of subjectivity throughout the qualitative analyses, providing one possible explanation for the low coefficients.

Given that correlation does not necessarily imply causation in any relationship, a second causative performance prediction measure is formulated using the subjective and objective data collected. Based on Buckingham’s Pi theorem for the formation of dimensionless groups [74], it utilises three key objective design attributes to provide a simple estimate of each subjective performance parameter, in an expression of the form:

$$P_n = (XD_1^a D_{II}^b D_{III}^c)_n$$

(11)

Where $P_n$ is the $n^{th}$ parameter performance rating ($n = 1, 2, ..., 9$), $D_1, D_{II}$ and $D_{III}$ are the key objective design parameters, the superscripts $a$, $b$ and $c$ are exponents whilst $X$ is a constant. The indices $a$, $b$, $c$ and constant $X$ are determined for each subjective performance parameter using non-linear regression of the subjective and objective data collected, by iteratively maximising the coefficient of determination. GraphPad Prism Version 5 [75] is employed to conduct the curve fitting. The three key objective design parameters for each subjective performance parameter are selected on the combined basis of all surveys and interviews conducted, QFD charts, and Spearman ranked correlations.

**Stability**

For on-snow stability, the three key objective attributes chosen based on the prior research are the contact length, average width and average stiffness. The projected length defines the overall length of any snowboard, crucial to the overall stability (straight line or turning). An average of the shovel, heel and waist widths is utilised as the second objective parameter, representing the resistance to roll about the longitudinal axis (along the chord) or stability during turns. The third key objective parameter selected is an average of the
body bending and torsional stiffness parameters, to incorporate both aspects of snowboard stiffness into the model. All of these parameters are pinpointed using the QFD charts as being crucial to on-snow stability. Using non-linear regression curve fitting, a stability measure is formulated:

$$St = 0.04 \times L_p^4 \cdot \bar{W}^{0.7} \cdot \bar{S}^1, R^2 = 0.97$$

(12)

Where $St$ is the stability, $L_p$ is the projected length (m), $\bar{W}$ is the average width (m) and $\bar{S}$ is the average stiffness (N.m$^2$). The calculated coefficient of determination for this parameter is 0.97. Thus, the measure provides an accurate comparative estimate of the on-snow stability of any snowboard based on the subjective and objective data collected. It is noted that the exponent for the average width parameter is positive, which contradicts the negative Spearman ranked correlation between the various width parameters and stability attained previously. However, given the strong dependence of stability on contact length, the different lengths of the snowboards tested are the primary driver of their perceived stability. Thus the effect of the different widths is overridden in the subjective performance ratings, causing the negative correlations.

**Manoeuvrability**

Unlike the stability, which deals with resistance to roll (driven by the contact length and key widths), the manoeuvrability of a snowboard is the response to rider input in any coordinate direction, either translational or rotational. It is hence inversely dependent on the overall mass, which is pinpointed using the QFD as highly important. The relationship is also confirmed by the medium negative correlation between the subjective manoeuvrability ratings and objective test snowboard data. An average of the bending and torsional stiffness, and the self-weighted camber are selected as the second and third parameters, based upon the QFD results, strong positive Spearman ranked correlations (see Section 3.2) and overall importance to the feel and performance of snowboards across the major riding styles. The manoeuvrability measure is formulated as follows:

$$Mn = 2.05 \times M^{-0.2} \cdot C^{0.2} \cdot \bar{S}^{0.2}, R^2 = 0.99$$

(13)

Where $Mn$ is the manoeuvrability, $M$ is the mass of the snowboard (kg), $\bar{S}$ is the average stiffness (N.m$^2$) and $C$ is the self-weighted bottom camber (mm). The coefficient of determination for this parameter is 0.99, again based on the subjective and objective data
collected in this research. From the derived performance measure, it appears that snowboard manoeuvrability is equally driven by these three key objective parameters. However, it is noted that whilst manoeuvrability has an inverse dependency on mass, it has an equal and opposite direct dependency on both camber and average stiffness.

**Accuracy**

The accuracy of a snowboard is defined as the precision of movement in response to rider input. It was determined to be strongly linked to the stability and edge grip from the online surveys and interviews, which is reflected in the results of the QFD and Spearman ranked correlations. As a consequence, the contact length, average width and average stiffness objective design parameters are selected to form the accuracy measure, defined as follows:

\[
Ac = 0.097 \times L_{co}^{2.5} \cdot \bar{W}^{-1} \cdot \bar{S}^{0.5}, \ R^2 = 0.99 \tag{14}
\]

Where \( Ac \) is the accuracy, \( L_{co} \) is the contact length, whilst \( \bar{W} \) and \( \bar{S} \) are as defined previously. The contact length is selected instead of the projected length for this performance measure as it represents the length of the effective edge. Compared to the stability measure, it is noted that the width has a negative influence on accuracy (as per the determined correlations), which contrasts with the positive effect of width on stability. The length and average stiffness also have a smaller direct effect on accuracy than stability.

**Edge Grip**

For the edge grip measure, the contact length (length of effective edge), average width and average stiffness are selected based on the previous reasoning, resulting in the following parametric performance expression:

\[
Gr = 2.085 \times 10^{-3} \cdot L_{co}^{1.5} \cdot \bar{W}^{-2} \cdot \bar{S}, \ R^2 = 0.99 \tag{15}
\]

Where \( Gr \) is the edge grip, whilst \( L_{co} \), \( \bar{W} \) and \( \bar{S} \) are as defined previously. The edge grip measure shows a higher dependence on average stiffness and width, and a lower dependence on contact length compared to the accuracy measure. The width relationship also concurs with a basic snowboard dynamic force balance, where the edge force increases as the width decreases for a given turning force imparted by the foot of the rider.
Speed

The speed of a snowboard depends strongly on the friction qualities of the base material, overall contact length and stiffness, which is reflected in the results of the QFD and Spearman ranked correlations. For consistency, an average of bending and torsional stiffness is again utilised as the stiffness parameter of interest, despite bending stiffness possessing a stronger QFD relationship with snowboard speed than torsional stiffness. The following speed measure is thus derived using non-linear regression:

\[
S_p = 5.93 \times 10^2 \cdot L_{co}^{0.3} \cdot \tilde{\xi}^{1.5} \cdot \bar{S}^{0.2} \cdot R^2 = 0.99
\]

Where \(S_p\) is the speed, \(L_{co}\) and \(\bar{S}\) are as defined previously, and \(\tilde{\xi}\) is the ratio of the wax absorption capabilities to the density of the base (base material parameter). The speed measure implies that the base material parameter is of paramount importance to the running speed of any snowboard, followed by the contact length and the average stiffness. Furthermore, it is noted that all objective parameters have a direct positive influence on the overall speed of a snowboard.

Feedback

The feedback parameter, whilst possessing the highest levels of subjectivity of all the performance parameters, is linked to the stiffness, camber and length of any snowboard. The length and stiffness parameters are pinpointed as all being strongly connected to rider feedback using the QFD (with medium ranked correlations), whilst the camber displays a direct correlation to feedback (and medium QFD importance). Hence, the feedback measure is formulated as follows:

\[
F_b = 4.97 \times L_p^{-2.5} \cdot C^{0.2} \cdot \bar{S}^{0.1} \cdot R^2 = 0.96
\]

Where \(F_b\) is the feedback, \(L_p\) is the projected length, whilst \(C\) and \(\bar{S}\) are as defined previously. The projected length is selected instead of the contact length for this measure as the heel and shovel sections have a significant contribution to the vibrational response of any snowboard. It is noted that the coefficient of determination is lower than the previous performance measures, which is postulated to be the result of the inherent subjectivity in the feedback parameter. The feedback measure possesses a strong inverse dependency on contact length, implying that shorter snowboards exhibit greater levels of...
rider feedback. Conversely, the measure displays smaller direct dependencies on camber and average stiffness.

**Forgiveness**

From the results of the QFD and Spearman ranked correlations, the forgiveness appears to be linked to the widths of a snowboard, together with the camber and overall stiffness. The average width parameter (utilised previously) and self-weighted camber are selected on the basis of strong QFD correlations and medium to strong statistical correlations, whilst the average stiffness on the basis of medium-strong QFD correlations and strong statistical correlations. The forgiveness measure is hence formulated as follows:

\[
F_g = 1.12 \times 10^3 \cdot \bar{W}^{0.5} \cdot C^{-0.1} \cdot S^{-0.8}, \quad R^2 = 0.99
\]  

(18)

Where \(F_g\) is the forgiveness, whilst \(\bar{W}\), \(C\) and \(S\) are as defined previously. The measure shows that the stiffness is of paramount importance to the overall forgiveness of a snowboard, where a softer board possesses a more forgiving ride. An increase in camber (greater rebound) will also slightly decrease forgiveness, whilst conversely, increasing the average snowboard width will promote forgiveness (greater contact area).

**Board Liveliness**

The liveliness of a snowboard is the perceived assistance provided to the rider for jumps, and is directly connected to the stiffness, camber and overall mass (reflected in the results of the QFD). The following performance measure is hence derived:

\[
L_v = 34.9 \times M^{-0.3} \cdot C^{0.4} \cdot S^{-0.4}, \quad R^2 = 0.97
\]  

(19)

Where \(L_v\) is the board liveliness, whilst \(M\), \(C\) and \(S\) are as defined previously. It is noted that the exponents linking mass and average stiffness to liveliness are of opposing nature to those predicted by the statistical correlations obtained. Firstly, the overall snowboard mass displays a positive correlation to liveliness, which contradicts general logic as a lighter board requires less rider force to perform jumps and tricks. This ranked correlation is caused by the slightly heavier freestyle snowboard possessing the highest liveliness ratings (due primarily to its large camber). As the mass is highly similar for all three test snowboards, this correlation is not reflective of the actual relationship between these parameters.
Secondly, the relationship between bending/torsional stiffness and liveliness is complex, dependent on the ability of the rider to flatten the camber out of the snowboard. This is strongly connected to the strength and mass of the rider, where a lighter rider may perceive a snowboard to be less lively if the stiffness of the body section is comparatively high. Conversely, if the snowboard has insufficient body stiffness relative to the mass of the rider, the board may feel limp and unresponsive. The liveliness exhibits a medium positive Spearman ranked correlation to the average body bending and torsional stiffness. This correlation coefficient is caused by the versatile test board possessing both the lowest overall stiffness and liveliness ratings. However, as the low camber levels of this test board were determined to be the primary cause of the low liveliness ratings, the positive correlation is hence deemed to not be reflective of the actual relationship between these parameters. It is postulated that for a given rider mass, increasing the average stiffness will decrease perceived liveliness. The positive correlation initially obtained would also have been a primary error source in the previous linear performance prediction model.

**Transition Smoothness**

The perceived smoothness of the transition between turns for any snowboard is driven by the width distribution (resistance to roll), camber (transition assistance from the snowboard), and overall body stiffness (flex and degree of independent foot movement). These parameters are pinpointed using the QFD as possessing a strong association with the transition smoothness for any snowboard within the major riding styles. Furthermore, the key widths also possess strong negative ranked correlations with this aspect of snowboard performance, whilst the camber and body bending/torsional stiffness possess medium negative and positive ranked correlation coefficients respectively. The resulting performance measure is hence derived as follows:

\[
Ts = 0.273 \times \bar{W}^{-0.9} \cdot C^{-0.9} \cdot \bar{S}^{0.8}, \quad R^2 = 0.99
\]  

(20)

Where \(Ts\) is the transition smoothness, whilst \(\bar{W}\), \(C\) and \(\bar{S}\) are as defined previously. It is noted that all three key objective parameters have similar indices, implying comparable dependence on each for a smooth transition. Furthermore, the measure reinforces the medium positive and negative ranked correlation coefficients described above. This confirms that lower camber levels, whilst decreasing overall snowboard liveliness, will be easier to control when transitioning between turns, thus increasing the smoothness.
Increasing the stiffness also appears to increase transition smoothness, by reducing independent rider foot movement.

**Scaling for Rider Characteristics**

The linear correlation and causative exponent performance prediction models are based on subjective performance ratings from the ‘average’ rider, possessing a mass of 77 kg, height 177.5 cm and US size 9 feet (see Section 2.1). However, it is noted that different rider characteristics will affect the perceived feel and performance of any snowboard within the major riding styles.

Thus a scaling system is devised to modify any set of objective design parameters to incorporate rider characteristics of sex, mass, height and foot size. The average bending/torsional stiffness, projected length and average width are selected as the objective parameters modified by different user characteristics. These design parameters are crucial to the individual performance measures formulated, and thus strongly affect the feel and performance of any snowboard. Table 19 summarises the effect of each user characteristic on the relevant objective design parameters.

<table>
<thead>
<tr>
<th>Table 19: Scaling for rider characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending/torsional stiffness</strong></td>
</tr>
<tr>
<td><strong>Sex</strong></td>
</tr>
<tr>
<td><strong>Mass</strong></td>
</tr>
<tr>
<td><strong>Height</strong></td>
</tr>
<tr>
<td><strong>Foot size</strong></td>
</tr>
</tbody>
</table>

The sex of the rider affects the required bending and torsional stiffness, due to the strength differential between male and female riders. In other words, the ability of the rider to flex and manoeuvre a snowboard is dependent on their sex. An 8.5% scaling factor is selected, based on average reported variances in strength for male and female skiers [76]. The contact length and average width of a snowboard are not modified by rider sex, due to their dependence on the related user characteristics of mass and height.

The mass of the rider also affects the bending and torsional stiffness levels required to achieve any on-snow feel and performance. Assuming a constant strength/weight ratio for
both male and female riders, stiffness levels are adjusted from the datum levels utilising a linear proportional increase or decrease. This modification ensures for example, that the return spring during manoeuvres is constant relative to rider mass. Conversely, the height or foot size of the rider has no effect on the required stiffness levels, as assuming constant rider mass, the flexural response of the snowboard is unaltered.

However, both rider mass and height affect the required projected length of a snowboard for comparable feel and performance. For example, a larger mass requires a larger projected length to ensure the pressure exerted by the snowboard on the snow does not drastically increase to the point where speed is compromised. Alternatively, as the height of the rider increases, the roll moment generated by the rider’s centre of gravity during turns also increases, diminishing stability. There are numerous manufacturer and user guides available that recommend snowboard lengths for any rider mass, height and desired riding style [77] - [79].

A scaling parameter for contact length incorporating both rider mass and height is formulated, using the exponent from the stability measure as the basis of the relationship:

\[
\bar{L}_p = L_p^{\text{input}} \cdot (HM^{\text{input}} / HM^{\text{datum}})^{1/4}
\]  

(21)

Where \( \bar{L}_p \) is the scaled projected length, \( L_p^{\text{input}} \) is the input projected length, \( HM^{\text{input}} \) is the input product of rider height and mass, whilst \( HM^{\text{datum}} \) is the datum rider height and mass product. Using the datum rider data of 76.9 kg and 177.5 cm, Equation 21 becomes:

\[
\bar{L}_p = L_p^{\text{input}} \cdot (HM^{\text{input}} / 13650)^{1/4}
\]  

(22)

This expression provides an approximate scaled projected length for equivalent feel and performance. The scaled length outputs for different rider masses and heights are also comparable to the recommended snowboard lengths contained in the available board selection charts.

The foot size of the rider will also affect the perceived feel and performance of any snowboard, as a larger foot will change the edging force applied during a turn and consequently the response of the board. To maintain an identical foot size/snowboard width ratio, a proportional adjustment is made to the average width parameter as the rider foot size increases or decreases.
4.2 Stiffness, Mass and Camber Prediction

All nine formulated performance measures require an input value of the average stiffness parameter, which is dependent on the geometry and composite sandwich architecture of the snowboard. Whilst geometric parameters can be specified at the design level, the bending/torsional stiffness profiles and mass of the snowboard must be determined using either an analytical method, finite element model or post manufacture laboratory test.

In order to predict the performance of a snowboard design prior to manufacture without resorting to the creation of time consuming finite element models, a snowboard stiffness code is developed, building on the pre-existing computational model formulated by Brennan [7]. The Brennan model utilises inputs of constituent layer properties and geometry along the chord to generate the bending and torsional stiffness distributions of the snowboard. However, the code requires the input of composite skin layer properties, which are not generally available from manufacturer data sheets, and furthermore are highly dependent on the fibre volume fraction achieved during manufacture.

Hence the model created by Brennan is extended in this research to consider the calculation of composite skin layer properties for various fabric configurations. The effect of temperature on snowboard stiffness and camber properties, as well as the calculation of total mass are also implemented into the computational model.

Fabric Configurations

Eleven different fabric composite configurations are modelled for the prediction code, based on the approach derived by Byun for braided tri-axial fabrics [55]. They are categorised as either unidirectional, stitched, braided or woven, and are listed in Table 20. All configurations consist of fibre bundles (tows) in a matrix. The different tow architectures for each type of fabric are pictorially displayed in Figures 33(a) - (k). It is noted that the bi-axial weave fabric configurations are identical to their braided counterparts when the braid angle is 45°.
Figure 33(a): Unidirectional

Figure 33(b): 1x1 bi-axial braid

Figure 33(c): 2x2 bi-axial braid

Figure 33(d): 1x1-A tri-axial braid

Figure 33(e): 1x1-E tri-axial braid

Figure 33(f): 2x2 tri-axial braid

Figure 33(g): 1x1 bi-axial weave

Figure 33(h): 2x2 bi-axial weave

Figure 33(i): Tri-axial weave

Figure 33(j): Bi-axial stitched

Figure 33(k): Tri-axial stitched
Table 20: Fabric configurations

<table>
<thead>
<tr>
<th>Unidirectional</th>
<th>Braided</th>
<th>Woven</th>
<th>Stitched</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Any unidirectional</td>
<td>• 1x1 bi-axial</td>
<td>• 1x1 bi-axial</td>
<td>• Bi-axial</td>
</tr>
<tr>
<td>configuration</td>
<td>• 2x2 bi-axial</td>
<td>• 2x2 bi-axial</td>
<td>• Tri-axial</td>
</tr>
<tr>
<td>• 1x1-A tri-axial</td>
<td>• Tri-axial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 1x1-E tri-axial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 2x2 tri-axial</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The geometric characteristics of each configuration are calculated using a simple unit-cell approach [55]. A repeating unit for the fabric is determined, characterised by the tow orientation angle ($\theta$), and spacing between the fill, warp and axial tows ($s^F, s^W$ and $s^A$ respectively), if present. The unit cell for the 1x1 bi-axial braid is shown in Figure 34, enclosed by the black dotted lines. Contained within the unit cell are fill and warp tows (shown by the blue lines), which are defined by the number of fibres in each bundle ($B^F$ and $B^W$ respectively), the diameters of the fibres utilised ($d^F$ and $d^W$ respectively), and their packing factor ($\kappa$) (ratio of the fibre occupied volume to total bundle volume; which is assumed to be constant).

The resulting cross-sectional areas of the fill and warp tows ($A^F$ and $A^W$ respectively) are calculated using the following expressions:

$$A^F = \frac{\pi B^F (d^F)^2}{4\kappa}$$ (23)

$$A^W = \frac{\pi B^W (d^W)^2}{4\kappa}$$ (24)

Alternatively, the fill and warp tow cross-sectional areas can be determined using fibre densities and tow yields (mass per unit length of each tow):

$$A^F = \frac{Y^F}{\rho^F \kappa}$$ (25)

$$A^W = \frac{Y^W}{\rho^W \kappa}$$ (26)

Where $\rho^F$ and $\rho^W$ are the densities of fibres comprising the fill and warp tows, respectively, whilst $Y^F$ and $Y^W$ are the relevant tow yields. For the fabric configurations
containing axial fibres, equivalent expressions for the cross-sectional area of the axial tows \( (A^A) \) are also incorporated into the computational model.

The height \( (h) \) and width \( (w) \) of each unit cell are dependent on the fabric configuration, where for a 1x1 bi-axial braid the dimensions are calculated using the following basic geometry:

\[
h = \frac{2s^F}{\sin2\theta} \tag{27}
\]

\[
w = \frac{2s^W}{\sin2\theta} \tag{28}
\]

Equivalent expressions for the remaining fabric configurations are determined from the respective unit cells in a similar manner (see Appendix E).

For all braided and woven fabric configurations, the fill and warp tows possess significant undulation or crimp. This causes variation in the mechanical properties of the tows, particularly the longitudinal modulus of elasticity. Conversely, the axial tows only possess low levels of crimp resulting from the manufacturing process (except for the tri-axial weave configuration), and are thus assumed to run straight between the fill and warp tows. For the stitched composites, the stitching creates a slight compression in each tow which must also be given consideration.
The extent of variation in the mechanical properties of the composite due to tow undulation is dependent on the maximum undulation or crimp angle for both the fill ($\phi^F$) and warp ($\phi^W$) tows (plus axial tows in the case of the tri-axial weave configuration). This angle is defined as the maximum undulation of the specified tow within the fabric. To determine the magnitude of these angles, the different cross-sections of each fabric are considered, where the warp tows cross-section of the 1x1 bi-axial braid configuration is shown in Figure 35. It is noted that the fill tows cross-section is identical to that displayed in the schematic, except the fill and warp tow superscripts are reversed.

Figure 35: 1x1 bi-axial braid cross-section

Figure 35 illustrates a fill tow undulating between warp tows, with the crimp angle ($\phi^F$) identified. Also shown in the figure are the respective thicknesses of the fill and warp tows ($t^F$ and $t^W$ respectively), the fill tow undulation half-length and span ($L^F_u$ and $L^F_s$ respectively), the radius of curvature of the fill tow ($r^F$), and the distance from the centreline of the fabric to the midline of the undulating fill tow ($u^F$). It is noted that the cross-sectional shape of the tows is lenticular, which has been well established in previous
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As a result, the exact thickness of the respective tows cannot be determined prior to manufacture by analytical means, and thus (if immeasurable) is approximated for the fill tow using the following empirical expression:

\[ t^F = t \sqrt{A^F / (\sqrt{A^F} + \sqrt{A^W})} \]  

(29)

Where \( t \) is the total thickness of the fabric composite, whilst \( A^F \) and \( A^W \) are as defined previously. The expression is based on an assumption that the cross-section of a lenticular tow is sufficiently close to a circle, and thus its thickness is comparable to the circle’s diameter. The thickness of the warp tows is calculated in a similar manner:

\[ t^W = t \sqrt{A^W / (\sqrt{A^F} + \sqrt{A^W})} \]  

(30)

If axial tows are also present in the configuration, expressions for the axial, fill and warp tow thicknesses are as follows:

\[ t^A = t \sqrt{A^A / (\sqrt{A^A} + \sqrt{A^F} + \sqrt{A^W})} \]  

(31)

\[ t^F = t \sqrt{A^F / (\sqrt{A^A} + \sqrt{A^F} + \sqrt{A^W})} \]  

(32)

\[ t^W = t \sqrt{A^W / (\sqrt{A^A} + \sqrt{A^F} + \sqrt{A^W})} \]  

(33)

Where \( t^A \) is the thickness of the axial tows, and all remaining parameters are as defined previously. Expressions for the undulation span and centreline to midline distance can be determined using the unit-cell and cross-sectional geometry. For the 1x1 bi-axial braid configuration shown in Figure 35:

\[ L^F_s = \frac{w}{2} = \frac{s^W}{\sin 2\theta} \]  

(34)

\[ L^W_s = \frac{h}{2} = \frac{s^F}{\sin 2\theta} \]  

(35)

\[ u^F = \frac{t^W}{2} \]  

(36)

\[ u^W = \frac{t^F}{2} \]  

(37)

Where \( L^W_s \) and \( u^W \) are the warp tows undulation span and amplitude, respectively, whilst all other parameters are as defined previously. Equivalent expressions for the remaining
fabric configurations are listed in Appendix E, together with schematics for each cross-section if tow undulation is present. Equations for the remaining parameters illustrated in Figure 35 (and equivalent warp tow properties) are identical for all configurations, and are given by the following geometric expressions:

\[ r^F = \frac{(\frac{L_F}{2})^2 + (u_F)^2}{2u_F} \]  \hspace{1cm} (38)

\[ r^W = \frac{(\frac{L_W}{2})^2 + (u_W)^2}{2u_W} \]  \hspace{1cm} (39)

\[ \phi^F = \sin^{-1}\left(\frac{L_F}{2r_F}\right) \]  \hspace{1cm} (40)

\[ \phi^W = \sin^{-1}\left(\frac{L_W}{2r_W}\right) \]  \hspace{1cm} (41)

\[ L_u^F = 2r^F \phi^F \]  \hspace{1cm} (42)

\[ L_u^W = 2r^W \phi^W \]  \hspace{1cm} (43)

Where \( r^W \) and \( \phi^W \) are the warp tows radius of curvature and undulation angle, respectively, whilst all remaining parameters are as per previous. To determine the proportions of fill, warp and axial tows (if present) together with the total fibre volume fraction, the respective volumes of fibres within the unit cell are calculated. For the 1x1 bi-axial braid configuration:

\[ V^F = 4L_u^F A^F \]  \hspace{1cm} (44)

\[ V^W = 4L_u^W A^W \]  \hspace{1cm} (45)

Where \( V^F \) and \( V^W \) are the volumes of fill and warp tows within the unit cell, respectively, whilst \( L_u^F, L_u^W, A^F \) and \( A^W \) are as defined previously. Again, equivalent expressions for the remaining fabric configurations are listed in Appendix E. Thus, the proportion of fill and warp tows (\( c^F \) and \( c^W \) respectively), and the total fibre volume fraction (\( f \)) for all bi-axial configurations are:

\[ c^F = \frac{V^F}{V^F + V^W} \]  \hspace{1cm} (46)
For all tri-axial configurations:

\[ c^A = \frac{V^A}{V^A + V^F + V^W} \]  

\[ c^F = \frac{V^F}{V^A + V^F + V^W} \]  

\[ c^W = \frac{V^W}{V^A + V^F + V^W} \]  

\[ f = \frac{\kappa(V^F + V^W)}{hwt} \]  

Where \( V^A \) and \( c^A \) are the volume and volume fraction respectively of axial tows within the unit cell, and all remaining parameters in Equations 46 – 52 are as previously defined. Finally, the areal (dry) weight in g/m\(^2\) of the fabric can be determined using the following expressions:

For bi-axial fabrics:

\[ Wt = \frac{\kappa(V^F \rho^F + V^W \rho^W)}{hw} \]  

Whilst for tri-axial fabrics:

\[ Wt = \frac{\kappa(V^A \rho^A + V^F \rho^F + V^W \rho^W)}{hw} \]  

Where \( Wt \) is the areal weight, \( \rho^A \) is the density of fibres comprising the axial tows, and all remaining parameters are as defined previously.

Composite Layer Thermo-Mechanical Properties

To calculate the mechanical and thermal properties of the resulting composite layer, each fabric configuration is idealised as the sum of multiple unidirectional composite layers of varying orientation and constant fibre volume fraction [56]. Any tow undulation is accounted for via a reduction of the in-plane properties of the composite. This simple
method is selected as an alternative to a more complex 3-D analysis of thermo-mechanical properties, such as the models described by Tan et al. [80] or Vandeurzen et al. [81], [82]. Although some accuracy is sacrificed using the described method, considering the difficulty of consistent composite manufacturing to strict tolerances (due to skewed tows, varying fibre volume fraction, matrix voids etc.), variances in resulting composite properties are often of greater magnitude than any accuracy loss [56].

Hashin’s cylinder model is utilised to calculate the thermo-mechanical properties of each unidirectional composite layer from the properties of the constituent fibre and matrix phases [83]. In the following equations (Equations 55 – 69), \( E \) is the elastic modulus, \( G \) is the shear modulus, \( k \) is the transverse bulk modulus, \( \nu \) is the Poisson’s ratio and \( f \) is the fibre volume fraction described in the previous section. The superscripts \( f \) and \( m \) refer to fibre and matrix properties respectively, whilst the subscripts \( L \), \( T \) and \( R \) refer to longitudinal, transverse and radial directions respectively.

The longitudinal modulus (parallel to the fibres) of the composite can be expressed by:

\[
E_L = fE_L^f + (1 - f)E_L^m + \frac{4f(1-f)(\nu_L^f - \nu_L^m)^2}{k^m f^m f^{1-f} \frac{1}{G_{TR}}} \tag{55}
\]

The longitudinal-transverse Poisson’s ratio (\( \nu_{LT} \)) can be evaluated using a similar expression:

\[
\nu_{LT} = f\nu_L^f + (1 - f)\nu_L^m + \frac{f(1-f)(\nu_L^f - \nu_L^m)(\frac{1}{k^m} - \frac{1}{k^f})}{k^m f^{1-f} + \frac{1}{G_{TR}}} \tag{56}
\]

Conversely, the longitudinal-transverse shear modulus (\( G_{LT} \)) is determined using the following equation:

\[
G_{LT} = G_{LT}^m + \frac{f}{G_{LT}^m - \frac{G_{LT}^m}{G_{LT}} \frac{1}{G_{LT}}} \tag{57}
\]

For the transverse-radial shear modulus (\( G_{TR} \)), Hashin’s cylinder model prescribes expressions for upper and lower bounds, which are denoted in Equations 58 – 65 by the + and – superscripts.

If \( G_{TR}^f > G_{TR}^m \),
\[ G_{TR}^- = G_{TR}^m + \frac{f}{c_{TR}^m - c_{TR}^m (1-f)(k^m + 2c_{TR}^m)} \]  
\[ G_{TR}^+ = G_{TR}^m (1 + \frac{f(1+\beta^m)}{\eta - f(1+3(1-f)\beta^m)} \]  
(58)  
(59)

Where:

\[ \eta = \frac{\frac{c_{TR}^m + \beta^m}{c_{TR}^m}}{\frac{c_{TR}^m}{c_{TR}^m} - 1} \]  
\[ \gamma = \frac{\beta m - \frac{c_{TR}^m \beta f}{1 + \frac{c_{TR}^m \beta f}{c_{TR}^m}}} \]  
\[ \beta^m = \frac{k^m}{k^m + 2c_{TR}^m} \]  
\[ G_{TR}^m = G_{TR}^m (1 + \frac{f(1+\beta^m)}{\eta - f(1+3(1-f)\beta^m)} \]  
\[ G_{TR}^+ = G_{TR}^m + \frac{f}{c_{TR}^m - c_{TR}^m (1-f)(k^m + 2c_{TR}^m)} \]  
\[ \]  
\[ (58) \]  
\[ (59) \]  

If \( G_{TR}^- > G_{TR}^f \),

\[ G_{TR}^- = G_{TR}^m (1 + \frac{f(1+\beta^m)}{\eta - f(1+3(1-f)\beta^m)} \]  
\[ G_{TR}^+ = G_{TR}^m + \frac{f}{c_{TR}^m - c_{TR}^m (1-f)(k^m + 2c_{TR}^m)} \]  
(64)  
(65)

The transverse elastic modulus \( (E_T) \) and transverse-radial Poisson’s ratio \( (\nu_{TR}) \) of the composite are also given upper and lower bounds (denoted by the superscript ±, or conversely ∓), determined using:

\[ E_T^\pm = \frac{4kG_{TR}^\pm}{k + mG_{TR}^\pm} \]  
\[ \nu_{TR}^\pm = \frac{k - mG_{TR}^\pm}{k + mG_{TR}^\pm} \]  
(66)  
(67)
where:

\[ k = k^m + \frac{f}{k^f - k^m^f} \left( \frac{1 - f}{k^m + G_{PR}} \right) \]  \hspace{1cm} (68)

\[ m = 1 + \frac{4k_v L T^2}{E_L} \]  \hspace{1cm} (69)

the longitudinal and transverse thermal expansion coefficients of each unidirectional composite layer (\( \alpha_L \) and \( \alpha_T \) respectively) are also determined using expressions (in tensor notation) from Hashin’s model [83]:

\[ \alpha_{ij} = f \alpha^f_{ij} + (1 - f) \alpha^m_{ij} + (\alpha^f_{kl} - \alpha^m_{kl}) K_{klrs} (S_{rsij} - (f S^f_{rsij} + (1 - f) S^m_{rsij})) \]  \hspace{1cm} (70)

\[ K_{klrs} (S^f_{rsij} - S^m_{rsij}) = l_{kl} \]  \hspace{1cm} (71)

where \( S_{rsij} \) are the composite elastic compliances, \( l_{kl} \) is the 4th order symmetric unit tensor, \( K_{klrs} \) is a Hashin 4th order tensor solved using equation 71, \( \alpha_{ij} \) are the composite thermal expansion coefficients, \( \alpha^f_{ij} \) and \( \alpha^m_{ij} \) (or \( \alpha^f_{kl} \) and \( \alpha^m_{kl} \)) are the phase thermal expansion coefficients, and \( i,j,k,l,r,s = 1,2,3 \). For the case of a transversely isotropic composite comprised of transversely isotropic phases, these expressions can be simplified as follows [84]:

\[ \alpha_L = f \alpha^f_1 + (1 - f) \alpha^m_1 + (\alpha^f_i - \alpha^m_i) K_{ij} (S_{ij} - (f S^f_{ij} + (1 - f) S^m_{ij})) \]  \hspace{1cm} (72)

\[ \alpha_T = f \alpha^f_2 + (1 - f) \alpha^m_2 + (\alpha^f_i - \alpha^m_i) K_{ij} (S_{ij} - (f S^f_{ij} + (1 - f) S^m_{ij})) \]  \hspace{1cm} (73)

\[ K_{ij} (S^f_{jk} - S^m_{jk}) = l_{ik} \]  \hspace{1cm} (74)

where \( i,j,k = 1,2,3,4,5,6 \). The non-zero elements of the symmetric composite layer compliance matrix \( (S_{ij}) \), and phase thermal expansion coefficients \( (\alpha^f_i \) and \( \alpha^m_i ) \) are as follows [49]:

\[ S_{11} = \frac{1}{E_L} \]  \hspace{1cm} (75)

\[ S_{22} = S_{33} = \frac{1}{E_T} \]  \hspace{1cm} (76)
\[ S_{12} = S_{13} = -\frac{v_{LT}}{E_L} \]  
(77)

\[ S_{23} = -\frac{v_{TR}}{E_T} \]  
(78)

\[ S_{44} = \frac{1}{G_{TR}} \]  
(79)

\[ S_{55} = S_{66} = \frac{1}{G_{LT}} \]  
(80)

\[ \alpha_f^1 = \alpha_L^f \]  
(81)

\[ \alpha_f^2 = \alpha_T^f \]  
(82)

\[ \alpha_m^1 = \alpha_L^m \]  
(83)

\[ \alpha_m^2 = \alpha_T^m \]  
(84)

Where all parameters contained in Equations 75 – 84 are as defined previously, with the lower bound of \( E_T \) and \( G_{TR} \), together with the upper bound of \( v_{TR} \) (calculated in Equations 64, 66 and 67) utilised to determine the relevant compliances. Equivalent expressions for the phase elastic compliances \( S_{jk}^f \) and \( S_{jk}^m \) are obtained by substituting \( E_L, E_T, G_{LT}, G_{TR}, v_{LT} \) and \( v_{TR} \) by the corresponding fibre and matrix phase properties.

To account for out-of-plane tow undulation (if present) in the final fabric composite, the in-plane properties of the axial, fill and warp tow composite layers are reduced accordingly. This reduction is based on standard expressions for an in-plane transformation of unidirectional composite layer properties. The undulation angles determined in Equations 40 and 41 (or listed in Appendix E) are used as the magnitude of the rotation in the following reduction equations [85]:

\[ E_L^\phi = \frac{1}{\cos^4\phi \left( \frac{1}{E_L} + \frac{1}{G_{LT}} \frac{2v_{LT}}{E_T} \cos^2\phi \sin^2\phi + \frac{1}{E_T} \sin^4\phi \right)} \]  
(85)

\[ G_{LT}^\phi = \frac{1}{2 \left( \frac{1}{E_L} + \frac{2v_{LT}}{E_T} + \frac{1}{G_{LT}} \right) \cos^2\phi \sin^2\phi + \frac{1}{G_{LT}} \left( \cos^4\phi + \sin^4\phi \right)} \]  
(86)

\[ v_{LT}^\phi = E_L \left( \frac{v_{LT}}{E_L} \left( \cos^4\phi + \sin^4\phi \right) - \left( \frac{1}{E_L} + \frac{1}{E_T} - \frac{1}{G_{LT}} \right) \cos^2\phi \sin^2\phi \right) \]  
(87)
Equations (85) – (88) are the established expressions for off-axis ply moduli, Poisson’s ratio and thermal expansion coefficient, where the superscript $\phi$ denotes a property reduced due to tow undulation, and all other parameters are as defined previously. It is noted that only longitudinal composite properties are modified, as the in-plane layer transverse properties are unaffected by an out-of-plane tow rotation.

As stated previously, each fabric configuration is idealised as the sum of multiple unidirectional composite layers of varying orientation and constant fibre volume fraction. These layers are characterised by the standard 2-D plane-stress stiffness and thermal expansion matrices, formulated using reduced unidirectional composite properties (due to tow undulation) as follows [49]:

$$
\begin{align*}
\left[ Q^\phi \right] & = \begin{bmatrix}
\frac{1}{E_L^\phi} & -\frac{v_{LT}^\phi}{E_L^\phi} & 0 \\
-\frac{v_{LT}^\phi}{E_L^\phi} & \frac{1}{E_T^\phi} & 0 \\
0 & 0 & \frac{1}{\alpha_{LT}^\phi}
\end{bmatrix}^{-1} \\
\left[ \alpha^\phi \right] & = \begin{bmatrix}
\alpha_L^\phi \\
\alpha_T^\phi \\
0
\end{bmatrix}
\end{align*}
$$

To transform the thermo-mechanical properties of each composite layer to account for the different fibre orientations present in the fabric (in-plane rotation), the following matrix equations are utilised:

$$
\begin{align*}
\left[ Q^\phi_{\theta} \right] & = \left[ T_{\theta} \right] \left[ Q^\phi \right] \left[ T_{\epsilon} \right]^{-1} \\
\left[ \alpha^\phi_{\theta} \right] & = \left[ T_{\epsilon} \right]^{-1} \left[ \alpha^\phi \right]
\end{align*}
$$

Where $\left[ Q^\phi_{\theta} \right]$ and $\left[ \alpha^\phi_{\theta} \right]$ are the transformed stiffness and thermal expansion matrices, respectively, whilst $\left[ T_{\sigma} \right]$ and $\left[ T_{\epsilon} \right]$ are the stress and strain transformation matrices respectively for an in-plane counter-clockwise rotation [49]:

$$
\alpha_L^* = \alpha_L \cos^2 \phi + \alpha_T \sin^2 \phi
$$
\[
[T_{\sigma}] = \begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & 2\sin \theta \cos \theta \\
\sin^2 \theta & \cos^2 \theta & -2\sin \theta \cos \theta \\
-\sin \theta \cos \theta & \sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta 
\end{bmatrix}
\] (93)

\[
[T_{\epsilon}] = \begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & \sin \theta \cos \theta \\
\sin^2 \theta & \cos^2 \theta & -\sin \theta \cos \theta \\
-2\sin \theta \cos \theta & 2\sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta 
\end{bmatrix}
\] (94)

Where as defined previously, \( \theta \) is the tow orientation angle. To combine the oriented unidirectional layers comprising each fabric composite to obtain its final thermomechanical properties, a common uniform strain assumption is applied. It is noted from Figures 33(a) – (k) that all bi-axial fabric configurations possess fill and warp tows at angles of \( \theta/\theta \) relative to the reference longitudinal axis. Therefore, the following volume average expressions apply to any bi-axial configuration for the calculation of the final fabric composite stiffness matrix \([\bar{Q}]\), thermal expansion matrix \([\bar{\alpha}]\) and overall density \(\bar{\rho}\) [49]:

\[
[\bar{Q}] = c^F [Q_\theta^F] + c^W [Q_\theta^W]
\] (95)

\[
[\bar{\alpha}] = c^F [\alpha_\theta^F] + c^W [\alpha_\theta^W]
\] (96)

\[
\bar{\rho} = f (c^F \rho^F + c^W \rho^W) + (1-f)\rho^m
\] (97)

Where \([Q_\theta^F], [Q_\theta^W], [\alpha_\theta^F]\) and \([\alpha_\theta^W]\) are the oriented fill and warp layer stiffness and thermal expansion matrices, respectively, and as per previous, \(c^F\) and \(c^W\) are the relevant tow volume proportions, \(f\) is the calculated fibre volume fraction of the fabric composite, whilst \(\rho^F\), \(\rho^W\) and \(\rho^m\) are the densities of the fill tow fibres, warp tow fibres and matrix phase, respectively. The corresponding tri-axial fabric composite equations with the addition of axial tow terms are as follows:

\[
[\bar{Q}] = c^A [Q^A] + c^F [Q^F_\theta] + c^W [Q^W_\theta]
\] (98)

\[
[\bar{\alpha}] = c^A [\alpha^A] + c^F [\alpha^F_\theta] + c^W [\alpha^W_\theta]
\] (99)

\[
\bar{\rho} = f (c^A \rho^A + c^F \rho^F + c^W \rho^W) + (1-f)\rho^m
\] (100)

Where all parameters in Equations 98 – 100 are as defined previously. It is noted that the axial tow layer stiffness and thermal expansion matrices are untransformed, as the axial
tows are defined to lie parallel to the longitudinal reference axis. If during layup of the fabric composite on the base layer, the longitudinal reference axis is not aligned with the snowboard chord, the fabric composite layer properties are modified using the standard transformation equations [49]:

$$[\tilde{Q}_\lambda] = [T_\sigma][\tilde{Q}][T_\varepsilon]^{-1}$$  \hspace{1cm} (101)

$$[\tilde{\alpha}_\lambda] = [T_\varepsilon]^{-1}[\tilde{\alpha}]$$  \hspace{1cm} (102)

Where the stress and strain transformation matrices are evaluated using the utilised layup angle ($\lambda$), resulting in the final transformed stiffness ($[\tilde{Q}_\lambda]$) and thermal expansion matrices ($[\tilde{\alpha}_\lambda]$).

If the relevant layers comprising the final fabric composite are stitched together instead of woven or braided, the composite possesses areas where tows are distorted. A slightly different reduction system is applied to determine the effect of tow distortion on resulting thermo-mechanical properties, dependent on the volume fraction of distorted fibres ($f^\varphi$), and the average misalignment angle of the distorted fibres ($\varphi$). The volume fraction of distorted fibres is determined using the following expression [86]:

$$f^\varphi = \frac{2V^\varphi n^\varphi}{t}$$  \hspace{1cm} (103)

Where $V^\varphi$ is the volume of fibres distorted on each surface of the composite (usually 0.5 – 2.0 mm$^3$), $n^\varphi$ is the areal density of the stitches (usually 0.05 - 0.12 stitches/mm$^2$), and $t$ is the fabric composite thickness. Property reductions for the distorted region are calculated in the same manner as the undulation effects considered in Equations 85 – 88, using the average distortion angle in place of the undulation angle. The stitched unidirectional composite layer stiffness and thermal expansion matrices ($[Q']$ and $[\alpha']$ respectively) are then determined using a volume average of the distorted and undistorted regions:

$$[Q'] = f^\varphi [Q^\varphi] + (1 - f^\varphi)[Q]$$  \hspace{1cm} (104)

$$[\alpha'] = f^\varphi [\alpha^\varphi] + (1 - f^\varphi)[\alpha]$$  \hspace{1cm} (105)

Where $[Q]$ and $[\alpha]$ are the standard 2-D plane-stress stiffness and thermal expansion matrices of the unidirectional composite layer (as per Equations 89 and 90 utilising unaltered properties), $[Q^\varphi]$ and $[\alpha^\varphi]$ are the layer stiffness and thermal expansion matrices
formulated using reduced composite properties (due to tow distortion), whilst $f^\varphi$ is the volume fraction of distorted fibres defined above. The final stiffness and thermal expansion matrices of the stitched fabric composite are calculated using Equations 91 – 102, with the stitched composite volume average property matrices ($[Q']$ and $[\alpha']$) used in place of the tow undulation reduced property matrices ($[Q^\varphi]$ and $[\alpha^\varphi]$). The effect of the stitching on the overall density of the fabric composite layer is neglected, thus Equations 97 and 100 also apply to stitched bi-axial and tri-axial fabric configurations.

**Snowboard Stiffness Properties**

The final snowboard structure comprises one or more of the previously described fabric composite layers either side of a core, enclosed by a topsheet and base layer (see Chapter 1). A sidewall is usually added to the sides of the core (for impact protection), whilst steel edges are attached to the lower corners. A basic schematic of the cross-sectional structure (half-width displayed) is shown in Figure 36. It is noted that whilst several sidewall angle configurations are utilised in modern snowboards (such as 45°, 90° and 45°/90°), for the purposes of the computational model, the sidewall is assumed to be 90° only. This ensures that the width of the snowboard is constant for each cross-section considered.

![Figure 36: General snowboard cross-sectional structure](image)

To calculate the bending and torsional stiffness along the snowboard chord, the classic laminate thin beam/plate theory is utilised (as per Brennan [7]). The effect of the sidewall
and edges are initially neglected using this approach, and are built into the model at a later stage. Using thin laminate theory, the strain and curvature response of the simplified sandwich composite (of \( n_l \) layers) to forces and moments in the two principal directions \((x, y)\) is calculated using the following matrix expression [49], [85]:

\[
\begin{bmatrix}
[N] \\
[M]
\end{bmatrix} = \begin{bmatrix} [A] & [B] \\
[B] & [D]
\end{bmatrix} \begin{bmatrix} [\varepsilon^0] \\
[\kappa]
\end{bmatrix}
\]  (106)

Where:

\[
[N] = \begin{bmatrix} N_x \\
N_y \\
N_{xy}
\end{bmatrix}
\]  (107)

\[
[M] = \begin{bmatrix} M_x \\
M_y \\
M_{xy}
\end{bmatrix}
\]  (108)

\[
[\varepsilon^0] = \begin{bmatrix} \varepsilon^0_x \\
\varepsilon^0_y \\
\gamma_{xy}
\end{bmatrix}
\]  (109)

\[
[\kappa] = \begin{bmatrix} \kappa_x \\
\kappa_y \\
\kappa_{xy}
\end{bmatrix}
\]  (110)

Matrix equations 107 - 110 define forces, moments, strains and curvatures respectively, in the two principal directions. The \([A]\), \([B]\) and \([D]\) laminate stiffness matrices are calculated using the respective constituent layer stiffness matrices \([Q_i]\) for \( i = 1, 2, 3, \ldots, n_l \), and the distances from the laminate reference plane to the top and bottom surfaces of each layer \( (h_i \text{ for } i = 1, 2, 3, \ldots, n_l) \). In the absence of a known neutral plane for the laminate, the geometric centre is set as the datum, which does not affect the results for bending and torsional stiffness. Thus:

\[
[A] = \sum_{i=1}^{n_l} (h_{i+1} - h_i)[Q_i]
\]  (111)

\[
[B] = \frac{1}{2} \sum_{i=1}^{n_l} (h_{i+1}^2 - h_i^2)[Q_i]
\]  (112)

\[
[D] = \frac{1}{3} \sum_{i=1}^{n_l} (h_{i+1}^3 - h_i^3)[Q_i]
\]  (113)
The compliance matrix of the simplified snowboard sandwich composite is determined using the inverse of the combined stiffness matrix, defined as:

\[
\begin{bmatrix}
[a] & [b] \\
[b] & [d]
\end{bmatrix} = \begin{bmatrix}
[A] & [B] \\
[B] & [D]
\end{bmatrix}^{-1}
\]

(114)

Where:

\[
[a] = \begin{bmatrix}
a_{11} & a_{12} & a_{16} \\
a_{12} & a_{22} & a_{26} \\
a_{16} & a_{26} & a_{66}
\end{bmatrix}
\]

(115)

\[
[b] = \begin{bmatrix}
b_{11} & b_{12} & b_{16} \\
b_{12} & b_{22} & b_{26} \\
b_{16} & b_{26} & b_{66}
\end{bmatrix}
\]

(116)

\[
[d] = \begin{bmatrix}
d_{11} & d_{12} & d_{16} \\
d_{12} & d_{22} & d_{26} \\
d_{16} & d_{26} & d_{66}
\end{bmatrix}
\]

(117)

Matrix elements \(a_{ij}\), \(b_{ij}\) and \(d_{ij}\) (for \(i, j = 1,2,6\)) are the in-plane, coupling and bending elastic compliances, respectively, of the laminate. The bending stiffness \((EI')\) of the simplified snowboard structure is calculated with the following expression [49]:

\[
EI' = \frac{W}{a_{11}}
\]

(118)

Where \(W\) is the width of the snowboard for the cross-section considered. Conversely, the torsional stiffness \((GJ')\) is calculated using the following equation [49]:

\[
GJ' = \frac{4W}{a_{66}}
\]

(119)

These expressions allow the determination of the key snowboard stiffness properties, neglecting the effect of the sidewall and edges (if present). To incorporate these elements into the calculations of bending and torsional stiffness, the approach described by Brennan is followed [7]. The method employs beam theory and considers the snowboard structure as the sum of a main laminate, sidewalls and edges, as shown in Figure 37 (half-width displayed).
The location of the centroid of each element is initially determined, relative to the $y - z$ coordinate system shown in Figure 37. It is noted that the $y$ axis is located along the lower snowboard surface, whilst the $z$ axis is the through-thickness axis of symmetry. Assuming the sidewalls and edges are homogeneous, the centroids of these elements are located at their respective geometric centres. For the main laminate, the centroid is located at a certain height along the $z$ axis, which also defines its neutral $x - y$ plane (where normal forces in the $x$ direction do not cause out-of-plane curvatures). This height is determined using the following expression [49]:

$$
\bar{Z}_1 = \frac{t_1}{2} + \frac{-b_{11}}{d_{11}}
$$

(120)

Where $\bar{Z}_1$ is the height of the centroid of the main laminate (element 1) above the $y$ axis, $t_1$ is the total thickness of the main laminate, whilst $b_{11}$ and $d_{11}$ are as defined previously. The combined compliance matrix of the main laminate must also be referenced to its neutral $x - y$ plane, with new elements determined using the following equations [49]:

$$
\bar{a}_{ij} = a_{ij} + \frac{-b_{11}}{d_{11}} (b_{ij} + d_{ji}) + \left(\frac{-b_{11}}{d_{11}}\right)^2 d_{ij}
$$

(121)

$$
\bar{b}_{ij} = b_{ij} + \frac{b_{11}}{d_{11}} d_{ij}
$$

(122)

$$
\bar{d}_{ij} = d_{ij}
$$

(123)

For $i, j = 1, 2, 6$, where $\bar{a}_{ij}$, $\bar{b}_{ij}$ and $\bar{d}_{ij}$ are the elements of the $[\bar{a}]$, $[\bar{b}]$ and $[\bar{d}]$ revised laminate compliance matrices (referenced to the neutral $x - y$ plane), whilst $a_{ij}$, $b_{ij}$, $d_{ij}$
and $d_{ij}$ are the elements of these matrices previously calculated (referenced to the laminate geometric centre).

The stiffness matrix for the full snowboard structure is determined using the following matrix expression [49]:

$$[P] = \sum_{k=1}^{n_e}[R_k]^T[\omega_k]^{-1}[R_k]$$ (124)

Where $[P]$ is the final snowboard stiffness matrix and $n_e$ is the total number of elements considered. For the snowboard structure shown in Figure 37, although only three different elements are present, due to the $z$ axis of symmetry two sidewalls and two edges must be incorporated into the above expression (five elements in total). The $[R_k]$ matrix for each element is defined as [49]:

$$[R_k] = \begin{bmatrix} 1 & \bar{z}_k & \bar{y}_k & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$ (125)

Where $\bar{z}_k$ and $\bar{y}_k$ are the coordinates of the centroid for each element. The $[\omega_k]$ matrix is given by [49]:

$$[\omega_k] = \frac{1}{w_k} \begin{bmatrix} (\bar{a}_{11})_k & (\bar{b}_{11})_k & 0 & -\frac{1}{2}(\bar{b}_{16})_k \\ (\bar{b}_{11})_k & (\bar{a}_{11})_k & 0 & -\frac{1}{2}(\bar{d}_{16})_k \\ 0 & 0 & 12 & 0 \\ -\frac{1}{2}(\bar{b}_{16})_k & -\frac{1}{2}(\bar{d}_{16})_k & 0 & 1/4(\bar{d}_{66})_k \end{bmatrix}$$ (126)

Where $b_k$ is the width of each element, $(\bar{a}_{11})_k$, $(\bar{b}_{11})_k$, $(\bar{a}_{11})_k$, $(\bar{b}_{16})_k$, $(\bar{d}_{16})_k$ and $(\bar{d}_{66})_k$ are the compliance matrix components for each structural element (referenced to their neutral $x-y$ plane) for $k = 1, 2, ..., n_e$, and $(\bar{A}_{11})_k$ is determined using the following relationship [49]:

$$\begin{bmatrix} (\bar{A}_{11})_k \\ (\bar{A}_{12})_k \\ (\bar{A}_{13})_k \\ (\bar{A}_{21})_k \\ (\bar{A}_{22})_k \\ (\bar{A}_{23})_k \\ (\bar{A}_{31})_k \\ (\bar{A}_{32})_k \\ (\bar{A}_{33})_k \end{bmatrix} = \begin{bmatrix} (\bar{a}_{11})_k & (\bar{b}_{11})_k & (\bar{b}_{16})_k \\ (\bar{b}_{11})_k & (\bar{d}_{11})_k & (\bar{d}_{16})_k \\ (\bar{b}_{16})_k & (\bar{d}_{16})_k & (\bar{d}_{66})_k \end{bmatrix}^{-1}$$ (127)

The final calculated snowboard stiffness matrix $[P]$ has a different form to the previous stiffness matrices, and links the in-plane forces and moments to strains and curvatures in three dimensions using the following expression [49]:
\[
\begin{bmatrix}
\vec{N}_x \\
\vec{M}_y \\
\vec{M}_z \\
\vec{T}_x
\end{bmatrix}
= 
\begin{bmatrix}
P_{11} & P_{21} & P_{31} & P_{41} \\
P_{12} & P_{22} & P_{32} & P_{42} \\
P_{13} & P_{23} & P_{33} & P_{43} \\
P_{14} & P_{24} & P_{34} & P_{44}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x^0 \\
\kappa_y \\
\kappa_z \\
\vartheta_x
\end{bmatrix}
\]

(128)

Where \( P_{ij} \) for \( i, j = 1, 2, 3, 4 \) are the elements of \([P]\), \( \vec{N}_x \) and \( \varepsilon_x^0 \) are the forces and strains in the principal \( x \) direction, respectively, \( \vec{M}_y \), \( \vec{M}_z \) and \( \kappa_y \), \( \kappa_z \) are the moments and curvatures in the principal \( y \) and \( z \) directions, respectively, whilst \( \vec{T}_x \) is the torque and \( \vartheta_x \) the rate of twist in the principal \( x \) direction.

The final snowboard compliance matrix \([W]\) is calculated using the following relationship [49]:

\[
[W] = [P]^{-1}
\]

(129)

Where \([W]\) has elements \( W_{ij} \) for \( i, j = 1, 2, 3, 4 \).

The bending stiffness \((EI)\) for each snowboard cross-section is then calculated using the following equation [49]:

\[
EI = \frac{1}{W_{22}}
\]

(130)

Whilst the torsional stiffness \((GJ)\) is calculated with the following expression [49]:

\[
GJ = \frac{1}{W_{44}}
\]

(131)

The calculations of bending and torsional stiffness for the complete snowboard structure can be compared to the results of Equations 118 and 119 to evaluate the effect of adding the sidewall and edge elements on the key stiffness properties. However, it is noted that the element based stiffness calculation method described in Equations 124 to 131 does not take into consideration the fact that laminate material is removed to allow the addition of the sidewall and edges (the method is purely additive). As a result, when determining the compliance matrices of the sidewall and edge elements from relevant material data inputs (refer to Equations 75 – 80), the differences in extensional and shear moduli between these elements and the main laminate are used as the input parameters (not considered by Brennan [7]). Thus, if the main laminate has higher moduli than the edges or sidewall materials, negative inputs are utilised.
To determine the bending and torsional stiffness distributions of any snowboard structure, these calculations are repeated along the chord, with different width and thickness inputs. It is assumed in the computations that the topsheet, fabric composite layers and base layer are of constant thickness, with only the core layer possessing variable thickness. The smoothness of the resulting stiffness distributions is hence dependent on the number of geometric input datasets.

**Snowboard Mass**

The overall mass of the snowboard is determined by integrating the mass per unit length (calculated for each cross-section) over the entire chord. The mass per unit length of any cross-section is calculated from the respective densities of the composite sandwich layers, sidewall and edge elements using the following expression:

\[
\tilde{M} = \left( \sum_{i=1}^{n_l} W(h_{i+1} - h_i)\rho_i \right) + \left( \sum_{k=2}^{n_e} w_k t_k(\tilde{\rho}_k - \tilde{\rho}_1) \right)
\]  

(132)

Where \( \tilde{M} \) is the snowboard mass per unit length, \( W \) is the snowboard cross-sectional width, \( h_i \) and \( \rho_i \) (for \( i = 2, 3, ..., n_l \)) are the snowboard laminate layer heights and densities, respectively, whilst \( w_k, t_k \) and \( \rho_k \) (for \( k = 2, 3, ..., n_e \)) are the respective widths, thicknesses and densities of the sidewall and edge elements (if present). Finally, \( \tilde{\rho}_1 \) is the average density of the main laminate, calculated using:

\[
\tilde{\rho}_1 = \sum_{i=1}^{n_l} \frac{(h_{i+1} - h_i)\rho_i}{h_{i+1} - h_i}
\]  

(133)

Where all parameters are as defined previously. It is noted that as per the stiffness calculations, the differences between the densities of the main laminate and remaining elements are implemented into the mass per unit length equation, to avoid element volumes being considered twice.

**Snowboard Thermal Response**

The classic laminate theory is also utilised to determine the thermal response of the snowboard structure to a known temperature change. In this case, the thermal forces, moments, strains and curvatures are linked by the combined stiffness matrix using the following expression [49], [85]:
\[
[N^t] = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{bmatrix} [\varepsilon^{0t}] \\ [\kappa^t] \end{bmatrix}
\]  
(134)

Where:

\[
[N^t] = \begin{bmatrix} N_x^t \\ N_y^t \\ N_{x y}^t \end{bmatrix}
\]  
(135)

\[
[M^t] = \begin{bmatrix} M_x^t \\ M_y^t \\ M_{x y}^t \end{bmatrix}
\]  
(136)

\[
[\varepsilon^{0t}] = \begin{bmatrix} \varepsilon_{x}^{0t} \\ \varepsilon_{y}^{0t} \\ Y_{x y}^{0t} \end{bmatrix}
\]  
(137)

\[
[\kappa^t] = \begin{bmatrix} \kappa_x^t \\ \kappa_y^t \\ \kappa_{x y}^t \end{bmatrix}
\]  
(138)

Where all terms are as described previously, with the superscript \( t \) referring to a thermal property. The thermal forces and moments can be calculated with the following equations [49]:

\[
[N^t] = \Delta T \sum_{i=1}^{n_l} (h_{i+1} - h_i) [Q_i] [\alpha_i]
\]  
(139)

\[
[M^t] = \frac{1}{2} \Delta T \sum_{i=1}^{n_l} (h_{i+1}^2 - h_i^2) [Q_i] [\alpha_i]
\]  
(140)

Where \( \Delta T \) is the temperature change input, whilst \( h_i, [Q_i] \) and \( [\alpha_i] \) for \( i = 1, 2, 3, ..., n_l \) are the layer surface heights (from the determined neutral \( x - y \) plane), layer stiffness matrices and layer thermal expansion properties, respectively. As a result, the thermal strains and curvatures of the snowboard sandwich composite can be calculated using the previously determined combined compliance matrix (referenced to the neutral \( x - y \) plane) with the following matrix equation:

\[
\begin{bmatrix} [\varepsilon^{0t}] \\ [\kappa^t] \end{bmatrix} = \begin{bmatrix} [\bar{a}] & [\bar{b}] & [N^t] \\ [\bar{b}] & [\bar{d}] & [M^t] \end{bmatrix}
\]  
(141)
Whilst the on-snow performance of any snowboard will only be minimally affected by thermal strains over a defined temperature interval, thermal curvatures will cause a camber change which may strongly alter on-snow feel and performance. To determine the resulting camber change from the calculated thermal curvature for each structural cross-section, the following expressions are derived:

\[
\bar{\kappa}_x^t = \frac{1}{L_{co}} \int_0^{L_{co}} \kappa_x^t \, dx \tag{142}
\]

\[
\bar{\psi} = \sin^{-1} \left( \frac{1}{2}, \bar{\kappa}_x^t, L_{co} \right) \tag{143}
\]

\[
\Delta C = \frac{1 - \cos(\bar{\psi})}{\bar{\kappa}_x} \tag{144}
\]

Where \( \bar{\kappa}_x^t \) is the average longitudinal thermal curvature over the contact length, \( \bar{\psi} \) is the average camber change angle, \( L_{co} \) is the snowboard contact length and \( \Delta C \) is the resulting camber change. Equations 143 and 144 are based on the simple camber change geometry shown in Figure 38.

\[
\begin{align*}
\Delta C &= \frac{1 - \cos(\bar{\psi})}{\bar{\kappa}_x} \tag{144} \\
\end{align*}
\]

\[
\begin{align*}
\bar{\kappa}_x^t &= \frac{1}{L_{co}} \int_0^{L_{co}} \kappa_x^t \, dx \\
\bar{\psi} &= \sin^{-1} \left( \frac{1}{2}, \bar{\kappa}_x^t, L_{co} \right) \\
\Delta C &= \frac{1 - \cos(\bar{\psi})}{\bar{\kappa}_x}
\end{align*}
\]

\[
\begin{align*}
\Delta C &= \frac{1 - \cos(\bar{\psi})}{\bar{\kappa}_x} \tag{144} \\
\end{align*}
\]

Figure 38: Camber change geometry

It is noted that the thermal strain and curvature calculations are solely for the main laminate, and neglect the influence of the sidewall and edge elements. The camber change results are therefore only indicative of the thermal response of any snowboard structure. However, the model allows the approximate on-snow camber level to be calculated from
room-temperature material properties, which is required for the prediction of snowboard performance (see Section 4.1).

To determine the effect of temperature on the bending and torsional stiffness properties of the snowboard structure, the individual temperature responses of constituent layer materials must be known. It is well established that the wooden core, composite layer matrix, UHMWPE base layer and ABS topsheet all have temperature dependent extensional and shear moduli (refer to Section 3.3). The effect of on-snow temperature on snowboard stiffness properties can thus be determined by altering the material property inputs to the model for a defined temperature differential.
5. VALIDATION

5.1 Snowboard Performance Prediction Model

The developed snowboard performance prediction models have been validated against the existing subjective and objective data collected in this research. For the linear correlation based model, the average coefficient of determination for the performance modeling scale plots (see Figures 32(a) – (i)) is 0.84. Conversely, for the causative exponent based performance model, the average coefficient of determination is 0.98.

Whilst these coefficients indicate that the predictive capability of both models is high, it is recognised that the two performance measures are based on three snowboard models tested (subjectively by nine experts) across the freeride-freestyle riding styles. To improve the general applicability of the computational models, further snowboards within the spectrum need to be examined both subjectively and objectively. This will not only strengthen the statistical basis of the Spearman ranked correlations, but higher confidence can then be placed in both facets of the performance prediction model.

At present, the performance prediction model represents a useful tool for the comparison of snowboards currently on the market, and furthermore can be assumed to provide an approximate assessment of overall feel and performance for any snowboard design within the major riding styles.

Regarding the scaling of objective design inputs for different rider characteristics, the scaling parameters are based purely on published data between relative strengths of male and female skiers, together with logical considerations of the effect of mass, height and foot size on snowboard feel and performance. Whilst the formulated scales compare favourably to existing snowboard selection charts, further testing of currently available snowboard models by different expert riders would again allow a more comprehensive validation to be undertaken.
5.2 Snowboard Stiffness, Mass and Camber Prediction Model

To confirm the general applicability of the developed stiffness, mass and camber prediction model, only the fabric composite properties, total mass and camber change sub-models require an in-depth validation, as the elemental snowboard stiffness component has already been validated by Brennan [7]. Thus, three sandwich composite samples with different geometry, fabric architecture and core material are constructed. They are subjected to the previously described static bending and torsion tests to determine their stiffness properties, weighed on a basic scale, and finally examined at low temperature to evaluate their thermal response. The results are compared to the output of the model and an error analysis is conducted.

The structure, thermo-mechanical properties and geometry of the sandwich composite samples are shown in Table 21, which provides all the necessary inputs for the sandwich composite model. An image of the test samples is also shown in Figure 39. It is noted that for the tri-axial stitched fibreglass, due to the absence of accurate tow distortion volume and stitching density data, these parameters are assigned nominal values.

Figure 39: Sandwich composite samples
Table 21: Sample data [49], [61], [86] - [93]

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>290</td>
<td>315</td>
<td>275</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>502</td>
<td>1350</td>
<td>531</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Core</th>
<th>Hexcel Nomex HRH-10</th>
<th>Pine Plywood</th>
<th>Rohacell Rist 51 Foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>10</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>(\rho) (g/cm(^3))</td>
<td>0.064</td>
<td>0.45</td>
<td>0.052</td>
</tr>
<tr>
<td>(E_1) (GPa)</td>
<td>0.105</td>
<td>13</td>
<td>0.075</td>
</tr>
<tr>
<td>(E_2) (GPa)</td>
<td>0.0105</td>
<td>0.7</td>
<td>0.075</td>
</tr>
<tr>
<td>(\nu_{12})</td>
<td>0.26</td>
<td>0.5</td>
<td>0.56</td>
</tr>
<tr>
<td>(G_{12}) (GPa)</td>
<td>0.002</td>
<td>0.63</td>
<td>0.024</td>
</tr>
<tr>
<td>(\alpha_1) (10(^6) K(^{-1}) @ 20°C)</td>
<td>35</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>(\alpha_2) (10(^6) K(^{-1}) @ 20°C)</td>
<td>35</td>
<td>34</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Upper Fabric Layer</th>
<th>Carbon fibre (AS4)</th>
<th>Fibreglass (E-Glass)</th>
<th>Carbon fibre (AS4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric designation</td>
<td>Sigmatex PC2070950</td>
<td>Colan WRE300</td>
<td>Sigmatex PC2070950</td>
</tr>
<tr>
<td>Fabric configuration</td>
<td>2x2 0°/90° bi-axial weave</td>
<td>2x2 0°/90° bi-axial weave</td>
<td>2x2 0°/90° bi-axial weave</td>
</tr>
<tr>
<td>Fabric weight (g/m(^2))</td>
<td>220</td>
<td>320</td>
<td>220</td>
</tr>
<tr>
<td>Layer stacking</td>
<td>0°/45°/0° (3 layers)</td>
<td>45°/0°/45° (3 layers)</td>
<td>0°/45°/0° (3 layers)</td>
</tr>
<tr>
<td>Layer thickness (mm)</td>
<td>0.25</td>
<td>0.23</td>
<td>0.25</td>
</tr>
<tr>
<td>Tow spacing (mm)</td>
<td>1.89/1.89</td>
<td>1.79/1.92</td>
<td>1.89/1.89</td>
</tr>
<tr>
<td>Tow density (g/cm(^2))</td>
<td>1.78</td>
<td>2.54</td>
<td>1.78</td>
</tr>
<tr>
<td>Yarn bundle size</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
</tr>
<tr>
<td>Yarn diameter (µm)</td>
<td>7.1</td>
<td>7.0</td>
<td>7.1</td>
</tr>
<tr>
<td>(E_1) (GPa)</td>
<td>235</td>
<td>71</td>
<td>235</td>
</tr>
<tr>
<td>(E_2) (GPa)</td>
<td>14</td>
<td>71</td>
<td>14</td>
</tr>
<tr>
<td>(\nu_{12})</td>
<td>0.2</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>(G_{12}) (GPa)</td>
<td>6.9</td>
<td>29.1</td>
<td>6.9</td>
</tr>
<tr>
<td>(\alpha_1) (10(^6) K(^{-1}) @ 20°C)</td>
<td>-0.4</td>
<td>5</td>
<td>-0.4</td>
</tr>
<tr>
<td>(\alpha_2) (10(^6) K(^{-1}) @ 20°C)</td>
<td>18</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td><strong>Lower Fabric Layer</strong></td>
<td>Carbon fibre (AS4)</td>
<td>Fibreglass (E-Glass)</td>
<td>Fibreglass (E-Glass)</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------</td>
<td>---------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td><strong>Fabric designation</strong></td>
<td>Sigmatex PC2070950</td>
<td>Colan MT1100</td>
<td>Colan MT1100</td>
</tr>
<tr>
<td><strong>Fabric configuration</strong></td>
<td>2x2 0°/90° bi-axial weave</td>
<td>0°/45°/−45° stitched tri-axial</td>
<td>0°/45°/−45° stitched tri-axial</td>
</tr>
<tr>
<td><strong>Fabric weight (g/m²)</strong></td>
<td>220</td>
<td>1106</td>
<td>1106</td>
</tr>
<tr>
<td><strong>Layer stacking</strong></td>
<td>0°/45°/0° (3 layers)</td>
<td>0° (1 layer)</td>
<td>0° (1 layer)</td>
</tr>
<tr>
<td><strong>Layer thickness (mm)</strong></td>
<td>0.25</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Tow spacing (mm)</strong></td>
<td>1.89/1.89</td>
<td>2.55/2.55/1.80</td>
<td>2.55/2.55/1.80</td>
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<tr>
<td><strong>Tow density (g/cm³)</strong></td>
<td>1.78</td>
<td>2.54</td>
<td>2.54</td>
</tr>
<tr>
<td><strong>Yarn bundle size (Fill/Warp/Axial) (k)</strong></td>
<td>3/3</td>
<td>6/6/12</td>
<td>6/6/12</td>
</tr>
<tr>
<td><strong>Yarn diameter (µm)</strong></td>
<td>7.1</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Distorted volume (mm³)</strong></td>
<td>-</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Stitch density (mm⁻²)</strong></td>
<td>-</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>E₁ (GPa)</strong></td>
<td>235</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td><strong>E₂ (GPa)</strong></td>
<td>14</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td><strong>ν₁₂</strong></td>
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<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>G₁₂ (GPa)</strong></td>
<td>6.9</td>
<td>29.1</td>
<td>29.1</td>
</tr>
<tr>
<td><strong>α₁ (10⁶ K⁻¹ @ 20°C)</strong></td>
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<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>α₂ (10⁶ K⁻¹ @ 20°C)</strong></td>
<td>18</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Matrix</strong></th>
<th>West System Epoxy 105/207</th>
<th>West System Epoxy 105/207</th>
<th>West System Epoxy 105/207</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ρ (g/cm³)</strong></td>
<td>1.18</td>
<td>1.18</td>
<td>1.18</td>
</tr>
<tr>
<td><strong>E (GPa)</strong></td>
<td>2.83</td>
<td>2.83</td>
<td>2.83</td>
</tr>
<tr>
<td><strong>ν</strong></td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
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<tr>
<td><strong>G (GPa)</strong></td>
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<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td><strong>α (10⁶ K⁻¹ @ 20°C)</strong></td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
</tbody>
</table>

The experimental bending and torsional stiffness validation data is acquired using the standard laboratory tests described previously, with the setups for the bending and torsional stiffness tests shown in Figures 15(a) – (b) and 20, respectively. Bending and torsional deflection values are obtained at 30 mm intervals along the longitudinal
centreline for each sandwich composite sample, and each test is repeated to evaluate the variance in the results, and minimise the effect of data aberrations. The longitudinal stiffness distributions of each sample are shown graphically in Figures 40 and 41, which includes determined uncertainty ranges (error components calculated as per previous).

Regarding the outputs of the sandwich composite model for the validation inputs shown in Table 21, Table 22 displays the crucial intermediate calculation of the fibre volume fraction for each fabric composite layer type, together with the undulation angle, percentage knockdown in longitudinal modulus and areal weight. A comparison of averaged experimental data to the final model stiffness and mass outputs is shown in Table 23, which also contains the baseline classical laminate theory (no tow undulation considered) prediction of bending and torsional stiffness for each input dataset.

**Figure 40:** Bending stiffness validation tests
Table 22: Calculated fabric properties

<table>
<thead>
<tr>
<th></th>
<th>Woven bi-axial carbon fibre</th>
<th>Stitched tri-axial fibreglass</th>
<th>Woven bi-axial fibreglass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre volume fraction</td>
<td>0.50</td>
<td>0.44</td>
<td>0.54</td>
</tr>
<tr>
<td>Undulation angle</td>
<td>3.8°/3.8°</td>
<td>-</td>
<td>3.3°/3.8°</td>
</tr>
<tr>
<td>(Fill/Warp)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knockdown in</td>
<td>18%/18%</td>
<td>1%</td>
<td>3%/4%</td>
</tr>
<tr>
<td>longitudinal modulus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Areal weight (g/m²)</td>
<td>224.3</td>
<td>1112.5</td>
<td>316.9</td>
</tr>
</tbody>
</table>

For the thermal tests, the composite samples are placed in the -17°C environment previously utilised (see Section 3.3) to evaluate their thermal contraction properties. Due to the relatively low levels of thermal strain present for the tested temperature differential (approximately -40°C from laboratory temperature), only two parameters are measured, the longitudinal contraction and the camber change (maximum thermal bending height). A comparison between experimental thermal measurements and model outputs for each of the samples is also shown in Table 23. Again, the classical laminate theory (no tow
undulation) prediction of the two aforementioned thermal parameters is also included for comparative purposes.

**Table 23:** Comparison of experimental results to model outputs

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th></th>
<th>Sample 2</th>
<th></th>
<th>Sample 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.</td>
<td>Model</td>
<td>Class.</td>
<td>Exp.</td>
<td>Model</td>
<td>Class.</td>
</tr>
<tr>
<td><strong>Bending stiffness</strong> (avg) (N.m²)</td>
<td>561.8</td>
<td>542.2</td>
<td>648.2</td>
<td>366.3</td>
<td>378.0</td>
<td>381.0</td>
</tr>
<tr>
<td><strong>Torsional stiffness</strong> (avg) (N.m²)</td>
<td>486.1</td>
<td>501.1</td>
<td>593.7</td>
<td>293.7</td>
<td>300.5</td>
<td>305.2</td>
</tr>
<tr>
<td><strong>Mass (g)</strong></td>
<td>502.0</td>
<td>497.5</td>
<td>-</td>
<td>1350.0</td>
<td>1350.8</td>
<td>-</td>
</tr>
<tr>
<td><strong>Longitudinal contraction (mm)</strong></td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.25</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Camber change (mm)</strong></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Discussion of Results**

Overall, the experimental static bending and torsional stiffness tests on the sandwich composite samples produced consistent results (see Figures 40 and 41). Table 24 contains the experimental errors for the stiffness tests, including calculated average uncertainties (relative and absolute) for each data point, as well as average relative standard error (RSE) calculations and data ranges between individual stiffness tests and stiffness values along the chord.

Considering firstly the calculated uncertainties in the bending and torsional stiffness values, the error component breakdown (not displayed) is as per previous tests, where the experimental errors associated with the measurement of curvature (bending) and angular deformation (torsion) are the dominant sources. From the data shown in Table 24, it is noted that the Nomex core sample (Sample 1) possesses the highest relative and overall uncertainties in bending/torsion (8.5%/10.2% and 47.4/50.4 N.m² respectively), whilst the foam core sample (Sample 3) possesses the lowest (5.9%/9.1% and 10.3/14.6 N.m² respectively). This trend can be attributed to the relatively small deformations in bending
and torsion exhibited by the highly stiff Nomex core sample (compared to the remaining samples), thus resulting in the larger relative and absolute experimental measurement errors.

**Table 24: Experimental stiffness errors**

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td>8.5%</td>
<td>10.2%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Torsion</td>
<td>10.2%</td>
<td>8.0%</td>
<td>9.6%</td>
</tr>
<tr>
<td>Overall relative (avg)</td>
<td>8.5%</td>
<td>10.2%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Overall absolute (avg) ($N.m^2$)</td>
<td>47.4</td>
<td>50.4</td>
<td>29.5</td>
</tr>
<tr>
<td>RSE (Avg. between tests)</td>
<td>1.4%</td>
<td>3.4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>RSE (Avg. along chord)</td>
<td>1.0%</td>
<td>1.7%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Range (Avg. between tests) ($N.m^2$)</td>
<td>14.0</td>
<td>38.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Range (Avg. along chord) ($N.m^2$)</td>
<td>56.0</td>
<td>84.0</td>
<td>23.4</td>
</tr>
</tbody>
</table>

Regarding the relative standard errors, as expected, the bending stiffness data points display slightly less scatter than the torsional stiffness data points (both between individual tests as well as along the chord), with all RSE values less than 2.0%. The torsional stiffness RSE values are all less than 5.0%, though the majority are approximately 2 - 4%, with the high RSE (between tests) for the foam core sample (4.4%) due to slight scatter and relatively low overall torsional stiffness. As per the findings of the previous static stiffness tests, the torsional stiffness tests have a higher propensity for error due to a more complicated setup (more experimental error sources) and lower accuracy for the angular deformation measurements (compared to curvature measurements). Interestingly, the wood and foam core sample exhibit a far more consistent response both in bending and torsion than the Nomex core sample, despite its high overall stiffness (refer to Table 24). There is significant fluctuation in stiffness values both between individual tests (14.0/38.6 N.m$^2$ in bending/torsion) and calculation data points (56.0/84.0 N.m$^2$ in bending/torsion), implying that Nomex or perhaps honeycomb core composites in general possess inconsistent properties and mechanical response.

Considering the outputs of the thermo-mechanical model (see Tables 22 and 23) for the input data displayed in Table 21, the crucial fibre volume fraction calculation for each type of fabric reinforcement produced results all within reasonable bounds for manufacture (0.4
Similarly, the determined average tow undulation angle for each fabric are consistent with values listed in Dadkhah et al. [56], whilst the calculated areal weights agree well with the manufacturers specifications (see Table 21). Notably, the percentage knockdowns in longitudinal modulus illustrate that, according to the model, woven bi-axial carbon fibre is substantially more affected by tow undulation than stitched or woven fibreglass. This is a direct result of the relatively high longitudinal and low transverse modulus of carbon fibre strands (transversely isotropic), in contrast to the isotropic nature of glass fibre filaments.

The final bending/torsional stiffness and mass outputs of the model compare favourably to the experimental values (Table 23). Furthermore, inclusion of the classic laminate theory stiffness predictions demonstrate the benefits of the tow undulation model, particularly for the composite samples containing bi-axial carbon weave (due to the high knockdown in fabric longitudinal modulus). In the case of Sample 1, with reinforcement layers entirely comprised of bi-axial carbon weave, the difference between prediction methods is considerable. On the basis of the experimental data collected in the validation, the composite model possessed a coefficient of determination ($R^2$) of 0.994, compared to 0.852 for the classic laminate theory. Thus, the tow undulation model appears to improve on the classic laminate theory in the stiffness prediction of composite sandwich structures.

A basic error analysis of the validation process is displayed in Table 25, referenced to the experimental data collected. The percentage inaccuracies of the classic laminate theory predictions are also shown for completeness. Using a two-tailed Student’s t test, error in the predictions of both the undulation model and classic laminate theory are statistically insignificant (based on a significance level of 0.05), with p values calculated at 0.616 and 0.068, respectively. However, these values show that based on the validation sample size utilised, the undulation model has far less significant imprecision.

Therefore, despite the assumptions and simplifications utilised in the various stages of development of the stiffness prediction model, and the scatter in the experimental data, the errors presented in Table 25 are reasonable and insignificant. The stiffness outputs of the model for all the samples are also all within the data range for the laboratory experiments shown in Figures 40 and 41. Overall, the code predicts the bending and torsional stiffness of the three manufactured composite samples with much higher accuracy than the classic laminate theory. It can thus be assumed to be universally applicable to any sandwich composite utilising the fabric configurations modelled.
Table 25: Validation errors

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th></th>
<th>Sample 2</th>
<th></th>
<th>Sample 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
<td>Classical</td>
<td>Model</td>
<td>Classical</td>
<td>Model</td>
<td>Classical</td>
</tr>
<tr>
<td><em>Bending stiffness (N.m²)</em></td>
<td>3.5%</td>
<td>15.4%</td>
<td>3.2%</td>
<td>4.0%</td>
<td>0.2%</td>
<td>8.2%</td>
</tr>
<tr>
<td><em>Torsional stiffness (N.m²)</em></td>
<td>3.1%</td>
<td>22.1%</td>
<td>2.7%</td>
<td>3.9%</td>
<td>1.0%</td>
<td>8.4%</td>
</tr>
<tr>
<td>_Mass (g)</td>
<td>0.9%</td>
<td>-</td>
<td>0.1%</td>
<td>-</td>
<td>0.6%</td>
<td>-</td>
</tr>
<tr>
<td>_Longitudinal contraction (mm)</td>
<td>20.0%</td>
<td>20.0%</td>
<td>20.0%</td>
<td>20.0%</td>
<td>24.0%</td>
<td>20.0%</td>
</tr>
<tr>
<td>_Camber change (mm)</td>
<td>-</td>
<td>-</td>
<td>0.0%</td>
<td>0.0%</td>
<td>5.0%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

Regarding the thermal outputs, only strain and camber change in the longitudinal direction are validated due to the difficulty of measuring the remaining small-scale thermal outputs without specialised apparatus. These parameters were measured in the -17°C environment to approximately 0.25 mm of accuracy (12.5% - 100% relative error). It is noted that at this level of measurement precision, the difference between the undulation model and classic laminate theory predictions is negligible for all samples, regardless of their architecture. Hence there appears to be little benefit to the more complicated modelling approach adopted in relation to thermal properties. Considering the resolution of the measurements, it is not surprising that the validation errors shown in Table 25 are higher than the preceding bending and torsional stiffness calculations. However, both the undulation model and classic theory appear to provide a good indication of thermal strains present in the tested sandwich composite samples.
6. OPTIMISATION

To examine the feasibility of the optimal performance targets (for each riding style) specified by the experts during the qualitative analysis (see Tables 4(a) and (b)), a design optimisation process is undertaken using the developed performance prediction models. Esteco ModeFrontier V4 [94] (a multi-objective optimisation and design environment) is utilised to conduct the optimisation, centred on minimisation of the following performance expression:

\[
\bar{P} = \sum_{n=1}^{9} (I_n \times |P_{n1} - O_n| + I_n \times |P_{n2} - O_n|)
\]  

(145)

Where \(\bar{P}\) is the overall performance measure, \(I_n\) is the subjective parameter importance level, \(P_{n1}\) and \(P_{n2}\) are the performance outputs (linear correlative and exponent based) of the prediction model and \(O_n\) is the optimal parameter level for \(n = 1, 2, ..., 9\). The optimisation expression computes the weighted difference between the predicted performance outputs and optimal parameter levels, summated over the nine subjective parameters. Performance outputs are calculated for the average rider (non-scaled) of mass 77 kg, height 177.5 cm and US size 9 feet.

To minimise the computation time (from weeks to hours), the number of objective design parameters under consideration is collapsed from 31 to 16. This is achieved by firstly utilising simple assumptions to derive ten of the objective design parameters, which are listed in Table 26 with their basis of derivation.

Furthermore, the five parameters with no correlation data (asymmetrical offset, body/shovel/heel edge sharpness and edge material) are also neglected in the optimisation. Whilst this results in slightly lower design freedom, particularly for the curved portions of the snowboard, the assumptions are necessary to drastically reduce the computation time for the generation of optimal design solutions.

The ModeFrontier workflow is setup as shown in Figure 42. Displayed are the 16 input variables (‘Lc’, ‘Ls’, ‘Lh’ blocks etc.), feeding into a Microsoft Excel 2007 [95] spreadsheet (shown by the ‘Excel16’ block) which determines the overall performance expression output (‘Net’ block) using the previously defined linear correlation and exponent based measures. This output is minimised using the ModeFrontier simulated annealing processor (represented by the ‘DOE’ and ‘Scheduler: MOSA’ blocks) [94],
which uses the performance of previous design solutions to generate an improved solution. The processor eventually determines an approximation of the global optimum within the defined search space (‘Objective’ block), which may then require some subsequent manual fine-tuning of individual input design parameter values to achieve a more exact optimal solution.

Bounds for each of the 16 input variables are determined by increasing the objective test snowboard data range from Table 7 by 100%. Whilst this allows potentially non-feasible (from a manufacturing perspective) combinations of design parameters to be generated, an analysis addressing this issue is undertaken during post-processing. It is also noted that for the freestyle design, to ensure it performed equally forwards and backwards, design constraints are applied to make the snowboard design non-directional. Thus, the heel and shovel lengths, thicknesses and stiffness parameters are set as equal.

Table 26: Parameter derivation

<table>
<thead>
<tr>
<th>Derived Parameters</th>
<th>Derivation Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length</td>
<td>Equal to the projected length</td>
</tr>
<tr>
<td>Projected length</td>
<td>Sum of the contact, shovel and heel lengths</td>
</tr>
<tr>
<td>Shovel radius</td>
<td>Derived as an ellipse from the shovel width and shovel length</td>
</tr>
<tr>
<td>Heel radius</td>
<td>Derived as an ellipse from the heel width and heel length</td>
</tr>
<tr>
<td>Tail height</td>
<td>Equal to the tip height</td>
</tr>
<tr>
<td>Heel width</td>
<td>Equal to the shovel length</td>
</tr>
<tr>
<td>Sidecut radius</td>
<td>Derived as a circle from the waist, heel/shovel widths and contact length</td>
</tr>
<tr>
<td>Shovel core material</td>
<td>Calculated from the shovel bending stiffness and total mass</td>
</tr>
<tr>
<td>Body core material</td>
<td>Calculated from the body bending stiffness and total mass</td>
</tr>
<tr>
<td>Heel core material</td>
<td>Calculated from the heel bending stiffness and total mass</td>
</tr>
</tbody>
</table>
The results of the optimisation are displayed in Figures 43 – 44 and Tables 27 - 30. The optimisation solution path determined by ModeFrontier is displayed for freeride and freestyle snowboards in Figures 43 and 44, respectively. In both figures, the horizontal $x$ axis displays the design ID number, representing each individual design solution generated by the software. Conversely, the vertical $y$ axis shows the output of the overall performance measure for each design. The solution paths illustrate the progression towards the global minima, which is the optimal design solution for each riding style. Tables 27 and 28 contain the optimised objective design parameter values generated by ModeFrontier for freeride and freestyle snowboards, respectively. These are the optimal design solutions for the ideal performance levels specified by the expert riders surveyed. Also shown in Tables 27 and 28 is the equivalent quantitative data for the freeride and freestyle test snowboards, respectively, for comparative purposes. Tables 29 and 30 display a performance analysis of the optimised freeride and freestyle designs. The tables contain the importance and ideal levels of the subjective performance parameters for each style (refer to Tables 4(a) and (b)), alongside the predicted performance of the optimal design using both the correlative and exponent based predictive measures. How well the optimal freeride and freestyle designs satisfy the subjective performance targets is also illustrated through the calculation of the net weighted difference ($P$) between the predictions and ideal levels.
**Figure 43:** Freeride optimisation path

**Figure 44:** Freestyle optimisation path
### Table 27: Freeride optimal design solution

<table>
<thead>
<tr>
<th>Objective Parameter</th>
<th>Optimal Value</th>
<th>Test Board Value</th>
<th>Objective Parameter</th>
<th>Optimal Value</th>
<th>Test Board Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length</td>
<td>1600.0</td>
<td>1569.5</td>
<td>Body thickness</td>
<td>11.9</td>
<td>10.0</td>
</tr>
<tr>
<td>Contact length</td>
<td>1210.0</td>
<td>1199.5</td>
<td>Shovel thickness</td>
<td>5.7</td>
<td>5.2</td>
</tr>
<tr>
<td>Projected length</td>
<td>1600.0</td>
<td>1571.5</td>
<td>Heel thickness</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Shovel length</td>
<td>200.0</td>
<td>193.5</td>
<td>Camber</td>
<td>11.0</td>
<td>8.1</td>
</tr>
<tr>
<td>Shovel radius</td>
<td>185.2</td>
<td>183.0</td>
<td>Shovel bending stiffness</td>
<td>31.0</td>
<td>30.5</td>
</tr>
<tr>
<td>Tip height</td>
<td>99.0</td>
<td>56.0</td>
<td>Body bending stiffness</td>
<td>229.0</td>
<td>234.3</td>
</tr>
<tr>
<td>Shovel width</td>
<td>303.0</td>
<td>291.0</td>
<td>Heel bending stiffness</td>
<td>39.0</td>
<td>28.9</td>
</tr>
<tr>
<td>Heel length</td>
<td>190.0</td>
<td>178.5</td>
<td>Body torsional stiffness</td>
<td>251.0</td>
<td>266.0</td>
</tr>
<tr>
<td>Heel radius</td>
<td>178.1</td>
<td>188.0</td>
<td>Mass</td>
<td>2.90</td>
<td>2.87</td>
</tr>
<tr>
<td>Tail height</td>
<td>99.0</td>
<td>55.0</td>
<td>Shovel core material</td>
<td>10.7</td>
<td>10.6</td>
</tr>
<tr>
<td>Heel width</td>
<td>303.0</td>
<td>291.0</td>
<td>Body core material</td>
<td>79.0</td>
<td>81.6</td>
</tr>
<tr>
<td>Waist width</td>
<td>247.0</td>
<td>246.0</td>
<td>Heel core material</td>
<td>13.4</td>
<td>10.1</td>
</tr>
<tr>
<td>Sidecut radius</td>
<td>6.6</td>
<td>8.4</td>
<td>Base material</td>
<td>0.027</td>
<td>0.027</td>
</tr>
</tbody>
</table>

### Table 28: Freestyle optimal design solution

<table>
<thead>
<tr>
<th>Objective Parameter</th>
<th>Optimal Value</th>
<th>Test Board Value</th>
<th>Objective Parameter</th>
<th>Optimal Value</th>
<th>Test Board Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length</td>
<td>1598.0</td>
<td>1515.5</td>
<td>Body thickness</td>
<td>5.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Contact length</td>
<td>1198.0</td>
<td>1149.5</td>
<td>Shovel thickness</td>
<td>5.2</td>
<td>5.3</td>
</tr>
<tr>
<td>Projected length</td>
<td>1598.0</td>
<td>1512.5</td>
<td>Heel thickness</td>
<td>5.2</td>
<td>5.3</td>
</tr>
<tr>
<td>Shovel length</td>
<td>200.0</td>
<td>181.5</td>
<td>Camber</td>
<td>13.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Shovel radius</td>
<td>186.5</td>
<td>189.0</td>
<td>Shovel bending stiffness</td>
<td>33.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Tip height</td>
<td>109.0</td>
<td>54.5</td>
<td>Body bending stiffness</td>
<td>222.0</td>
<td>200.5</td>
</tr>
<tr>
<td>Shovel width</td>
<td>312.0</td>
<td>299.0</td>
<td>Heel bending stiffness</td>
<td>33.0</td>
<td>32.7</td>
</tr>
<tr>
<td>Heel length</td>
<td>200.0</td>
<td>181.5</td>
<td>Body torsional stiffness</td>
<td>178.0</td>
<td>172.6</td>
</tr>
<tr>
<td>Heel radius</td>
<td>186.5</td>
<td>189.0</td>
<td>Mass</td>
<td>2.90</td>
<td>3.02</td>
</tr>
<tr>
<td>Tail height</td>
<td>109.0</td>
<td>53.0</td>
<td>Shovel core material</td>
<td>11.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Heel width</td>
<td>312.0</td>
<td>299.0</td>
<td>Body core material</td>
<td>76.6</td>
<td>66.3</td>
</tr>
<tr>
<td>Waist width</td>
<td>221.0</td>
<td>253.5</td>
<td>Heel core material</td>
<td>11.4</td>
<td>10.8</td>
</tr>
<tr>
<td>Sidecut radius</td>
<td>4.0</td>
<td>7.2</td>
<td>Base material</td>
<td>0.024</td>
<td>0.020</td>
</tr>
</tbody>
</table>
Table 29: Performance analysis of optimised freeride design

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>6.7</td>
<td>8.8</td>
<td>8.4</td>
<td>-0.4</td>
<td>8.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>6.3</td>
<td>8.8</td>
<td>8.3</td>
<td>-0.5</td>
<td>8.0</td>
<td>-0.7</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5.7</td>
<td>8.5</td>
<td>8.5</td>
<td>0.0</td>
<td>8.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Edge grip</td>
<td>5.4</td>
<td>8.1</td>
<td>8.8</td>
<td>0.7</td>
<td>8.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.4</td>
<td>6.4</td>
<td>4.9</td>
<td>-1.5</td>
<td>4.3</td>
<td>-2.1</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>4.4</td>
<td>7.1</td>
<td>5.2</td>
<td>-1.9</td>
<td>5.9</td>
<td>-1.2</td>
</tr>
<tr>
<td>Speed</td>
<td>4.6</td>
<td>7.5</td>
<td>8.5</td>
<td>-0.1</td>
<td>8.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>Liveliness</td>
<td>4.0</td>
<td>7.5</td>
<td>7.5</td>
<td>0.0</td>
<td>7.4</td>
<td>-0.2</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>3.4</td>
<td>7.4</td>
<td>8.9</td>
<td>1.5</td>
<td>6.9</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

WSum 30.0  WSum 23.4  Net 53.4

Table 30: Performance analysis of optimised freestyle design

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>5.4</td>
<td>7.3</td>
<td>6.9</td>
<td>-0.4</td>
<td>7.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>7.0</td>
<td>8.5</td>
<td>8.1</td>
<td>-0.4</td>
<td>8.0</td>
<td>-0.4</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5.3</td>
<td>7.8</td>
<td>7.5</td>
<td>-0.2</td>
<td>7.7</td>
<td>-0.1</td>
</tr>
<tr>
<td>Edge grip</td>
<td>3.1</td>
<td>6.6</td>
<td>7.4</td>
<td>0.8</td>
<td>6.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.9</td>
<td>5.1</td>
<td>5.1</td>
<td>0.0</td>
<td>4.4</td>
<td>-0.7</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>7.0</td>
<td>7.8</td>
<td>5.4</td>
<td>-2.3</td>
<td>6.6</td>
<td>-1.1</td>
</tr>
<tr>
<td>Speed</td>
<td>2.4</td>
<td>6.5</td>
<td>6.5</td>
<td>0.0</td>
<td>6.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Liveliness</td>
<td>7.6</td>
<td>8.6</td>
<td>7.9</td>
<td>-0.7</td>
<td>8.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>2.3</td>
<td>7.0</td>
<td>7.2</td>
<td>0.2</td>
<td>5.1</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

WSum 30.6  WSum 21.0  Net 51.6
Discussion of Results

Examining firstly the optimal freeride design solution, after approximately 800 ModeFrontier iterations (displayed in Figure 43) and limited manual fine-tuning (maximum 5% change in any input variable), the optimised set of objective design parameters shown in Table 27 was generated. It is noted that overall, the design is highly similar to the freeride test snowboard examined during the research. Comparing individual specifications, the optimised freeride design is slightly longer (2% based on projected length), wider (3% based on average width) and possesses greater camber (16%) than the freeride test snowboard. However, the optimised stiffness properties are notably lower than the highly stiff freeride test snowboard, with a reduction in body bending stiffness of 8% and body torsional stiffness of 11%. The heel and shovel bending stiffness are also 7% and 15% lower, respectively. Finally, it is also noted that the tip and tail heights (set as equal) are considerably greater (by approximately a factor of two) than any of the three test snowboards.

Regarding feasibility of manufacture, the optimised matrix of the objective design variables is empirically assessed to identify any apparent conflict between parameter output values. Given the geometric similarity of the design to the freeride test snowboard, the generated parametric solution displayed in Table 27 appears to be feasible. However, given that snowboard stiffness characteristics are driven by its thickness distribution, the determined average thickness values along the chord may not match the optimised stiffness characteristics. This assumes as per previous that the composite skin layup is constant along the chord of the snowboard, and only the core layer possesses variable thickness. The optimised body thickness parameter is 19% greater than the value for the freeride test snowboard, whilst the heel and shovel thicknesses are 10% greater and 4% lower respectively. Thus, it appears that it is not possible to achieve the required stiffness reductions along the chord whilst also satisfying the thickness requirements. However, given the high importance of stiffness to overall performance, and conversely the limited direct effect of the thickness parameters, the latter can be modified to suit the desired stiffness characteristics with a minimal loss in predicted performance. The comparatively large tip and tail heights generated do not affect the overall feasibility of manufacture of the optimised freeride snowboard.

Considering the optimal freestyle design, the matrix of objective design parameters (contained in Table 28) was manually fine-tuned (again maximum 5% change in any input
variable) after approximately 750 ModeFrontier iterations (shown in Figure 44). It is noted that the design is highly similar to the optimised freeride design, and hence considerably different to the freestyle test snowboard examined previously. The freestyle design generated is only 0.1% shorter based on projected length, 1% narrower based on average width and the body section 3% less stiff in bending compared to the optimised freeride design. Conversely, the key objective design parameters possessing the greatest variation between riding styles are the camber (21% greater for the freestyle design) and torsional stiffness (21% less for the freestyle design). These parameters also possess the greatest relative differences between the test snowboards examined in the research, again reinforcing their importance to altering the feel and performance of a snowboard across the major riding styles. Thus, it is concluded that based on the information collected and analysed, a significant change in only two key design parameters is required to effect a change in perceived riding style.

Assessing the freestyle design solution from a feasibility of manufacture standpoint, overall, the matrix of parameters generated appears to fall within reasonable bounds, with key design parameters such as mass, average bending/torsional stiffness and camber all achievable based on the data collected for the test snowboards. As per the freeride results however, the generated optimal average thicknesses are inconsistent with the desired stiffness characteristics, with the body thickness value less than the heel/shovel thickness value. Thus the body thickness would again have to be modified to ensure the key objective design parameter of body bending stiffness is satisfied, causing a small drop in overall predicted performance compared to the ideal levels.

Considering the optimised freeride and freestyle performance ratings contained in Tables 29 and 30, it is firstly noted that the net weighted performance difference for both styles are comparable, with the freeride sum 3% higher than the freestyle sum. The average absolute difference between predicted performance and ideal level is also 0.6 for both riding styles, further indicating the optimality levels of the two parametric designs is highly similar. Also, with the exception of the feedback parameter, each performance facet possesses almost identical average absolute differences across the two major riding styles, with a maximum variation of 0.25. The forgiveness parameter possesses the highest average absolute difference across the two riding styles, at 1.7 rating points.

Comparing the results from the individual performance models, there is an average difference of 0.5 and 0.7 rating points between the performance measures for the freeride
and freestyle designs, respectively. Furthermore, the maximum differences are 2.0 and 2.2, and minimums 0.0 and 0.1, respectively. The maximums are both for transition smoothness, indicating that there is potentially a mis-match between models, despite the fact that the correlations match the exponents for the transition smoothness measure. The low transition smoothness ratings from the exponent model are a result of the relatively high average widths, high camber and low stiffness for both optimised designs, having a much greater influence on the results of the exponent model than the correlative model.

The feedback parameter possesses the greatest average absolute difference for the freeride design, whilst conversely the forgiveness the greatest difference for the freestyle solution. Given the subjectivity of the feedback parameter, little can be gleaned from this high sub-optimality, and the level of detriment to the overall feel and performance. However, the consistent sub-optimality of the forgiveness parameter indicates that achieving high forgiveness in any snowboard is very difficult without significant performance sacrifices in other areas. Even with the high importance of forgiveness to freestyle snowboards (7.0), the parameter still possesses the greatest sub-optimality. Thus, based on the optimal performance targets specified by the expert riders, the snowboard design performance model is able to generate solutions for both major riding styles within reasonable performance error bounds. However, the optimisation process reinforces the fact that for any snowboard design, the overall on-snow performance will be a balance between mutually exclusive facets.
7. CONCLUSIONS

In order to characterise the feel of modern snowboards, objective snowboard design parameters and subjective user requirements for each of the major riding styles have been identified. Style requirements, user profiling and subjective performance data has been obtained through a range of online surveys, focus group interviews, industry consultation (the Canadian Snowboard Federation) and on-snow tests. Objective technical data was obtained for selected snowboard models through a variety of laboratory tests or from published data sheets, and consisted of geometric, stiffness and material properties. The information collected was then processed in a Quality Function Deployment (QFD) analysis to pinpoint the key objective snowboard design parameters for each major riding style. Market Opportunity Mapping (MoM) was also utilised to identify design innovation opportunities for the snowboard equipment market. From the results of the QFD and MoM, a deeper investigation into the key objective design attributes of bending/torsional stiffness and camber was undertaken.

The information collected was then utilised in the formulation of a general parametric design model for modern snowboards. The model allows the input of any discrete set of objective snowboard design parameters together with individual user characteristics, and outputs a prediction of the on-snow feel of the design. Key objective properties of bending/torsional stiffness, mass and camber are considered in a sub-model, allowing their determination from the input of fundamental layup construction data, along with material, geometric and thermal properties. The general parametric design model was validated against the existing subjective and objective datasets, with an overall coefficient of determination generated. Validation of the stiffness, mass and camber portion of the model was achieved through the manufacture and static laboratory testing of three composite samples of varying layer structure and geometry. The validated snowboard prediction model together with obtained performance targets were utilised to generate an optimal feel design for each major riding style.

The general research outcomes of this thesis are hence as follows, which are described in detail below:

• Feel in snowboarding has been characterised and correlated to snowboard design
• Key design parameters affecting feel in the main riding styles have been identified and characterised
• A user-centred snowboard design customisation approach has been devised
• It has been confirmed that there is no absolute optimal in snowboard design

Feel in snowboarding has been characterised and correlated to snowboard design

The following comprehensive list of subjective parameters has been formulated, which aim to not only fully characterise the feel and performance of freestyle and freeride snowboards, but be easily discerned by both riders and manufacturers:

Table 31: Subjective performance parameter list

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>How stable the rider feels on the board</td>
</tr>
<tr>
<td>Feedback</td>
<td>The amount of stress felt on the rider's body including the effects of board chatter</td>
</tr>
<tr>
<td>Speed</td>
<td>The gliding speed of the board compared to other boards of similar length</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The precision of board movement in response to rider input</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>The tolerance of the board to errors from the rider.</td>
</tr>
<tr>
<td>Edge grip</td>
<td>The level of grip exhibited during turns</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>How easily the board responds to rider inputs</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>How easily the board flows from edge to edge</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>The level of 'pop' or spring in the board when performing a jump</td>
</tr>
</tbody>
</table>

These non-technical parameters allow the on-snow performance of any snowboard to be rated using a universal 1 - 10 scale, and also form a functional basis of rider requirements for customised snowboard designs. Hence the parameters and associated rating system allow snowboard performance reviews and rider requirements to now be easily and systematically conveyed to snowboard manufacturers, improving the overall snowboard design process.

Statistical analyses of snowboard ratings and requirements collected during the survey process have determined that stability, edge grip and accuracy are significantly linked for
any snowboard within the major riding styles. Therefore they must be considered collectively when formulating performance requirements for a customised snowboard. Furthermore, feedback possessed the highest variance in results and was pinpointed as the most subjective parameter. It is thus the most difficult attribute to accurately quantify and customise to any user requirements. Finally, forgiveness was identified as a performance facet requiring significant improvement in modern snowboard design and development, possessing the lowest satisfaction ratings throughout the survey process.

Regarding specific requirements for the major riding styles, stability, manoeuvrability and accuracy are the most important performance aspects for freeride snowboards, whilst liveliness, manoeuvrability and forgiveness are crucial to freestyle snowboard performance. The full set of performance parameter importance ratings for each riding style are displayed in Table 32.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Freeride</th>
<th>Freestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>6.7 ± 2.7</td>
<td>5.4 ± 3.0</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>6.3 ± 2.6</td>
<td>7.0 ± 1.4</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5.7 ± 3.1</td>
<td>5.3 ± 2.3</td>
</tr>
<tr>
<td>Edge grip</td>
<td>5.4 ± 2.1</td>
<td>3.1 ± 1.9</td>
</tr>
<tr>
<td>Speed</td>
<td>4.6 ± 3.6</td>
<td>2.4 ± 1.3</td>
</tr>
<tr>
<td>Feedback</td>
<td>4.4 ± 2.1</td>
<td>4.9 ± 1.6</td>
</tr>
<tr>
<td>Forgiveness</td>
<td>4.4 ± 1.6</td>
<td>7.0 ± 1.7</td>
</tr>
<tr>
<td>Board liveliness</td>
<td>4.0 ± 2.9</td>
<td>7.6 ± 1.9</td>
</tr>
<tr>
<td>Transition smoothness</td>
<td>3.4 ± 1.6</td>
<td>2.3 ± 1.3</td>
</tr>
</tbody>
</table>

However, it was determined that the key performance parameters for freestyle snowboards are considerably more important than the corresponding freeride parameters, where for the latter style, a more balanced blend of all nine performance parameters is desired by riders. This is a direct result of riders requiring all-mountain and rounded performance from freeride snowboards, as opposed to the specific trick oriented performance desired from freestyle boards.
The qualitative analysis also indicated that modern riders are searching for snowboards that are able to both handle variable terrain and perform tricks successfully. In other words, the distinction between freestyle and freeride boards has become blurred, and versatility of snowboards within the two main riding styles is now desired by the users. This is difficult to achieve given the specific performance requirements for snowboards in each riding style, implying that either a compromise must be found for each performance feature, or alternatively, relevant attributes of the snowboard must be varied depending on the desired application.

*Key design parameters affecting feel in the main riding styles have been identified and characterised*

The developed user-centred performance measures have been linked to the full matrix of objective design parameters that define any snowboard using the QFD method. The analysis provided a better understanding of the relative importance of different snowboard features for different riding styles in relation to the identified user requirements. It has been determined that the body stiffness and material parameters are significantly more important to both styles than any other objective design feature. This implies that the bending stiffness distribution and mass of the main body section are crucial in the design of any snowboard. The major lengths, widths, sidecut radius, mass and torsional stiffness are also important to both freeride and freestyle snowboard performance. Furthermore, the major lengths and camber were shown to have the largest difference in relative importance between the major riding styles. The camber is considerably more important to freestyle designs due to its importance to liveliness and forgiveness, which drive trick performance and landing. Conversely, the major lengths are more important to freeride designs, with the focus of the style on stability, accuracy and edge grip. This information provides a strong basis for design customisation approaches.

The formulation of an overall performance measure using the qualitative data collected has allowed comparison and ranking of existing snowboards using a Market Opportunity Map, which identified gaps and opportunities within the current snowboard marketplace. The MoM confirmed that there is a potential design innovation opportunity for high performing, versatile snowboards that span the two major riding styles. In order to realise this opportunity for a novel snowboard design, the key objective parameters that drive
versatility were identified using a newly defined versatility value, which was derived in this research using a combination of objective data ranges between selected test snowboards and relative importance values of each parameter obtained from the QFD analysis. The bending and torsional stiffness distribution as well as the camber characteristics have been identified as the key objective design parameters influencing the versatility of modern snowboards. This bending stiffness versatility value was a result of the high relative importance of this design feature to any snowboard, whilst conversely, the torsional stiffness and camber values were caused by the significant variation in these parameters between freeride and freestyle snowboards. Customisation of snowboard performance across the major riding styles will hence be primarily achieved through variation of the stiffness and camber characteristics. These key attributes have been characterised at on-snow temperatures through laboratory testing of selected snowboard models, with relevant data ranges spanning the major riding styles shown in Table 33.

Table 33: Snowboard stiffness and camber characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Data Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shovel bending stiffness (avg)</td>
<td>N.m²</td>
<td>37.7 – 50.8</td>
</tr>
<tr>
<td>Body bending stiffness (avg)</td>
<td>N.m²</td>
<td>216.4 - 249.9</td>
</tr>
<tr>
<td>Heel bending stiffness (avg)</td>
<td>N.m²</td>
<td>37.4 – 49.8</td>
</tr>
<tr>
<td>Body torsional stiffness (avg)</td>
<td>N.m²</td>
<td>196.2 - 283.3</td>
</tr>
<tr>
<td>Camber</td>
<td>mm</td>
<td>7.7 – 11.5</td>
</tr>
</tbody>
</table>

A user-centred snowboard design customisation approach has been devised

An in-depth examination of the objective properties and on-snow performance data of the selected test snowboards has facilitated the formulation of a prototype snowboard performance prediction model. The ability to predict snowboard performance prior to manufacture will allow customisation of snowboard designs for specific performance objectives, resulting in higher customer satisfaction levels. It would also reduce the overall cost and time of the snowboard design process, which is currently plagued by trial and error.

The developed model uses any discrete set of objective design parameters together with user characteristics of height, weight and foot size to predict the on-snow performance of
the design. Two different performance prediction measures were implemented in the model. The first is a correlation based measure, which utilises individual Spearman ranked correlations between the objective design parameters and subjective performance parameters determined in this research. Conversely, the second exponent based performance measure uses three key objective design attributes to estimate each subjective performance parameter. The complete performance prediction model was validated against the subjective and objective data collected in the research, and was shown to predict the performance of the snowboards tested to an acceptable level of accuracy. To increase the confidence in the model as a general predictive and performance comparison tool for any snowboard design, further datasets need to be incorporated into the model. It is however a strong methodological basis for snowboard design customisation with respect to the desired performance and feel experienced within the major riding styles.

In order to generate the required performance prediction model inputs of body bending/torsional stiffness and mass at the design level, a computational prediction code has been developed to calculate these properties for any snowboard sandwich composite structure that utilises common fabric configurations. A geometric unit-cell approach is employed to predict the overall fibre volume fraction, average tow undulation and areal weight for the fabric layers, which are crucial properties for the strength and stiffness of any manufactured composite part. Effective elastic properties are calculated using a modified Hashin’s cylinder model to incorporate the effects of tow undulation or stitching, together with common coordinate transformations and volumetric averaging methods. Laminate beam theory is applied to calculate the key stiffness properties along the chord for the full snowboard composite sandwich, including consideration of the topsheet, base layer, sidewall and edges. The overall snowboard mass is calculated using the respective densities and geometry of the various elements comprising the snowboard structure.

Furthermore, the code also generates an estimation of the changes to stiffness and camber properties of any snowboard structure for a specified temperature differential. This allows the effect of on-snow temperature on the performance of any snowboard to also be predicted during the design phase. Standard thermal strain and curvature calculations for composite structures are employed to assess the average curvature and hence camber change over the entire snowboard chord. Conversely, the effect of temperature on snowboard stiffness properties is calculated through appropriate modification of the
various input moduli for the base, composite, core and topsheet layers of the sandwich composite.

The developed thermo-mechanical prediction model represents a useful tool for the calculation of the stiffness and thermal properties for any snowboard sandwich composite structure. It allows the effects of variations of thermal and mechanical properties, geometry and composite architecture to be determined easily through appropriate input parameter modification, without the need for a lengthy finite element analysis. The model was validated through the manufacture and static testing of three sandwich composite samples of different structure and geometry, and was shown to predict the key objective properties of bending/torsional stiffness, camber change and mass within reasonable error bounds. Therefore, it provides an alternative to more complex and time consuming CAD/FEA models for the analysis of snowboard sandwich composites for each design option, particularly considering the difficulty in manufacturing composite parts that consistently comply with strict performance targets.

Table 34 summarises the process for the design, analysis, manufacture and testing of customised snowboards within the major riding styles utilising the developed performance prediction models and thermo-mechanical code. It includes the specification of all required rider inputs, together with the methods, analyses and information drawn from the current research. For the preliminary design phase, the personal characteristics of the rider must initially be noted, which consists of height (m), mass (kg) and foot size (US). The rider’s performance requirements for the customised snowboard are also inputs of this step, including the ideal levels and importance (both on a scale of 1 – 10) of the defined subjective performance parameters (refer to Section 2.1). All of this information is then fed into a multi-variable optimisation routine (such as ModeFrontier) to generate the optimal matrix of objective design parameters (refer to Section 2.2 and Chapter 6). The optimisation software should be linked to both the linear correlation and exponent based performance prediction models (refer to Section 4.1 and Chapter 6), together with the objective parameter scaling method summarised in Table 19 to find a design solution that best meets the performance targets of the rider.

As shown in Table 34, after the optimisation stage the rider must analyse the predicted performance of the proposed design to determine whether it sufficiently meets the specified subjective parameter levels. If the performance targets are not adequately met, the rider may then decide to vary the input importance or ideal level values and then re-
conduct the optimisation process. Alternatively, the rider may also decide to make minor modifications to the proposed set of objective design parameters to assess the effects of such changes on the predicted performance of the snowboard.

Conversely, if the proposed design is now satisfactory from a performance standpoint, suitable materials and cross-sectional geometry are selected for the constituent layers of the snowboard. The mechanical properties of the materials chosen must match relevant optimised objective design parameter values, such as the edge material and base material parameters. For the calculation of complex derived snowboard properties such as the bending/torsional stiffness distributions and mass, the computational models formulated in this research are utilised (see Section 4.2). Matching the outputs of the stiffness and mass prediction models to the relevant optimal design parameter values (such as the body bending and torsional stiffness) is a difficult process due to the number of input variables, and a further optimisation routine may be required (not shown in Table 34).

The generated design parameters and materials selected must then be analysed from a manufacturing perspective, to assess feasibility of the proposed geometry and mechanical characteristics. Unsuitable or illogical objective parameter values (geometry and materials) must be modified, and the design may then require a re-analysis of its predicted performance. If the proposed matrix of design parameters is completely unfeasible, the specified importance and ideal performance levels may have to be revisited and the design process repeated.

Once the proposed design is satisfactory from a performance and feasibility of manufacture perspective, it can be constructed using the usual methods employed for sandwich composites such as hand/wet lay-up or curing pre-impregnated layers in an oven or autoclave. The manufactured snowboard must then be tested on-snow (refer to Section 2.1) to ensure it meets the feel and performance requirements of the rider.

Whilst the described design process is multi-faceted, the time and resources utilised are considerably reduced compared to the existing design methodologies, which are highly experimental and possess significant trial and error. The information, methodologies and analytical tools developed in this research would hence be highly useful for modern snowboard manufacturers. Furthermore, the customised snowboard designs made possible using this process could potentially increase user satisfaction across the product market and improve on-snow rider performance.
<table>
<thead>
<tr>
<th>Phase</th>
<th>Inputs</th>
<th>Information/Methods Utilised</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary design generation</td>
<td>• User characteristics&lt;br&gt;• Performance requirements&lt;br&gt; (refer to Sections 2.1 and 4.1)</td>
<td>• Linear correlation prediction model&lt;br&gt;• Exponent based prediction model&lt;br&gt;• Objective parameter scaling method&lt;br&gt;• Multi-variable optimisation routine&lt;br&gt; (refer to Section 4.1 and Chapter 6)</td>
<td>• Initial parametric design solution&lt;br&gt; (refer to Section 2.2 and Chapter 6)</td>
</tr>
<tr>
<td>Design analysis and refinement</td>
<td>• User characteristics&lt;br&gt;• Performance requirements&lt;br&gt;• Initial parametric design solution</td>
<td>• Linear correlation prediction model&lt;br&gt;• Exponent based prediction model&lt;br&gt;• Objective parameter scaling method&lt;br&gt;• Multi-variable optimisation routine</td>
<td>• Refined parametric design solution</td>
</tr>
<tr>
<td>Layer architecture design and analysis</td>
<td>• Layer material properties&lt;br&gt;• Cross-sectional geometry&lt;br&gt;• Refined parametric design solution</td>
<td>• Stiffness prediction model&lt;br&gt;• Mass prediction model&lt;br&gt; (refer to Section 4.2)</td>
<td>• Detailed parametric design solution</td>
</tr>
<tr>
<td>Manufacturability analysis</td>
<td>• Detailed parametric design solution</td>
<td>• Stiffness and mass prediction models&lt;br&gt; • Performance prediction models</td>
<td>• Final parametric design solution</td>
</tr>
<tr>
<td>Snowboard manufacture</td>
<td>• Final parametric design solution&lt;br&gt;• Layer materials</td>
<td>• Standard composite manufacturing procedure</td>
<td>• Customised snowboard</td>
</tr>
<tr>
<td>On-snow testing</td>
<td>• Customised snowboard&lt;br&gt;• On-snow testing course</td>
<td>• On-snow testing and assessment procedure&lt;br&gt; (refer to Section 2.1)</td>
<td>• Subjective performance ratings</td>
</tr>
</tbody>
</table>
It has been confirmed that there is no absolute optimal in snowboard design

The various qualitative and quantitative analyses conducted in this research have demonstrated that ‘optimal feel’ of the snowboard is highly user specific, depending on preferred riding style, personal characteristics such as height, weight and foot size, and most importantly, performance requirements of the rider. Thus there is no absolute optimal in snowboard design, only user-dependent optimality, which underlines the importance of design customisation to achieve rider satisfaction.

Furthermore, the design optimisation process conducted in this research (with respect to desired performance levels specified by the expert focus group) demonstrated that many performance facets of the snowboard are mutually exclusive. Thus, the matrix of performance requirements specified by the user may not be attainable through variation of the objective design parameters comprising any modern snowboard. Certain areas of performance would therefore need to be sacrificed to generate a design solution, with a user-specific optimal design dependent on the importance placed on satisfying the desired level of each subjective performance parameter.

Overall, the knowledge-base developed by the research will provide a novel technological platform for design customisation of modern snowboards for desired feel over the major riding styles. Specifically, a new, systematic method to characterise snowboard performance from the standpoint of the rider has been determined, using easily discerned non-technical parameters which are rated using a universal 1 – 10 rating system. This method allows snowboard performance reviews and rider requirements to now be easily and systematically conveyed to snowboard manufacturers, improving the overall snowboard design process. The evaluation of these performance parameters for modern snowboards including their subjectivity, importance to each style and links between them has also increased the knowledge available to snowboard designers to target specific performance areas in new prototype models, facilitating an increase in user satisfaction.

The modern snowboard structure has been deconstructed in this research into objective design parameters, improving on the available published standard and limited existing technical literature. Simple standard procedures for determination of bending and torsional stiffness distributions have also been formulated. The knowledge hence provides a new benchmark for future parametric design and analysis of modern snowboards. Identification and characterisation of the design parameters crucial to the feel of snowboards across the
major riding styles also provides highly useful knowledge for designers to manipulate the on-snow feel of new snowboard models. The gap identified in the current snowboard market using MoM could also be used by snowboard manufacturers to develop new prototype models that exploit this opportunity.

The developed novel parametric snowboard design model allows the performance of new snowboard designs to be systematically predicted prior to manufacture, which was not possible to the same extent using the pre-existing knowledge-base. It could thus potentially be a highly useful new design tool for snowboard manufacturers to minimise the trial and error approach currently plaguing snowboard design, resulting in significant cost and time savings. Furthermore, the design guidelines formulated would allow the customisation of modern snowboards to specific rider requirements, increasing user satisfaction in the product and improving on-snow rider performance.
REFERENCES


APPENDIX A: SURVEY ONE CONTENT

1. WELCOME

This survey has been designed for experienced snowboarders to test and rate boards currently available on the market.

The results will be used to aid research on snowboard design in relation to different riding styles and terrains. It is stressed that all data entered will remain entirely confidential and only be used for research purposes by the School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, Australia.

The survey covers all areas of riding, from straight line boarding, to carving turns, as well as the performance of tricks. It requires the rider to have a good understanding of the dynamic performance of their board and where its strengths and limitations lie.

Each section begins with a description of the snowboarding parameters that are being tested. The rating system for each feature consists of the following:

• Whether the feature is too low, too high or optimal
• A numbered assessment from 1-10
• An importance rating from 1-10

The survey should take approximately 15 minutes to complete and if you have any queries, do not hesitate to contact us.

Thank you very much for your contribution.

Regards

Patrick Clifton          Jordi Beneyto Ferre
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2. RIDER AND BOARD DETAILS

Sex:
- Male
- Female

Boarding experience (years):
- 0-1
- 2-3
- 4-7
- 8-10
- 11+

Weight:
- Under 50 kg (110 lbs)
- 50-59 kg (110-130 lbs)
- 60-69 kg (131-152 lbs)
- 70-79 kg (153-174 lbs)
- 80-89 kg (175-196 lbs)
- 90-99 kg (197-218 lbs)
- 100+ kg (219+ lbs)

Height:
- Under 150 cm (5'0)
- 150-159 cm (5'0-5'3)
- 160-169 cm (5'4-5'7)
- 170-179 cm (5'8-5'11)
- 180-189 cm (6'0-6'3)
- 190-199 cm (6'4-6'7)
- 200+ cm (6'8+)

What style(s) of boarding are you primarily interested in? (Choose 1 or more):
- Freestyle
- Freeride/All Mountain
- Freecarve/Alpine
- Other (please specify)
**Current board details:**

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>Length</th>
<th>Year</th>
</tr>
</thead>
</table>

Do you use an extra-wide model?

- Yes
- No

**Board condition:**

- New
- Excellent
- Good
- Poor

**Time since last board waxing (weeks):**

- Less than 1
- 1-5
- 6-10
- 11+

**How many different boards have you owned to date?**

- 1
- 2
- 3
- 4
- 5
- 6
- 7+

List your 5 previous boards (Make/Model/Year):
(If applicable)

1
2
3
4
5

If possible, would you consider upgrading your board?

Yes  No

Desired board details:
(If applicable)

Make
Model

Current binding details:

Make
Model
Year
Rate the influence of the factors below in the decision to purchase your current board:

<table>
<thead>
<tr>
<th>Factor</th>
<th>None</th>
<th>Low</th>
<th>Average</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall performance (ie carving, edge grip, speed, board pop etc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aesthetics (visual appeal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brand reputation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technological innovation (ie shape, materials, vibration control)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Any additional comments on why you purchased this particular board:


How would you define the following terms in relation to a snowboard?

Feel

Performance

Snow Condition:

- Groomed
- Powder
- Ice
- Slush
- Other
### 3. OVERALL PERFORMANCE

This section rates the board's overall performance, from straight line boarding, to carve turns and the performance of tricks. Note the following definitions:

- **Stability** = How stable the rider feels on the board.
- **Feedback** = The amount of stress felt on the rider's body including the effects of board chatter.
- **Speed** = The gliding speed of the board compared to other boards of similar length.
- **Accuracy** = The precision of board movement in response to rider input.
- **Forgiveness** = The tolerance of the board to errors from the rider.
- **Edge Grip** = The level of grip exhibited during turns.
- **Manoeuvrability** = How easily the board responds to rider inputs.
- **Transition smoothness** = How easily the board flows from edge to edge.
- **Board Liveliness** = The level of ‘pop’ or spring in the board when performing a jump.

Rate the board's overall performance under the following headings:

(Note: 10 = High, 1 = Low)

<table>
<thead>
<tr>
<th></th>
<th>Rating</th>
<th>Assessment Index</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedback</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forgiveness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge grip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transition smoothness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoothness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Board Liveliness</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rate the overall performance of the board:
(Note: 10 = Optimal, 1 = Poor)

Any additional comments regarding board performance:
APPENDIX B: SURVEY TWO CONTENT

1. WELCOME BACK

First of all we would like to thank you for your fantastic contribution to the first snowboard survey. Your valuable results and feedback will be indispensable to our research.

Due to the high quality of your answers in the first survey, we are hoping for further input on your part, this time a little more specific. This second release is aimed at discovering what YOU as a consumer and boarder would want to see in snowboards across the various riding styles.

We are no longer asking you for feedback on your current snowboard, we want to know what your experience riding snowboards has taught you about boards in general, and particularly what the current boards on the market are lacking that hinders your riding. Your responses will hopefully allow us to develop new design concepts that satisfy everything that you would like to see on a snowboard.

This time the survey has been divided into two parts based on the current dominant snowboarding styles, FREERIDE/ALL MOUNTAIN and FREESTYLE.

Please do not hesitate to contact us if you have any questions or suggestions about this survey.

Thank you very much for your continued contribution.

Regards

Patrick Clifton           Jordi Beneyto Ferre
PhD Research Student     Masters Research Student
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RMIT University
Melbourne, Australia
2. FREESTYLE

Note the following definitions (please use these parameters if possible in answering the questions below):

Stability = How stable the rider feels on the board.
Feedback = The amount of stress felt on the rider's body including the effects of board chatter.
Speed = The gliding speed of the board compared to other boards of similar length.
Accuracy = The precision of board movement in response to rider input.
Forgiveness = The tolerance of the board to errors from the rider.
Edge Grip = The level of grip exhibited during turns.
Manoeuvrability = How easily the board responds to rider inputs.
Transition smoothness = How easily the board flows from edge to edge.
Board Liveliness = The level of 'pop' or spring in the board when performing a jump.

1. What is the main characteristic or feature that you look for in a Freestyle board? (Using the above parameters if possible)

2. What is the main characteristic or feature that you've found has been missing in the Freestyle boards you have tried? (Using the above parameters if possible)

3. Have you ever felt that your board didn’t allow you to progress with your Freestyle technique?
   - Yes
   - No

   If so, why?

   (You may type your answer here.)
4. What is the best feature of your Freestyle board?
(Using the above parameters if possible

5. What is the worst feature of your Freestyle board?
(Using the above parameters if possible

6. What would you modify on your Freestyle board to improve its performance (ie edges, geometry, stiffness, etc)?

7. Please evaluate the IMPORTANCE of the following parameters on a Freestyle board.
(10 = High importance, 1 = Low importance)

Stability
Feedback
Speed
Accuracy
Forgiveness
Edge Grip
Manoeuvrability
Transition
Smoothness
Board Liveliness
8. Please evaluate the IDEAL LEVEL of the following parameters on a Freestyle board. (Eg for Stability, 10 = High stability, 1 = Low stability)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td></td>
</tr>
<tr>
<td>Feedback</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
</tr>
<tr>
<td>Forgiveness</td>
<td></td>
</tr>
<tr>
<td>Edge Grip</td>
<td></td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td></td>
</tr>
<tr>
<td>Transition</td>
<td></td>
</tr>
<tr>
<td>Smoothness</td>
<td></td>
</tr>
<tr>
<td>Board Liveliness</td>
<td></td>
</tr>
</tbody>
</table>

9. Have we overlooked any parameters in the previous questions?

- Yes
- No

If so, please identify them, as well as their position in the importance list and their ideal level for Freestyle boards.
3. FREERIDE/ALL MOUNTAIN

Note the following definitions (please use these parameters if possible in answering the questions below):

*Stability* = How stable the rider feels on the board.

*Feedback* = The amount of stress felt on the rider's body including the effects of board chatter.

*Speed* = The gliding speed of the board compared to other boards of similar length.

*Accuracy* = The precision of board movement in response to rider input.

*Forgiveness* = The tolerance of the board to errors from the rider.

*Edge Grip* = The level of grip exhibited during turns.

*Manoeuvrability* = How easily the board responds to rider inputs.

*Transition smoothness* = How easily the board flows from edge to edge.

*Board Liveliness* = The level of 'pop' or spring in the board when performing a jump.

1. What is the main characteristic or feature that you look for in a Freeride/All Mountain board? (Using the above parameters if possible)

2. What is the main characteristic or feature that you've found has been missing in the Freeride/All Mountain boards you have tried? (Using the above parameters if possible)

3. Have you ever felt that your board didn’t allow you to progress with your Freeride/All Mountain technique?

   - Yes
   - No

   If so, why?

   [Blank space for answer]
4. What is the best feature of your Freeride/All Mountain board?
(Using the above parameters if possible)

5. What is the worst feature of your Freeride/All Mountain board?
(Using the above parameters if possible)

6. What would you modify on your Freeride/All Mountain board to improve its performance
(ie edges, geometry, stiffness, etc)?

7. Please evaluate the IMPORTANCE of the following parameters on a Freeride/All Mountain board. (10 = High importance, 1 = Low importance)

   - Stability
   - Feedback
   - Speed
   - Accuracy
   - Forgiveness
   - Edge Grip
   - Manoeuvrability
   - Transition
   - Smoothness
   - Board Liveliness
8. Please evaluate the IDEAL LEVEL of the following parameters on a Freeride/All Mountain board. (Eg for Stability, 10 = High stability, 1 = Low stability)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td></td>
</tr>
<tr>
<td>Feedback</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
</tr>
<tr>
<td>Forgiveness</td>
<td></td>
</tr>
<tr>
<td>Edge Grip</td>
<td></td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td></td>
</tr>
<tr>
<td>Transition</td>
<td></td>
</tr>
<tr>
<td>Smoothness</td>
<td></td>
</tr>
<tr>
<td>Board Liveliness</td>
<td></td>
</tr>
</tbody>
</table>

9. Have we overlooked any parameters in the previous questions?
- Yes
- No

If so, please identify them, as well as their position in the importance list and their ideal level for Freeride/All Mountain boards.
### APPENDIX C: SUBJECTIVE - OBJECTIVE PARAMETER CORRELATIONS

**Table 35: Subjective-objective parameter correlations**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stability</th>
<th>Manoeuvrability</th>
<th>Accuracy</th>
<th>Edge Grip</th>
<th>Feedback</th>
<th>Forgiveness</th>
<th>Speed</th>
<th>Board Liveliness</th>
<th>Transition Smoothness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length</td>
<td>1.00</td>
<td>0.50</td>
<td>1.00</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>Contact length</td>
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<td>Projected length</td>
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<td>1.00</td>
<td>-0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>Shovel length</td>
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<td>1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Shovel radius</td>
<td>-0.50</td>
<td>-1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>-0.50</td>
</tr>
<tr>
<td>Tip height</td>
<td>0.50</td>
<td>1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Shovel width</td>
<td>-1.00</td>
<td>-0.50</td>
<td>-1.00</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
<td>-1.00</td>
</tr>
<tr>
<td>Heel length</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
</tr>
<tr>
<td>Heel radius</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
</tr>
<tr>
<td>Tail height</td>
<td>0.50</td>
<td>1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Heel width</td>
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<td>-0.50</td>
<td>-1.00</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
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</tr>
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<td>-1.00</td>
<td>0.50</td>
<td>-1.00</td>
</tr>
<tr>
<td>Sidecut radius</td>
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<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Body thickness</td>
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<td>0.50</td>
<td>1.00</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>Shovel thickness</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
</tr>
<tr>
<td></td>
<td>Stability</td>
<td>Manoeuvrability</td>
<td>Accuracy</td>
<td>Edge Grip</td>
<td>Feedback</td>
<td>Forgiveness</td>
<td>Speed</td>
<td>Board Liveliness</td>
<td>Transition Smoothness</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------</td>
<td>-----------------</td>
<td>----------</td>
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<td>----------</td>
<td>-------------</td>
<td>-------</td>
<td>------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Heel thickness</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
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</tr>
<tr>
<td>Camber</td>
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<td>0.50</td>
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</tr>
<tr>
<td>Shovel bending stiffness</td>
<td>-0.50</td>
<td>0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
</tr>
<tr>
<td>Body bending stiffness</td>
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<td>1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Heel bending stiffness</td>
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<td>0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
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</tr>
<tr>
<td>Body torsional stiffness</td>
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<td>0.50</td>
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<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Mass</td>
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<td>-0.50</td>
<td>-1.00</td>
<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>-1.00</td>
<td>0.50</td>
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</tr>
<tr>
<td>Shovel core material</td>
<td>-0.50</td>
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<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
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<td>-0.50</td>
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<tr>
<td>Body core material</td>
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<td>0.50</td>
<td>0.50</td>
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<td>-1.00</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Heel core material</td>
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<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
<td>-0.50</td>
<td>1.00</td>
<td>-0.50</td>
</tr>
<tr>
<td>Base material</td>
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<td>0.87</td>
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<td>0.87</td>
<td>-0.87</td>
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</tr>
</tbody>
</table>
## APPENDIX D: SUBJECTIVE PARAMETER CORRELATIONS

### Table 36: Subjective parameter correlations

<table>
<thead>
<tr>
<th>Stability</th>
<th>Manoeuvrability</th>
<th>Accuracy</th>
<th>Edge Grip</th>
<th>Feedback</th>
<th>Forgiveness</th>
<th>Speed</th>
<th>Board Liveliness</th>
<th>Transition Smoothness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manoeuvrability</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>1</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge Grip</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedback</td>
<td>-0.5</td>
<td>0.5</td>
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<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forgiveness</td>
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<td>-1</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>Board Liveliness</td>
<td>-0.5</td>
<td>0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td>1</td>
<td>-0.5</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>Transition Smoothness</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>-0.5</td>
<td>-0.5</td>
<td>1</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
APPENDIX E: FABRIC CONFIGURATIONS

Unidirectional

The unidirectional fabric schematic is shown in Figure 45, with characteristic geometry defined by Equations 146 – 150. All parameters utilised are as defined previously (see Section 4.2), where $h$ and $w$ are the height and width respectively of the fabric unit cell, whilst $s^A$, $L_s^A$, $V^A$, $A^A$ and $t^A$ represent the axial tow spacing, span, volume within the unit cell, cross-sectional area and thickness, respectively.

\[
h = s^A \tag{146}
\]

\[
w = s^A \tag{147}
\]

\[
L_s^A = h = s^A \tag{148}
\]

\[
V^A = L_s A^A = s^A A^A \tag{149}
\]

\[
f = \frac{V^A}{h w t^A} = \frac{s^A A^A}{s^A s^A t^A} = \frac{A^A}{s^A t^A} \tag{150}
\]
2x2 Bi-Axial Braid

The unit cell schematic, cross-section (showing fill tow undulation) and characteristic equations for the 2x2 bi-axial braid configuration are shown in Figures 46 and 47, and Equations 151 – 158 below. The cross-section for warp tow undulation (not shown) is identical to Figure 47 with the superscripts $F$ and $W$ interchanged.

![Figure 46: 2x2 bi-axial braid schematic](image)

\[
h = \frac{4s^F}{2\sin\theta}
\]  

(151)

\[
w = \frac{4s^W}{2\sin\theta}
\]  

(152)

\[
L_s^F = \frac{w}{2} = \frac{2s^W}{\sin2\theta}
\]  

(153)

\[
u^F = \frac{t^W}{2}
\]  

(154)

\[
V^F = 8L_u^F A^F
\]  

(155)

And similarly, for warp tow undulation the characteristic equations are:

\[
L_s^W = \frac{h}{2} = \frac{2s^F}{\sin2\theta}
\]  

(156)
\[ u^W = \frac{t^F}{2} \]  
(157)

\[ V^W = 8l_u^W A^W \]  
(158)

Where in Equations 151 – 158, as per previous (see Section 4.2) \( h \) and \( w \) are the height and width respectively of the fabric unit cell, \( s^F \) and \( s^W \) are the fill and warp tow spacing, \( \theta \) is the braid angle, \( L_s^F \) and \( L_s^W \) are the fill and warp tow spans, \( u^F \) and \( u^W \) are the fill and warp tow undulation amplitudes, \( t^F \) and \( t^W \) are the fill and warp tow thicknesses, \( L_u^F \) and \( L_u^W \) are the fill and warp tow undulation lengths, \( A^F \) and \( A^W \) are the fill and warp tow cross-sectional areas, whilst \( V^F \) and \( V^W \) are the fill and warp tow volumes. In Figure 47, \( \phi^F \) and \( r^F \) (as per previous) represent the undulation angle and radius of curvature of the fill tows.

Figure 47: 2x2 bi-axial braid cross-section
1x1-A Tri-Axial Braid

The unit cell schematic, cross-section (showing fill tow undulation) and characteristic equations for the 1x1-A tri-axial braid configuration are shown in Figures 48 and 49, and Equations 159 – 167 below. The cross-section for warp tow undulation (not shown) is identical to Figure 49 with the superscripts $F$ and $W$ interchanged.

![Figure 48: 1x1-A tri-axial braid schematic](image)

\[ h = \frac{s^A}{\tan \theta} \]  
(159)

\[ w = s^A \]  
(160)

\[ s^F = s^W = s^A \cos \theta \]  
(161)

\[ L_s^F = L_s^W = \frac{h}{2 \cos \theta} = \frac{s^A}{2 \sin \theta} \]  
(162)

\[ u^F = \frac{t^A}{4} + \frac{t^W}{2} \]  
(163)

\[ u^W = \frac{t^A}{4} + \frac{t^F}{2} \]  
(164)

\[ V^A = hA^A \]  
(165)
\[ V^F = 2L^F u^F \] (166)

\[ V^W = 2L^W u^W \] (167)

Where \( s^{F,W} \) in Figure 48 refers to fill and warp tow spacing, whilst all remaining parameters utilised in Figures 48 and 49, as well as Equations 159 – 167 are as defined previously.

Figure 49: 1x1-A tri-axial braid cross-section
1x1-E Tri-Axial Braid

The unit cell schematic, cross-section (showing fill tow undulation) and characteristic
equations for the 1x1-E tri-axial braid configuration are shown in Figures 50 and 51, and
Equations 168 – 176 below. The cross-section for warp tow undulation (not shown) is
identical to Figure 51 with the superscripts $F$ and $W$ interchanged.

Figure 50: 1x1-E tri-axial braid schematic

\[
h = \frac{2s^A}{\tan \theta} \quad (168)
\]

\[
w = 2s^A \quad (169)
\]

\[
s^F = s^W = 2s^A \cos \theta \quad (170)
\]

\[
L_s^F = L_s^W = \frac{h}{2 \cos \theta} = \frac{s^A}{\sin \theta} \quad (171)
\]

\[
u^F = \frac{t}{2} - \frac{t^F}{2} \quad (172)
\]

\[
u^W = \frac{t}{2} - \frac{t^W}{2} \quad (173)
\]

\[
V^A = 2hA^A \quad (174)
\]
Where $t$ in Equations 172 and 173 refers to the overall thickness of the fabric composite, whilst all remaining parameters utilised in Figures 50 and 51, as well as Equations 168 – 176 are as defined previously.
2x2 Tri-Axial Braid

The unit cell schematic, cross-section (showing fill tow undulation) and characteristic equations for the 2x2 tri-axial braid configuration are shown in Figures 52 and 53, and Equations 177 – 185 below. The cross-section for warp tow undulation (not shown) is identical to Figure 53 with the superscripts \( F \) and \( W \) interchanged.

**Figure 52**: 2x2 tri-axial braid schematic

\[
h = \frac{s^A}{\tan \theta} \quad \text{(177)}
\]

\[
w = 2s^A \quad \text{(178)}
\]

\[
s^F = s^W = s^A \cos \theta \quad \text{(179)}
\]

\[
L_s^F = L_s^W = \frac{h}{\cos \theta} = \frac{s^A}{\sin \theta} \quad \text{(180)}
\]

\[
u^F = \frac{t^F}{2} - \frac{t^F}{2} \quad \text{(181)}
\]

\[
u^W = \frac{t^W}{2} - \frac{t^W}{2} \quad \text{(182)}
\]

\[
V^A = 2hA^A \quad \text{(183)}
\]

\[
V^F = 2L_u^F A^F \quad \text{(184)}
\]
\[ V^W = 2L_u^W A^W \] (185)

Where all parameters utilised in Figures 52 and 53, as well as Equations 177 – 185 are as defined previously.

**Figure 53:** 2x2 tri-axial braid cross-section
Tri-Axial Weave

The unit cell schematic, cross-section (showing fill tow undulation) and characteristic equations for the tri-axial weave configuration are shown in Figures 54 and 55, and Equations 186 – 198 below. The cross-section for warp and axial tow undulation (not shown) is identical to Figure 55 with the superscripts $F, W$ and $A$ interchanged.

![Tri-axial weave schematic](image)

**Figure 54:** Tri-axial weave schematic

\[
h = s^A \tag{186}
\]

\[
w = s^A \sin 60 \tag{187}
\]

\[
s^F = s^W = s^A \tag{188}
\]

\[
L_s^A = L_s^F = L_s^W = \frac{w}{2} = \frac{s^A \sin 60}{2} \tag{189}
\]

\[
u^A = \frac{t^F}{4} + \frac{t^W}{4} \tag{190}
\]

\[
u^F = \frac{t^A}{4} + \frac{t^W}{4} \tag{191}
\]
\[ u^W = \frac{t^A}{4} + \frac{t^F}{4} \]  
(192)

\[ r^A = \frac{\left(\frac{t^A}{2}\right)^2 + (u^A)^2}{2u^A} \]  
(193)

\[ \phi^A = \sin^{-1}\left(\frac{t^A}{2r^A}\right) \]  
(194)

\[ L^A = 2r^A \phi^A \]  
(195)

\[ V^A = 2L^A A^A \]  
(196)

\[ V^F = 2L^F A^F \]  
(197)

\[ V^W = 2L^W A^W \]  
(198)

Where \( u^A, r^A, \phi^A \) and \( L^A \) are the undulating axial tow amplitudes, radius of curvature, undulation angle and undulation length, respectively, whilst all remaining parameters utilised in Figures 54 and 55, as well as Equations 186 – 198 are as defined previously.

**Figure 55:** Tri-axial weave cross-section
Bi-Axial Stitched

The unit cell schematic and characteristic equations for the bi-axial stitched configuration are shown in Figure 56 and Equations 199 – 202 below. All parameters utilised are as defined previously.

Figure 56: Bi-axial stitched schematic

\[ h = \frac{s^F}{\sin 2\theta} \]  
(199)

\[ w = \frac{s^W}{\sin 2\theta} \]  
(200)

\[ V^F = wA^F = \frac{s^W A^F}{\sin 2\theta} \]  
(201)

\[ V^W = hA^W = \frac{s^F A^W}{\sin 2\theta} \]  
(202)
Tri-Axial Stitched

The unit cell schematic and characteristic equations for the tri-axial stitched configuration are shown in Figure 57 and Equations 203 – 208 below. All parameters utilised are as defined previously.

![Tri-axial stitched schematic]

\[ h = \frac{2s^A}{\tan \theta} \quad (203) \]
\[ w = 2s^A \quad (204) \]
\[ s^F = s^W = 2s^A \cos \theta \quad (205) \]
\[ V^A = 2hA^A \quad (206) \]
\[ V^F = \frac{hA^F}{\cos \theta} \quad (207) \]
\[ V^W = \frac{hA^W}{\cos \theta} \quad (208) \]