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Physical Experimental Static Testing and Structural Design Optimisation for a Composite Wind Turbine Blade

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Abstract

This study presents experimental testing on a 13 m long glass-fibre epoxy composite wind turbine blade. The results of the test were used to calibrate finite element models. A design optimisation study was then performed using a genetic algorithm. The goal of the optimisation was to minimise the material used in blade construction and, thereby, reduce the manufacturing costs. The thickness distribution of the composite materials and the internal structural layout of the blade were considered for optimisation. Constraints were placed on the objective based on the stiffness of the blade and the blade surface stresses. A variable penalty function was used with limits derived from the blade test and the structural layout of the turbine. The model shows good correspondence to the test results (blade mass within 6% and deflection within 9%) and the differences between test and model are discussed in detail. The genetic algorithm resulted in five optimal blade designs, showing a reduction in mass up to 24%. Structural modelling in combination with numerical search algorithms provide a powerful tool for designers and demonstrates that the reader can have confidence in the claimed potential savings when the reference blade models are calibrated against physical test data.

Keywords: optimisation, genetic algorithm, FRP composites, Puck criterion, structural testing, wind turbine

1 Introduction

Even as the scale of wind turbine blades is reaching for and exceeding the 60 m, mark there is considerable demand for medium-sized turbines. A recent review [1] of the current wind energy sector placed emphasis on the advantages of smaller scale wind turbines. The authors claim that smaller scale turbines are suitable for meeting domestic and commercial energy needs in a grid system that has less local environmental impact than large scale wind farms. The blade under investigation in this study is 13 m in length for a 225 kW rated turbine, placing the turbine in the medium commercial range of device size. One of the major disadvantages for smaller wind turbines is the high initial and maintenance costs, a major component of which is the blades. A combination of structural testing and finite element (FE) modelling can be used to help reduce these costs through improvements to the blade design.

Full-scale structural testing is used in the blade certification process to help ensure a reliable and secure blade design. The IEC 61400-23 [2] international standard for testing provides an outline of the structural design requirements that blades must meet. A primary requirement for the blades, and the one that is the focus of the present study, is the structural response under static loading. A number of

41 authors have presented results from such static blade testing. Overgaard et al [3] performed a static
42 test to collapse of a 34 m wind turbine blade in order to investigate the ultimate failure modes. Yang
43 et al [4] performed similar testing to failure for a 40 m wind turbine blade and found that a complex
44 series of failure modes resulted from an initial debonding of the adhesive joints of the outer
45 aerodynamic shells. Larwood and Musial [5] report on static and fatigue structural testing of 12 m
46 blades, identifying several regions of the blades for failures quite early in the fatigue tests. The blades
47 are the key component in the turbines and failures in the blade structure are among the most common
48 failure types during operation [6]. Failures in the blades can lead to significant downtime for the
49 turbine and, due to the often remote location of wind turbines, it may not be a simple operation to
50 repair a damaged blade, or worse, replace one completely [7].

51 In addition to full-scale structural testing, computational modelling methods have the potential to
52 improve on standard blade designs. The most common form of modelling wind turbine blades uses
53 3D plane stress shell elements to represent the thin-walled composite laminates from which the blade
54 is comprised. The plane stress assumption is quite valid for wind turbine blades, except for complex
55 regions with significant through-thickness stresses such as the root-hub connection of the blade. Many
56 authors have taken this approach and used it to develop parametric blade models for investigating
57 various structural and aerodynamic aspects of the design. Bonnet and Dutton [8] demonstrated the
58 adaptability of the combination of the Python scripting language and Abaqus finite element software
59 in the generation of parametric blade models. Montesano et al [9] developed a methodology
60 incorporating micromechanical material modelling and continuum damage mechanics and showed
61 how parameters such as chord length and twist angle of the blade can affect the damage distribution.
62 Vucina et al [10] have developed a methodology for the custom shape design of wind turbine blades
63 to achieve maximum energy production. This approach to modelling has been shown to be robust,
64 demonstrating good correspondence between tests and models [11] [12], and can investigate various
65 aspects of blade structural and aerodynamic design.

66 The modelling methods presented in this study have been developed from a tidal turbine blade design
67 methodology [13], [14]. The methodology generates parametric FE models of blades from basic
68 design information, such as chord length, twist angle and aerodynamic load distributions. In order to
69 assess the risk of failure, the FE models include a check for fibre failure and inter-fibre matrix failure
70 based on the Puck failure criterion. The criterion is a ply-level (meso-scale) analysis and consists of
71 five multi-axial stress interaction equations which define failure surfaces for the different failure
72 modes [15]. The criterion defines three modes of failure for matrix cracking, depending on the
73 combination of transverse and shear stress in the ply. Some failure modes, such as matrix cracking,
74 are often tolerable in a structure. However, the failure mechanisms can induce local deterioration in
75 the laminates which can act as the starting point for more serious failures, e.g. matrix cracking leading
76 to local delaminations [16]. The failure analysis is performed by the user-defined subroutine UVARM
77 in the commercial FE program Abaqus for each elemental integration point.

78 In this paper, a genetic search algorithm is used for the structural optimisation task to take advantage
79 of the parametric models, and the large design space they represent. Genetic algorithms effectively
80 provide a directed random search through a complex design space [17]. The directed aspect is due to
81 the user-defined objective function which is a measure of preference of one design over another. The
82 effectiveness of this optimisation method for complex composite laminates has been demonstrated
83 over the last two decades. For example, it has been applied to problems of variable thickness
84 distribution in composite structures [18] and combinatorial problems with multiple materials and
85 varying fibre direction [19]. Some authors have focused specifically on wind turbine blades for
86 structural and aerodynamic design. Pourrajabian et al [20] focused closely on the aerodynamic effects

87 of varying blade designs, using beam theory for structural analysis to reduce computational effort.
88 Barnes and Morozov [21] investigated novel internal structural layouts for wind turbine blades in an
89 effort to reduce mass. Fischer et al [22] describe their tool for a multi-objective optimisation of the
90 annual energy production, blade mass and rotor thrust. These all demonstrate how optimisation tools
91 can be combined with aerodynamic, structural or power performance tools to study complex blade
92 design problems.

93 The goal of the present study is to apply a genetic search algorithm, aided with an advanced failure
94 analysis, to the problem of wind turbine blade structural design. The parametric blade models that
95 enable the design optimisation are first compared to the results from a static structural test of a 13 m
96 blade. The details of the test campaign are provided and the differences between model and test
97 results are investigated. The design features explored in the optimisation relate to the internal blade
98 structure and the thickness of the laminates used in the blade construction. The objective of the design
99 study is to reduce the mass of the wind turbine blade without degradation of the structural
100 performance.

101 **2 Methodology**

102 The design methodology is outlined in four parts:

- 103 (i) A description of the details of the wind turbine blade geometry.
- 104 (ii) An overview of the design loads and the mechanical test loads.
- 105 (iii) Details on the construction of the parametric FE models.
- 106 (iv) An explanation of the genetic algorithm and the details of its operation.

107 **2.1 Blade definition**

108 The wind turbine blade examined in this study is based on the Vestas V27 turbine with a standard
109 power rating of 225 kW. The blade was manufactured using a novel “one-shot” manufacturing
110 process [23]. Commonly, the manufacture of wind turbine blades involves producing several distinct
111 parts, which are then assembled together to form the blade. The one-shot approach involves
112 polymerising the entire structure, including the embedded metal inserts at the root, in one single
113 process, thereby eliminating the need for gluing. Further details on the advantages and disadvantages
114 of the one-shot process for the manufacture of large scale composite structures are available in the
115 review by Flanagan et al [23].

116 The blades are constructed from glass-fibre (GF) with a powder epoxy resin. Steel inserts in the root
117 of the blade provide a connection to the turbine hub. The blades follow the normal structural
118 convention for wind turbines with a box spar providing flexural and torsional stiffness and with the
119 aerodynamic outer shells forming the blade shape. The box spar is made up of the spar caps, with
120 unidirectional (UD) plies oriented along the length of the blade, and webs which provide shear
121 strength to the structure. The shear webs are constructed from triaxial layers of GF-epoxy; each
122 triaxial layer consists of the layup $[0^\circ / \pm 45^\circ]$ oriented to the length of the blade. In the FE analysis,
123 each triaxial layer is made up of three plies of UD, with the appropriate orientations applied. The
124 outer shell is composed of layers of the triaxial weave with an imbedded balsa core towards the tip.
125 Figure 1 shows the various regions in detail on a cross-section of the blade.

126 Table 1 reports the in-plane stiffness values for a unidirectional layer of the GF-epoxy material. Table
127 1 also indicates the material properties for the balsa wood core layer and the gelcoat. The balsa wood
128 increases the panel buckling resistance in the aerodynamic shell laminates and the gelcoat is used for

129 protecting the outer surface of the blade from environmental damage [24]. Table 2 shows the
130 composite layups for the three main sections of the blade, i.e. the spar caps region, the outer
131 aerodynamic shells and the shear webs. The number of unidirectional and triaxial plies at each radial
132 blade station are noted as well as the locations of the core material. The layups used in the
133 optimisation study take a more generic form and are detailed in full in Section 2.4.1.

134 A study by Sandia National Labs [25] on the costs associated with wind turbine blades indicated that,
135 for large wind turbine blades (30 m in length and greater), the combined costs of materials and labour
136 contributed approximately 68% to the total costs of each blade. The materials costs cover such items
137 as the unidirectional and double-bias glass-fibre mat materials, gelcoat for surface protection, balsa
138 core material, resin and the root attachment system. The labour costs were estimated based on the
139 work flow, labour hours and equipment requirements for manufacturing each of the separate blade
140 components, assembling the blade, finishing, inspection, shipping and testing of the blade. The
141 remaining 28% of the total overall blade costs were associated with design development,
142 manufacturing plant overhead and blade transportation. This figure for costs of materials and labour
143 has been confirmed to be accurate with respect to the blade under investigation in the present study
144 and was used to determine the total percentage saving per blade achieved by the optimisation
145 methodology.

146 Table 3 outlines the geometry of the blade and includes the radial distributions of the chord length,
147 twist angle, aerodynamic profiles and blade thickness. The centreline of the spar caps is located at
148 approximately 32% of the chord length along the entire length of the blade. All of the necessary
149 details to model the blade were determined either from the masters theses of Mohamed [26] and
150 Froyd [27] or correspondence with the industrial partner.

151 **2.2 Test and load definition**

152 Structural testing of wind turbine blades involves applying an equivalent mechanical load to match
153 the aerodynamic loading the blade experiences during operation. In typical static testing, the loads are
154 applied via weights, cranes, hydraulic or electronic actuators connected to the blade at a number of
155 load points [28]. The greater the number of load points, the more accurately the bending moment
156 distribution is reproduced. Figure 2 shows the set-up for the static test performed on the 13 m wind
157 turbine blade. In this set-up, two blades are mounted on a support structure and are loaded using
158 chains and chain blocks. The load is transferred to each blade through three load saddles. The load
159 saddles contain plywood inserts which match the aerodynamic profile of the blade at the load
160 application points. Silicone sheeting was placed between the blade surface and the plywood inserts in
161 order to ensure an even distribution of load across the blade surface and to avoid any stress
162 concentrations due to the clamping force. One major advantage for the chosen set-up is the lower cost,
163 achieved by reacting one blade off of the other and, hence, significantly reducing the reactive loads on
164 the support structure. One caveat to the testing is that the support structure was not bolted to the floor
165 and the weight of the blades was supported by trolleys positioned at 10 m along each blade. Some
166 error was introduced into the blade deflection measurements due to movement of the reaction frame;
167 however, this was recorded and corrected for in the presented results.

168 The load saddles were located at 5 m, 10 m and 12 m from the root of the blade. The IEC test standard
169 [2] states that one of the key areas of interest in the blade is the region inboard up to where the change
170 in cross-section slows down. On the blade under investigation this includes the blade from root up to
171 approximately 9 m. Since the load saddles typically invalidate the results of the blade tests locally
172 (due to induced stress concentrations not experienced in operation) the outer two load saddles were

173 located at 10 m and 12 m. The chain block attached to each load saddle was adjusted to match the
174 target load sequentially. When all three load saddles reached their respective targets, the deflections
175 were recorded. Since the two blades were mounted with the same orientation, they experienced
176 different loading. The first blade was loaded with a positive bending moment and the second with a
177 negative bending moment referring to the flapwise direction (see Figure 2). Only the results for the
178 blade with positive flapwise bending moment, the left hand blade in Figure 2, are presented since this
179 configuration is representative of the blade loading during operation. The blades were monitored for
180 any signs of failure during the test, such as cracking, surface buckling or acoustic emissions. No such
181 signs of failure were observed and the blades passed the test for certification.

182 Normal operation of the turbine is for wind speeds between 3.5 and 25 m/s, with a nominal wind
183 speed of 14 m/s, after which the turbine uses a pitch control system to maintain constant power
184 production. The test loading on the blade was determined from a report by Riso contained in [26] and
185 is shown in Figure 3 (a). The test loads were determined from an expression for the wind load on the
186 blade for an extreme 50 m/s gust. Figure 3 (a) also shows the magnitude of the forces applied to the
187 blade at the load saddle locations. Figure 3 (b) shows a comparison of the bending moment profiles
188 along the blade for both load types. The bending moment on the blade due to the load saddles is
189 slightly higher (up to 13.4 kNm at 2 m along the blade) than that due to the original wind loads
190 indicating that the testing is conservative in nature. In the design optimisation study, the original wind
191 loading is applied to the models, not the test loading. The three test loads (acting on a much smaller
192 area) may induce local non-linear behaviour, hence the wind loads are more representative of the
193 actual operational loads of the turbine.

194 The aerodynamic lift and drag forces experienced by a wind turbine blade can be resolved into the
195 forces in the flapwise (perpendicular to the rotor plane) and lead(-lag)wise (parallel to the rotor plane)
196 directions [29]. The lead(-lag)wise forces contribute to the torque driving the turbine, while the
197 flapwise forces comprise the thrust acting on the blade. The thrust is the most significant force acting
198 on the blade. The static test is restricted to testing the blade in the flapwise direction only. Hence,
199 further testing to account for the lead(-lag)wise loading (and high-cycle fatigue testing for lifetime
200 assessment) is necessary to fully analyse the response of the structure under all loading conditions.
201 Table 4 shows the distribution of the wind loads along the length of the blade.

202 **2.3 FE Model Set-up**

203 The blades are made up of 3D lofted shell sections. The composite layups are then applied to the
204 shells in the FE models. This enables the development of parametric models for the quick and
205 efficient evaluation of a design's structural response. Computational efficiency is a key driver of the
206 methodology due to the large number of models required for the optimisation study. The FE models
207 are generated using a Python code developed in-house. The inputs to the code include:

- 208 • Chord length distribution along the blade,
- 209 • Aerodynamic twist distribution along the blade,
- 210 • Location of the leading edge of the blade in the x- and y-directions,
- 211 • Distribution of airfoils along the blade, and the chord-normalised coordinates for each airfoil
212 designation,
- 213 • Distribution of the location and width of the spar caps (normalised by the chord length),
- 214 • Distribution of the number and location of the shear webs,
- 215 • Material properties and layup sequences for each radial blade section,
- 216 • Flapwise and lead(-lag)wise loads on the blade,
- 217 • Mesh and FE job analysis settings.

218 The code automatically generates the full FE model and performs the analysis. Any of these
219 parameters can easily be considered for optimisation. However, the study presented here focuses on
220 the thickness distribution of the laminates and number of shear webs. Due to the large number of
221 potential layup sequences, this is an expansive design space for the search. Post-processing of the
222 results is also conducted using Python. The code has been previously used in the analysis of small-
223 scale wind turbine blades [30] and concept tidal turbine blades [14] and is well suited for parametric
224 studies.

225 The loads are applied to the blade using a form of multi-point constraint (MPC). All of the nodes in
226 the section where the load is applied are constrained to a single reference point onto which the force is
227 applied as a point load. The coupling distributes the load between the reference point and the nodes in
228 the section. The root of the blade is constrained in all six degrees of freedom.

229 The blade models use a combination of 4-node reduced integration (S4R) plane stress linear shell
230 elements with hourglass control and 3-node triangular (S3) linear shell elements. A mesh convergence
231 study was conducted as part of the development of the FE models, using the blade tip deflection as the
232 convergence criterion. From the study it was determined that a mesh with approximately 19500
233 elements (18800 nodes) was suitable for accurately modelling the test set-up. This level of mesh
234 refinement utilised elements with a side length of approximately 40 mm.

235 **2.4 Genetic Algorithm Optimisation**

236 The genetic algorithm (GA) is used to evaluate a population of randomly generated potential designs.
237 Then, applying genetic operations, it searches through the design space to find the optimum solution
238 to the problem. The flowchart in Figure 4 outlines the steps in the GA:

- 239 • Generate the initial population of potential designs.
- 240 • Evaluate the relative potential fitness of each individual in the population and rank the
241 population.
- 242 • Evolve the population for the next generation by the following methods:
 - 243 ○ Retain the best individuals.
 - 244 ○ Cross pairs of individuals to create new individuals.
 - 245 ○ Randomly mutate the design variables of some of the population.
- 246 • Evaluate the relative potential fitness of the new population and repeat the previous step until
247 the stop criterion is reached.
- 248 • Further analyse the optimum blade design.

249 The following sections provide a detailed description of the key processes involved in the genetic
250 search algorithm under the headings: *genetic encoding*, *crossover*, *gene mutation*, *elitist selection* and
251 *objective function*.

252 **2.4.1 Genetic encoding**

253 Each potential blade design is completely defined by a design vector which consists of thirty-two
254 variables. These variables define the distribution of biaxial and triaxial layers in the blade. Biaxial
255 layers are formed from two unidirectional plies with a layup oriented $\pm 45^\circ$. In the optimised blades,
256 biaxial layers replace the triaxial layers used in the shear webs of the original blade. Since the webs
257 predominantly support the blade in shear, the biaxial layers provided a similar level of support while
258 using less material.

259 The thirty-two variables in the design vector are split into four categories. The first three categories
260 relate to the outer shells, the spar caps and the shear webs respectively and each are made up of ten
261 design variables. The last category contains two variables that relate to the blade as a whole. Table 5

262 defines each of the variables and indicates each variable's upper and lower limit. The categories for
263 the variables are defined as follows:

- 264 1. The first ten design variables define the number of triaxial layers in the outer shells.
- 265 2. The next ten variables define the number of unidirectional plies in the spar caps.
- 266 3. The next ten variables define the number of biaxial layers in the shear webs.
- 267 4. The second last variable defines the end point of the balsa core in the shear webs and the last
268 variable defines the number of shear webs in the blade.

269 All of the variables are integer values within the set limits. The description alongside each variable in
270 Table 5 indicates what type of composite layer it relates to and to what region it is applied.

271 The schematic in Figure 5 outlines the convention used in setting up the blade's composite structure.
272 The three levels to the hierarchy are defined as S for the radial section along the blade, R for the
273 region within a blade section (e.g. suction side leading edge laminate) and L for layer in each region
274 (where the layers are numbered from the outer aerodynamic surface inwards). Defining ten design
275 variables for each structural component means there are ten possible locations for ply drop-offs
276 (discrete locations where the thickness of the composite laminates change). The radial sections are
277 located evenly along the length of the blade; these locations range from 2 m to 12 m along the blade
278 in 1 m intervals.

279 In order to maintain ply continuity along the blade, the design variables define the number of plies for
280 a certain length of the blade. For example, Figure 5 demonstrates a general case of the spar cap
281 laminates. The variable x_{11} refers to the number of unidirectional layers that span the entire length of
282 the blade (from S_0 to S_{10}). The variable x_{12} refers to the number of layers spanning the blade from S_0
283 to S_9 and so on until the final variable, x_{20} , defines the number of unidirectional plies in the region
284 spanning from S_0 to S_1 .

285 **2.4.2 Crossover**

286 In order to create the next generation's population, a crossover method is applied. The method used in
287 this work is known as fitness proportionate selection or roulette wheel selection. An individual's
288 probability of being chosen as parent is based on its fitness value; the better the fitness, the higher the
289 chance it will be used to create a new individual. With this method there is still a chance that a less fit
290 individual may be selected as a parent, which may prove beneficial overall if the weak solution has
291 some component that is favourable to the new child. New individuals are generated from two parent
292 individuals. The crossover involves setting a split point at a random location in the parents' vectors of
293 design variables. Then the child inherits all of the design variables to the left of the crossover point
294 from the male parent and all of the design variables to the right of the crossover point from the female
295 parent.

296 **2.4.3 Gene mutation**

297 Once the new population has been generated, each variable in each individual in the population has a
298 small chance of a random mutation. The mutation, if it occurs, is constrained by the original limits on
299 the design variables (Table 5). The objective of the mutation is to further promote genetic diversity
300 and to explore the design space around any local optima. This can also help to avoid early
301 convergence and has the largest impact on the results in later generations.

302 For each design variable in an individual, a random number is generated between zero and one. If the
303 number is smaller than the chance of mutation (m), then the variable's value is reassigned. For this

304 study, the value of m is varied based on the number of generations evaluated. The following equation
305 describes the variation in m over the course of the analysis:

$$m(g) = m_i + (m_f - m_i) \frac{g_f}{g} \quad (2)$$

306 where $m(g)$ is the chance of mutation at the current generation, m_i is the chance of mutation at the
307 beginning of the analysis, m_f is the chance of mutation at the end of the analysis, g_f is the total
308 number of generations and g is the current generation. Figure 6 shows the results of the power law
309 function as it increases from the initial value for the chance of mutation to the final value over the
310 course of the analysis. With this function the change in the chance of mutation only becomes
311 significant after the analysis has proceeded through approximately 60% of the generations. The higher
312 chance of mutation is considered beneficial in the latter stages of the analysis in order to avoid
313 premature convergence and to promote localised searching about the optimum solutions determined
314 so far.

315 **2.4.4 Elitist selection**

316 Several varieties of elitist selection are used in practise, e.g. single, multiple and variable elitist
317 strategies. A single elitist method works by retaining the fittest parent in the new generation in place
318 of the weakest new individual. In multiple elitist methods, a number of parents may be retained. On
319 the other hand, in variable elitist strategies, the retention rate varies during the analysis, e.g. as a
320 function of the number of generations. Soremekun et al [31] studied the effectiveness of several such
321 strategies and found the multiple elitist method to perform the strongest. This method performed well
322 in terms of number of optima found for a particular problem, effectiveness at searching through a
323 large number of similar near-optimum designs and in terms of overall computational effort. This
324 multiple elitist method involves retaining the top designs from the parent population and placing them
325 into the new population and simply generating the number of child designs to refill the population to
326 its original number. This is less computationally expensive than other methods where a whole new
327 child population is generated and ranked and then the best parent designs replace the weakest child
328 designs. In this study, five individuals from the previous generation with the highest fitness were
329 retained into the new population.

330 **2.4.5 Objective function**

331 The objective function is used to evaluate the performance of each individual. Providing an
332 appropriate evaluation function for the optimisation problem is the task of the designer and requires a
333 strong understanding of the problem at hand. The goal of this study is to minimise the mass of the
334 blade, and, hence, reduce the manufacturing costs.

335 If the design space is the complex landscape formed by the limits of the design variables, then the
336 solution space is the resulting landscape after the evaluation of the results of each of those potential
337 designs. The solution space can be considered to be made up of three regions: the feasible space, the
338 infeasible space and the illegal space. Illegal solutions do not meet the design constraints and can't be
339 considered as viable designs, e.g. a blade that fails one or more material failure criteria. Infeasible
340 solutions have met the basic criteria for a solution, but are still outside of the limits set by the design,
341 e.g. a blade with a large tip deflection which could negatively impact the turbine aerodynamics. Often
342 the optimum solution lies on the border between the infeasible and feasible regions. In order to keep
343 some infeasible solutions in the population a penalty is applied to the objective function values of
344 individuals that exceed the tip deflection from the physical test. The objective function is given by:

$$\min (f(\mathbf{x}) = M(\mathbf{x})p(\mathbf{x})) \quad (2)$$

345 where $M(\mathbf{x})$ is the mass of the blade, \mathbf{x} is the vector of design variables for each individual and $p(\mathbf{x})$
 346 is the penalty function given by,

$$p(\mathbf{x}) = e^{\frac{\delta_{tip} - \delta_{test}}{\delta_{test}}} \quad \text{for } p(\mathbf{x}) \geq 1 \quad (3)$$

$$p(\mathbf{x}) = 1 \quad \text{for } p(\mathbf{x}) < 1$$

347 where δ_{tip} is the tip deflection of the current individual and δ_{test} is the tip deflection of the blade from
 348 the static test. The penalty function is only applied when it exceeds a value of one. The function
 349 exponentially increases with increasing tip deflection. However, an additional legality constraint is
 350 placed on the tip deflection to account for the limited allowable distance to avoid tip fouling (the
 351 blade tip striking the tower). This limit is $2.5 \delta_{tip, test} \approx 1.5m$. These inherent limits on the deflection
 352 act as a means of quantifying the distance metric for the constraint. The distance metric is described
 353 by Smith and Coit [32] as a means of determining the closeness of a solution to feasibility. Other
 354 penalty methods exist which apply a linear penalisation or take a power law approach to the problem
 355 (such as those outlined by Herath et al [33]), but the exponential function method worked well for this
 356 study.

357 A legality constraint is applied to the stresses in the blade laminates. The values of the risk of failure
 358 (stress exposures) for FF and IFF are calculated for the outer plies of the blade and factors of safety
 359 are applied. If the risk values exceed the set limits then that individual is deemed illegal and is
 360 removed from the population before the evolution stage.

361 The failure criterion defined by Puck [15] is phenomenologically based. The criterion provides a
 362 robust and effective approach to the prediction of failure in composites based on extensive testing of
 363 composites and using the brittle fracture theory of Mohr as its basis. It is made up of five stress
 364 interaction equations, two to determine the risk of fibre failure (FF) in tension and compression and
 365 three to determine the risk of different forms of inter-fibre failure (IFF) occurring [15]. The equations
 366 defining the risk of failure (or stress exposure) for FF are:

$$f_E(FF)^+ = \frac{1}{\varepsilon_{1T}} \left(\varepsilon_1 + \frac{\nu_{12}}{E_1} m_{\sigma_f} \sigma_2 \right) \quad (4)$$

$$f_E(FF)^- = \frac{1}{\varepsilon_{1C}} \left| \left(\varepsilon_1 + \frac{\nu_{12}}{E_1} m_{\sigma_f} \sigma_2 \right) \right| + (10\gamma_{12})^2 \quad (5)$$

367 where $f_E(FF)^+$ and $f_E(FF)^-$ refer to the stress exposure values for tension and compression
 368 respectively; ε_{1T} and ε_{1C} refer to the failure strain in tension and compression, respectively; ε_1 is the
 369 in-plane longitudinal strain; σ_2 is the in-plane transverse stress; γ_{12} is the in-plane lamina oriented
 370 engineering shear strain ($(10\gamma_{12})^2$ is an empirical correction factor); ν_{12} is the major Poisson's ratio;
 371 E_1 is the in-plane fibre direction modulus and m_{σ_f} is the mean stress magnification factor.

372 IFF can be separated into three distinct types: Mode A, Mode B and Mode C, which depend on the
 373 combined state of transverse and shear stress in the laminate. Mode A IFF refers to a tensile
 374 transverse stress and shear stress combination, Mode B a combination of compressive transverse

375 stress and shear stress and Mode C is a similar compressive-shearing stress state though with
 376 significantly higher compressive stress, generally resulting in failure of the laminate. The three
 377 equations for IFF are:

$$f_E(IFF)_A = \sqrt{\left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(1 - p_{\parallel\perp}^{(+)} \frac{Y_T}{S_{12}}\right)^2 \left(\frac{\sigma_2}{Y_T}\right)^2} + p_{\parallel\perp}^{(+)} \frac{\sigma_2}{S_{12}} \quad (6)$$

$$f_E(IFF)_B = \frac{1}{S_{12}} \left(\sqrt{\tau_{12}^2 + (p_{\parallel\perp}^{(+)} \sigma_2)^2} + p_{\parallel\perp}^{(-)} \sigma_2 \right) \quad (7)$$

$$f_E(IFF)_C = \left[\left(\frac{\tau_{12}}{2(1 + p_{\parallel\perp}^{(-)}) S_{12}} \right)^2 + \left(\frac{\sigma_2}{Y_C} \right)^2 \right] \frac{Y_C}{(-\sigma_2)} \quad (8)$$

378 where $f_E(IFF)_A$, $f_E(IFF)_B$ and $f_E(IFF)_C$ refer to the stress exposure values for the three modes of
 379 IFF; σ_2 and τ_{12} refer to the in-plane transverse and shear stress in the laminate, respectively; S_{12} is the
 380 in-plane shear strength of the ply; Y_T is the transverse tensile strength; Y_C is the transverse
 381 compressive strength; and $p_{\parallel\perp}^{(+)}$, $p_{\parallel\perp}^{(-)}$, $p_{\parallel\parallel}^{(-)}$ and $p_{\perp\perp}^{(-)}$ are parameters for controlling the shape of the
 382 failure envelope formed by the three equations [34]. The values of the all of the material parameters
 383 necessary for assessing glass-fibre epoxy laminates are contained in Table 6. The Puck failure
 384 criterion has been shown to be effective when paired with an optimisation procedure [35]. When used
 385 to identify first ply failure (FPF) in a buckling study of composite plates it produced optimum designs
 386 satisfying both FPF strength and buckling requirements over other material failure criteria.

387 A factor of safety of two was applied to both of the FF stress exposure values. Similarly, for the three
 388 inter-fibre failure modes, if the value in any of the blade's laminates exceeds 0.75, then the legality
 389 constraint is violated. The failure criterion are calculated in the FE program using UVARM, a user-
 390 defined subroutine for generating output variables. Any of the regular output quantities for the
 391 integration point (such as stress, strain, displacement, etc.) are available to UVARM. The UVARM
 392 code produces six output variables: the five stress exposure values and a marker variable to indicate
 393 the mode of IFF the element is within range of.

394 **2.4.6 Genetic algorithm operating parameters**

395 Table 7 contains general information on the search performed. The total number of individuals in the
 396 population was set at 25. The total number of generations for each optimisation problem was 300,
 397 while the number of retained individuals in the multiple elitist scheme for each generation was 5 and
 398 the chance of mutation varied from 0.03 to 0.05 according to Equation 2. The GA was implemented in
 399 Python to easily interface with the parametric FE model generation code and Abaqus.

400 **3 Results and Discussion**

401 **3.1 Model Validation**

402 Figure 7 shows the results of the static test on the 13 m wind turbine blade along with the associated
 403 FE model results. The blade deflections are shown for the maximum load applied. A comparison of
 404 the results at the load saddle locations indicates that the FE model overestimated the blade deflections
 405 by 9% (56 mm) at the 12 m load saddle. This implies that the physical blade is stiffer than the FE
 406 model predicts. During the test, the blade rotated relative to the support structure, which was only

407 noted once the test was completed. It is believed that the deflection results may be overestimated by
408 up to 24 mm at the outer load saddle location, due to this error. The load deflection curve for the three
409 load saddles is shown in Figure 8. The three curves are linear in nature and in combination with
410 manual inspection of the blades during testing indicate that no damage or non-linear deflection
411 occurred for the extreme load. The kinks in the curves for the 5 m and 10 m saddles are due to the
412 issue with fixing the rotation of the root connection fixture.

413 The mass of the physical blade and blade model was compared as part of the model validation. The
414 mass of the blade components modelled (excluding the metal inserts) is approximately 529 kg, while
415 the numerical model's mass is 497 kg, a difference of 6%. The discrepancies between the blade model
416 and the physical blade may be attributed to several factors:

- 417 • Additional glass-fibre material added during the manufacturing procedure, but not accounted
418 for in the original manufacturing documents.
- 419 • A slight variability in material density and fibre volume content, which is inherent in the
420 production of composite structures.
- 421 • Additional non-structural material which was omitted from the FE models.
- 422 • The through-thickness stresses in the root region are not accounted for by plane stress
423 elements.

424 The results from the blade model are used as the reference for comparison with the design
425 optimisation results in the following sections.

426 **3.2 Optimisation Results**

427 **3.2.1 Optimum blade designs from GA**

428 Table 8 shows the optimised values of the design variables after application of the GA. Five near-
429 optimum solutions (objective function values within approximately 0.5%) were found using the
430 multiple elitist method described in Section 2.4.4. The final generation contained a number of
431 additional designs with high levels of competitiveness. The variables x_1 to x_{10} , controlling the
432 thickness of the outer shells, show no variation between the five optimum designs. Since the outer
433 shells don't significantly contribute to the overall stiffness of the blade, it is not surprising that these
434 variables have nearly all reached the minimum possible value. There is more variation in variables x_{11}
435 to x_{20} , which control the thickness of the spar caps. However, the differences in these variables are
436 minimal, with only x_{13} , x_{14} and x_{19} varying slightly. The variables controlling the shear web
437 thicknesses, x_{21} to x_{30} , are also all quite similar and, since they are all close to their lower limits,
438 indicate that they do not significantly affect the fitness of their blade designs. Variable x_{31} controls
439 the location of the drop-off of the balsa layer in the shear web and was found to be close to a
440 minimum in all but the second solution. The last variable x_{32} indicates that all five blade designs have
441 only one shear web. This is a promising result as manufacturing a blade with only a single web using
442 the one-shot process is less complex and costly than with two webs.

443 Table 9 shows the layups for spar caps, outer shells and shear web for the Solution 1 blade. The
444 number of unidirectional, triaxial and biaxial plies are indicated for each radial section as well as the
445 gelcoat and core layers. The table demonstrates how the encoding of the thirty-two design variables is
446 used to generate the blade layups. Table 10 shows the results for the five optimum blade designs. The
447 results include: the fitness value, blade mass, tip deflection, tip rotation, the maximum values of each
448 of the five stress exposures, the radial location of the blade centre of mass and the generation when
449 each design was first found. The results for fitness, mass and tip deflection were as follows:

- 450 • Solution 1 resulted in the best fitness value (387.2 kg). The design demonstrated a mass
451 saving of 22.9% (113.9 kg) from the reference blade. However, this resulted in a tip
452 deflection of approximately 809 mm, and was subsequently penalised.
- 453 • The next fittest design showed a saving in mass from the reference blade of 22.8% (113.3 kg).
454 This blade design also resulted in a tip deflection of approximately 809 mm.
- 455 • Solution 3 resulted in a mass saving of 24.1% (120 kg) and a tip deflection of 824 mm.
- 456 • Solution 4 resulted in a mass saving of 24.1% (119.8 kg) and a tip deflection of 823 mm.
- 457 • Solution 5 resulted in a mass saving of 22.3% (111 kg) and a tip deflection of 807 mm.

458 The cost saving per blade is also shown in Table 10. The optimisation resulted in savings of between
459 15.1% and 16.3% of the total costs of the blade, due to the reduction in material required and the
460 associated labour costs.

461 All of the designs were found to be slightly on the infeasible side of the solution space. A more severe
462 penalisation method would drive the GA to finding only solutions that meet this constraint; however,
463 the current penalty method was applied since some leeway is allowed in the final deflection of the
464 blade. Several of the alternative designs in the final population demonstrated a feasible tip deflection
465 of 800 mm or less. However, the best fitness value among these solutions was 412.6 kg, with a mass
466 saving of 17% from the reference blade design. This indicates the strong influence the penalty
467 function has in controlling the results of the genetic search and the added flexibility granted by
468 approaching the optimum from the infeasible space, as well as the feasible.

469 The tip rotation was determined to be approximately 10.6° , with the five optimum designs showing
470 little variation between them ($\sim 0.1^\circ$). The tip rotation of the reference blade was approximately 7.9° in
471 magnitude. The difference between the optimum and reference blades is attributed to the optimum
472 designs all containing only a single shear web and the reduced thickness of their outer shells. Both of
473 these factors reduce the torsional stiffness of the optimum blade designs. Since the loading situation
474 under investigation is an extreme gust, and not an operational wind speed, the degree of twist is not a
475 major concern. Further investigation of the response of the structure should be conducted to determine
476 the level of twist in the blade for operating wind loads, since added twist could significantly affect the
477 aerodynamics of the turbine. Table 10 also shows the radial location of the centre of mass of the blade
478 designs. Large changes in the location of the centre of mass may affect the dynamics of the turbine.
479 The largest change in radial location from the reference blade was 160 mm towards the tip, resulting
480 from solutions 3 and 4.

481 The results for the five stress exposure values for each of the blades showed little variation, indicating
482 the stresses in the blades to be of similar magnitude. The stress exposure values for FF in tension and
483 compression were the lowest of all the failure modes, with the value of the stress exposure for
484 compressive failures slightly higher than for tensile. A factor of safety was applied to the stress
485 exposures for the three IFF modes, which limited their values to 0.75. The result was that the GA
486 found designs bordering on this upper limit for Mode A IFF. The five designs show values between
487 0.720 and 0.743. The stress exposure values for Mode B and C are lower, with values of 0.234 and
488 0.238, respectively. Modes A and B of IFF are generally considered a tolerable failure mode.
489 However, the current design was specified to avoid all possible failures for the extreme load case. The
490 optimum blade designs showed a decrease in the stress exposure values from the reference blade for
491 the FF failure modes and Mode B IFF.

492 From Table 10 it can be seen that many of the designs are close to the optimum, but with slightly
493 varying design variables. As noted by Soremekun [31], for the blade bending problem, the outermost
494 plies have the greatest effect on the design's fitness value and adding inner plies may not significantly

495 change the results. Therefore, it's possible to end up with many solutions with high fitness values, but
496 slightly varying composite layups. The higher chance of mutation in the last number of generations is
497 intended to locally explore the design space around the optimum solutions. Table 10 shows the
498 generation that each of the optimum blade designs was first determined. Solutions 3 and 4 were
499 determined first, at generation 175 and 176, respectively. By retaining these individuals into the
500 following generations, and using them in the crossover process, their strong structural characteristics
501 were further exploited. Solutions 1, 2 and 3 were then determined at generation 190, 195 and 192,
502 respectively.

503 A number of the blade designs in the final population which met the overall design criterion also
504 showed the onset of local buckling in the shear web towards the root of the blade. A similar situation
505 was reported by Barnes and Morozov [21], who outlined a number of options for including buckling
506 checks, including: incorporating a buckling constraint using design formulae, conducting an
507 additional eigenvalue analysis or including additional high modulus material options in the design
508 variables. Future work will extend the GA to include a buckling load factor or a constraint on the ratio
509 of length to thickness of the shear web panels to avoid buckling.

510 Figure 9 shows a comparison between the thickness of the spar cap laminates for the reference and the
511 optimum blade (Solution 1) designs. Figure 10 shows the thickness variations of the laminates in the
512 optimum blade; the same layups are applied to both the suction and pressure sides of the blades. The
513 GA resulted in relatively evenly spaced drops in the thickness of the UD material over the length of
514 the blade. Stress concentrations appear in locations with a large drop in thickness. The largest single
515 drop in thickness occurs at 11 m on the optimum blade.

516 **3.2.2 Blade Analysis**

517 The following results are displayed for Solution 1. Figure 11 shows the distribution of the fibre
518 direction stress (σ_{11}) along the centreline of the spar caps for the optimum blade and reference blade
519 designs. As can be seen from Figure 9, the thickness of the two blade designs is not significantly
520 different up to 9 m on both blades. The result is a similar stress distribution in both blades up to this
521 location. The stress is nearly symmetric for the pressure and suction sides of the blade and is below 45
522 MPa for the majority of the blade. The reduction in thickness of the laminates towards the tip of the
523 blade has a notable effect on the stresses with a major spike at the 11 m location in the optimum
524 blade. The root region of the optimum blade also shows higher stresses than the reference blade;
525 however, the stresses are of a similar magnitude to the rest of the spar caps. The drop in thickness of
526 the spar caps near the root in the reference blade also causes a large spike in stress, which is not
527 evident in the optimum blade design.

528 Figure 12 shows contour plots of the distribution of the fibre direction strain (ϵ_{11}) in the plies on the
529 outer surface of the optimum blade at the maximum load applied. The strain is highest along the spar
530 caps and does not exceed 0.23% in tension or compression over the blade. Stress concentrations can
531 be seen where the cross-sectional shape of the blade changes from circular to the aerofoil shape at the
532 root. The geometry in this region is complex and may not be fully captured by the parametric models.
533 Future work will investigate mesh smoothing options to obtain a closer approximation to the
534 geometry of the blade in this location.

535 Figure 13 shows a contour plot of the stress exposure values for Mode A inter-fibre failure. The risk
536 of IFF Mode A is higher on the suction side of the blade (the side in compression) than the pressure
537 side. Most notably, the trailing edge laminates along the length of the blade experience both
538 transverse and longitudinal compression and may be under risk of local buckling. At approximately 3

539 m along the blade, there is a stress concentration where the spar cap meets the outer shell. This region
540 requires closer inspection to avoid possible delamination between shells and spar cap during
541 operation.

542 **3.2.3 GA performance**

543 Figure 14 shows the progression of the fitness of the population during optimisation. The shaded area
544 indicates the upper and lower bounds of the objective function values for the population at each
545 generation. The fitness of the population improves rapidly in the first 25 generations and by
546 generation 50 the GA has already determined several designs with improvements in fitness from the
547 reference blade. The large range of the fitness values in the last generations is caused by the higher
548 chance of mutation. As seen in the previous section, the multiple elitist scheme is capable of finding
549 multiple optima per analysis run. Future work will investigate the precision/accuracy trade-off for the
550 GA and determine the most effective values for the genetic operators. This will help determine the
551 total number of generations required by the algorithm to determine optimum solutions and minimise
552 computational time. Although the genetic operators are often problem specific, the study by
553 Soremekun et al [31], which examined the trade-off between computational cost and search
554 effectiveness, was useful in initially determining the GA parameters.

555 At several points in the analysis illegal individuals were generated through either crossover or
556 mutation processes. Examination of the illegal individuals indicated Mode A IFF failures for many of
557 the designs. As noted in the results in Table 10, the highest stress exposure values were for IFF Mode
558 A with the GA converging on results bordering the design limit value of 0.75. Therefore, it is not
559 surprising that individuals with higher values of $f_E(IFF)^A$ were generated. Several blade designs were
560 also found with tip deflections beyond the limit of $2.5 \delta_{test}$, which would lead to tip fouling.

561 The total number of models analysed in the GA search was approximately 3300. Since a number of
562 designs were retained each generation, significant computational savings were made by not re-running
563 previously completed analyses. This led to a saving of approximately 34% of the total possible
564 computational time. All computations were performed on an Intel core i7 desktop computer with 8
565 CPUs and 16 GB RAM. Each single analysis took approximately 1 minute to generate the model, run
566 the analysis and post-process the results and the entire search took approximately 55 hours to
567 complete.

568 **4 Conclusion**

569 The present study demonstrates the effectiveness of pairing a genetic search algorithm (GA) with
570 parametric finite element models for composite wind turbine blades. The FE models were
571 successfully calibrated against test data, working with the manufacturers to ensure the models
572 accurately reflect the structural makeup of the blade. The models and test showed good
573 correspondence for the mass and deflection data and the differences between blade model and
574 physical blade were discussed in detail. The static structural testing showed the current blade design is
575 sufficiently durable for an extreme 50 m/s gust loading. The most significant findings from the design
576 optimisation include:

- 577 • The GA determined a number of potential design options and resulted in a mass saving of
578 23% for the optimum blade design.
- 579 • The optimum blade resulted in a saving of approximately 15.5% on the total blade
580 manufacturing costs due to the reduction in mass of glass-fibre epoxy required.

- 581 • Due to the application of constraints on the optimisation this improvement in mass
- 582 subsequently results in a slight increase in blade deflection and in blade surface stresses.
- 583 • The multiple elitist scheme preserved a number of good designs (five) through each
- 584 generation, resulting in the GA finding several near-optimum designs for further analysis.
- 585 • It was found that a single shear web was sufficient in all five of the optimum designs. From a
- 586 manufacturing perspective this represents an opportunity for reductions in complexity and
- 587 cost.
- 588 • A combination of a relatively high number of retained designs and a variable chance of
- 589 mutation of the design variables resulted in a good balance between global searching of the
- 590 design space and localised searching around the optimum designs. This produced individuals
- 591 with superior fitness values, especially in later generations when the chance of mutation was
- 592 highest.
- 593 • The use of the Puck failure criterion enabled an analysis of the risk of failure of the plies in
- 594 the blades for several different failure modes, providing additional constraints for the GA.
- 595 The optimised blade models are within safety factors for fibre failure and inter-fibre failure
- 596 (matrix cracking) of the laminates.
- 597 • A number of the designs in the final population exhibited the onset of local buckling in their
- 598 shear web laminates, future work will include buckling checks as an additional constraint.
- 599 • Significant computational savings were made by storing the results from analyses for future
- 600 reference.

601 The GA analysis will also be expanded to include additional load cases, such as combined flapwise
 602 and lead(-lag)wise loading and operational static and dynamic loading. The methodology has been
 603 proved effective for medium scale wind turbine blades and is equally applicable to other composite
 604 blades and propellers. Hence, future uses include the analysis and design of small/domestic scale (15
 605 kW) wind turbine blades and large scale (1 MW) tidal turbine blades.

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612 **References**

- 613 [1] Tummala A, Velamati RK, Sinha DK, Indraja V, Krishna VH. A review on small scale wind
- 614 turbines. *Renewable and Sustainable Energy Reviews* 2016 ;56: 1351–71.
- 615 [2] International Electrotechnical Commission. Technical specification IEC TS 61400-23 wind
- 616 generator systems - part 23: full-scale structural testing of rotor blades. 2001.
- 617 [3] Overgaard LCT, Lund E, Thomsen OT. Structural collapse of a wind turbine blade. Part A:
- 618 Static test and equivalent single layered models. *Composites Part A: Applied Science and*
- 619 *Manufacturing* 2010 ;41: 257–70.
- 620 [4] Yang J, Peng C, Xiao J, Zeng J, Xing S, Jin J, et al. Structural investigation of composite wind
- 621 turbine blade considering structural collapse in full-scale static tests. *Composite Structures*
- 622 2013 ;97: 15–29.
- 623 [5] Larwood SM, Musial W. Comprehensive Testing of Nedwind 12-meter Wind Turbine Blades
- 624 at NREL. 19th American Society of Mechanical Engineers (ASME) Wind Energy Symposium
- 625 2000: 297–305.

- 626 [6] Ciang CC, Lee J-RJ, Bang HH-J. Structural health monitoring for a wind turbine system: a
627 review of damage detection methods. *Measurement Science and Technology* 2008 ;19:
628 122001.
- 629 [7] Lu B, Li Y, Wu X, Yang Z. A review of recent advances in wind turbine condition monitoring
630 and fault diagnosis. *Electronics and Machines in Wind* 2009: 1–7.
- 631 [8] Bonnet P, Dutton G. Parametric Modelling Of Large Wind Turbine Blades. Proc. 21st Abaqus
632 UK Reg. User Meet., Daventry, UK: 2007, p. 211–25.
- 633 [9] Montesano J, Chu H, Singh CV. Development of a physics-based multi-scale progressive
634 damage model for assessing the durability of wind turbine blades. *Composite Structures*
635 2016;141: 50–62.
- 636 [10] Vucina D, Marinic-Kragic I, Milas Z. Numerical models for robust shape optimization of wind
637 turbine blades. *Renewable Energy* 2016;87: 849–62.
- 638 [11] Jensen FM, Falzon BG, Ankersen J, Stang H. Structural testing and numerical simulation of a
639 34m composite wind turbine blade. *Composite Structures* 2006;76: 52–61.
- 640 [12] Overgaard LCT, Lund E. Structural collapse of a wind turbine blade. Part B: Progressive
641 interlaminar failure models. *Composites Part A: Applied Science and Manufacturing* 2010 ;41:
642 271–83.
- 643 [13] Fagan EM, Kennedy CR, Leen SB, Goggins J. Damage mechanics based design methodology
644 for tidal current turbine composite blades. *Renewable Energy* 2016 ;97: 358–72.
- 645 [14] Fagan EM, Leen SB, Kennedy CR, Goggins J. Finite element based damage assessment of
646 composite tidal turbine blades. *J. Phys. Conf. Ser.*, vol. 628, 2015, p. 12106.
- 647 [15] Puck A. Failure Analysis of FRP Laminates by means of Physically based Phenomenological
648 Models. *Composites Science and Technology* 1998 ;58: 1045–67.
- 649 [16] Renard J, Thionnet A. Damage in composites: From physical mechanisms to modelling.
650 *Composites Science and Technology* 2006 ;66: 642–6.
- 651 [17] Gen M, Cheng R. *Genetic Algorithms and Engineering Optimization*. vol. 7. 2000.
- 652 [18] Paluch B, Grédiac M, Faye A. Combining a finite element programme and a genetic algorithm
653 to optimize composite structures with variable thickness. *Composite Structures* 2008 ;83: 284–
654 94.
- 655 [19] Lund E, Stegmann J. On structural optimization of composite shell structures using a discrete
656 constitutive parametrization. *Wind Energy* 2005 ;8: 109–24.
- 657 [20] Pourrajabian A, Nazmi Afshar PA, Ahmadizadeh M, Wood D. Aero-structural design and
658 optimization of a small wind turbine blade. *Renewable Energy* 2015 ;87: 837–48.
- 659 [21] Barnes RH, Morozov EV. Structural optimisation of composite wind turbine blade structures
660 with variations of internal geometry configuration. *Composite Structures* 2016 ;152: 158–67.
- 661 [22] Fischer GR, Kipouros T, Savill AM. Multi-objective optimisation of horizontal axis wind
662 turbine structure and energy production using aerofoil and blade properties as design variables.
663 *Renewable Energy* 2014 ;62: 506–15.
- 664 [23] Flanagan MH, Doyle F, Fagan E, Goggins J, Leen SB, Doyle A, et al. Large Scale Structural
665 Testing of Wind Turbine Blades Manufactured Using a One- Shot Out-Of-Autoclave Process.
666 Proc. Civ. Eng. Res. Irel. Conf., Galway, Ireland: 2016.

- 667 [24] Bir GS, Lawson MJ, Li Y. Structural design of a horizontal-axis tidal current turbine
668 composite blade. ASME 30th International Conference on Ocean, Offshore, and Arctic
669 Engineering 2011: 14.
- 670 [25] TPI Composites. Cost Study for Large Wind Turbine Blades : WindPACT Blade System
671 Design Studies SAND2003-1428 2003.
- 672 [26] Mohamed AA. Modelling of Vestas V27-225kW wind turbine blade. MSc Thesis, University
673 of Stavanger, Stavanger, Norway, 2011.
- 674 [27] Frøyd L. Control System on a Wind Turbine. MSc Thesis, Norwegian University of Science
675 and Technology, Trondheim, Norway, 2009.
- 676 [28] Zhou HF, Dou HY, Qin LZ, Chen Y, Ni YQ, Ko JM. A review of full-scale structural testing
677 of wind turbine blades. Renewable and Sustainable Energy Reviews 2014 ;33: 177–87.
- 678 [29] Rooij R Van. Terminology, Reference Systems and Conventions. Report to: European
679 Commission Contract JOR3-CT98-0284. TU Delft: 2001.
- 680 [30] Fagan EM, Leen SB, Torre O De La, Goggins J. Experimental investigation and numerical
681 modelling of domestic scale wind turbine blades. Proc. Civ. Eng. Res. Irel. Conf., Galway,
682 Ireland: n.d.
- 683 [31] Soremekun G, Gürdal Z, Haftka RT, Watson LT. Composite laminate design optimization by
684 genetic algorithm with generalized elitist selection. Computers & Structures 2001 ;79: 131–43.
- 685 [32] Smith AE, Coit DW. Penalty functions. Handbook of Evolutionary Computation 1995 ;97: c5.
- 686 [33] Herath MT, Natarajan S, Prusty BG, John N St. Isogeometric analysis and Genetic Algorithm
687 for shape-adaptive composite marine propellers. Computer Methods in Applied Mechanics and
688 Engineering 2015 ;284: 835–60.
- 689 [34] Puck A, Kopp J, Knops M. Guidelines for the determination of the parameters in Puck’s action
690 plane strength criterion. Composites Science and Technology 2002 ;62: 371–8.
- 691 [35] Deveci HA, Aydin L, Secil Artem H. Buckling optimization of composite laminates using a
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759 *Table 8. The optimum values for each of the design variables from the genetic search algorithm.*

760

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762 *blade: the spar caps, outer aerodynamic shells and the shear webs.*

763

764 *Table 10. Breakdown of the results of the optimum designs found by the genetic algorithm.*

765

Figures

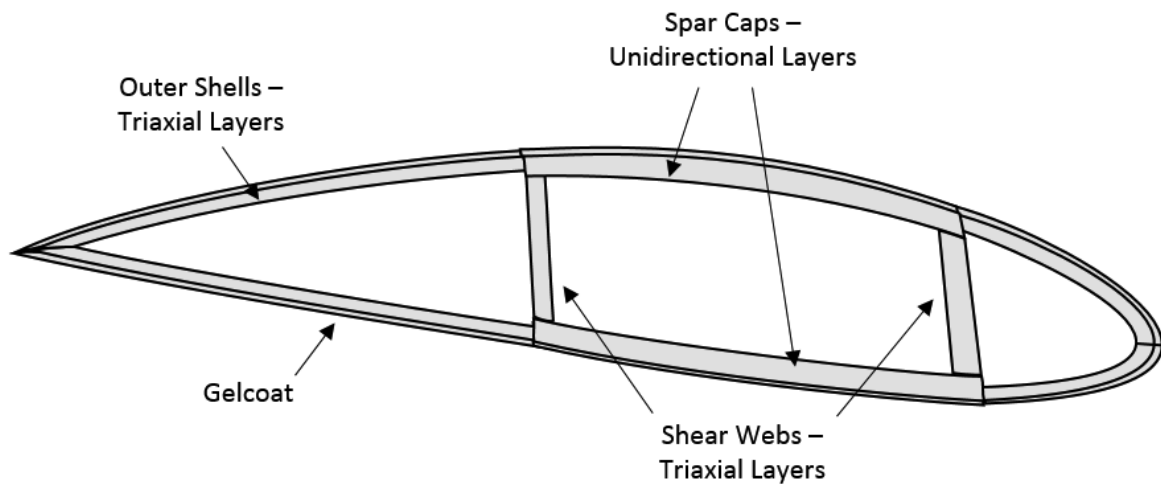


Figure 1. The principal layups for the three main sections of the wind turbine blade: the spar caps, shear webs and outer aerodynamic shells.

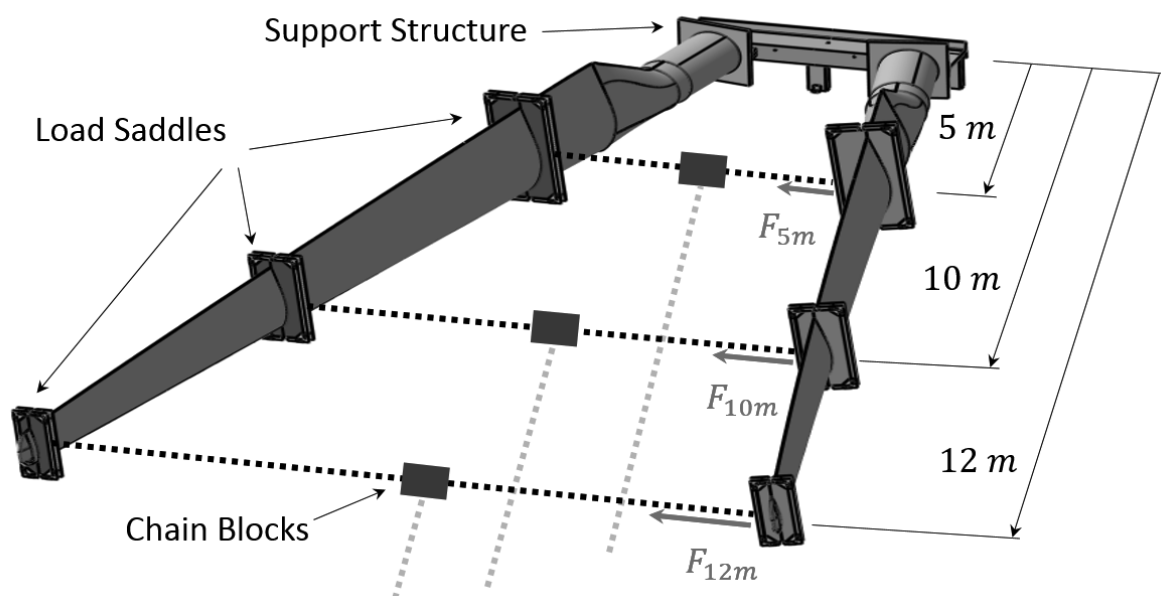
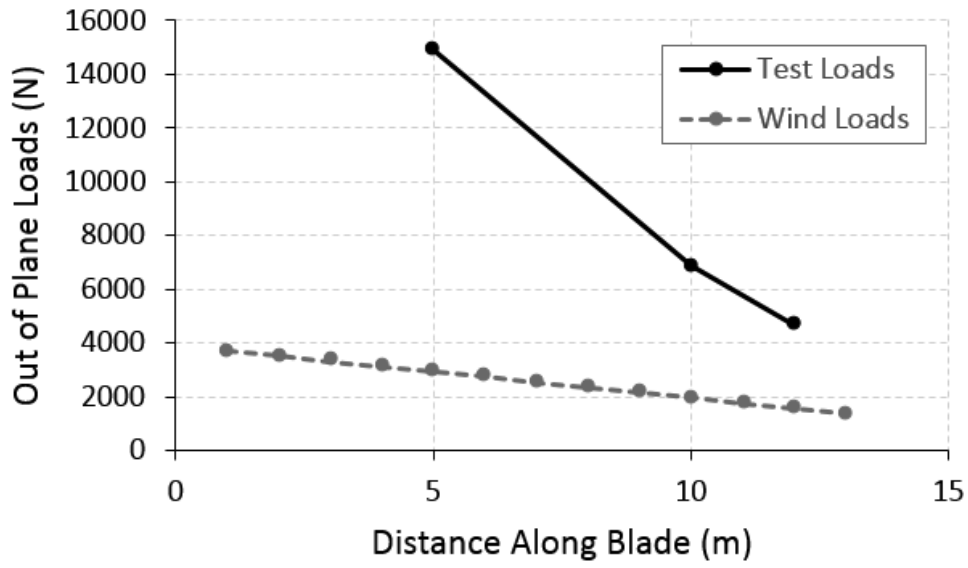


Figure 2. Set-up for the static test on the 13 m wind turbine blade.

(a)



(b)

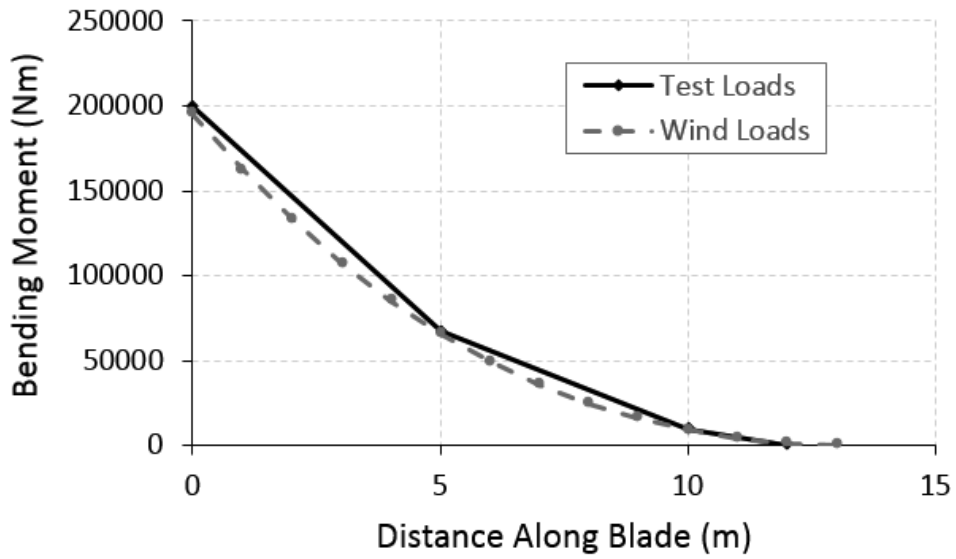


Figure 3. (a) Wind loads and mechanical test loads and (b) their respective bending moment profiles along the blade.

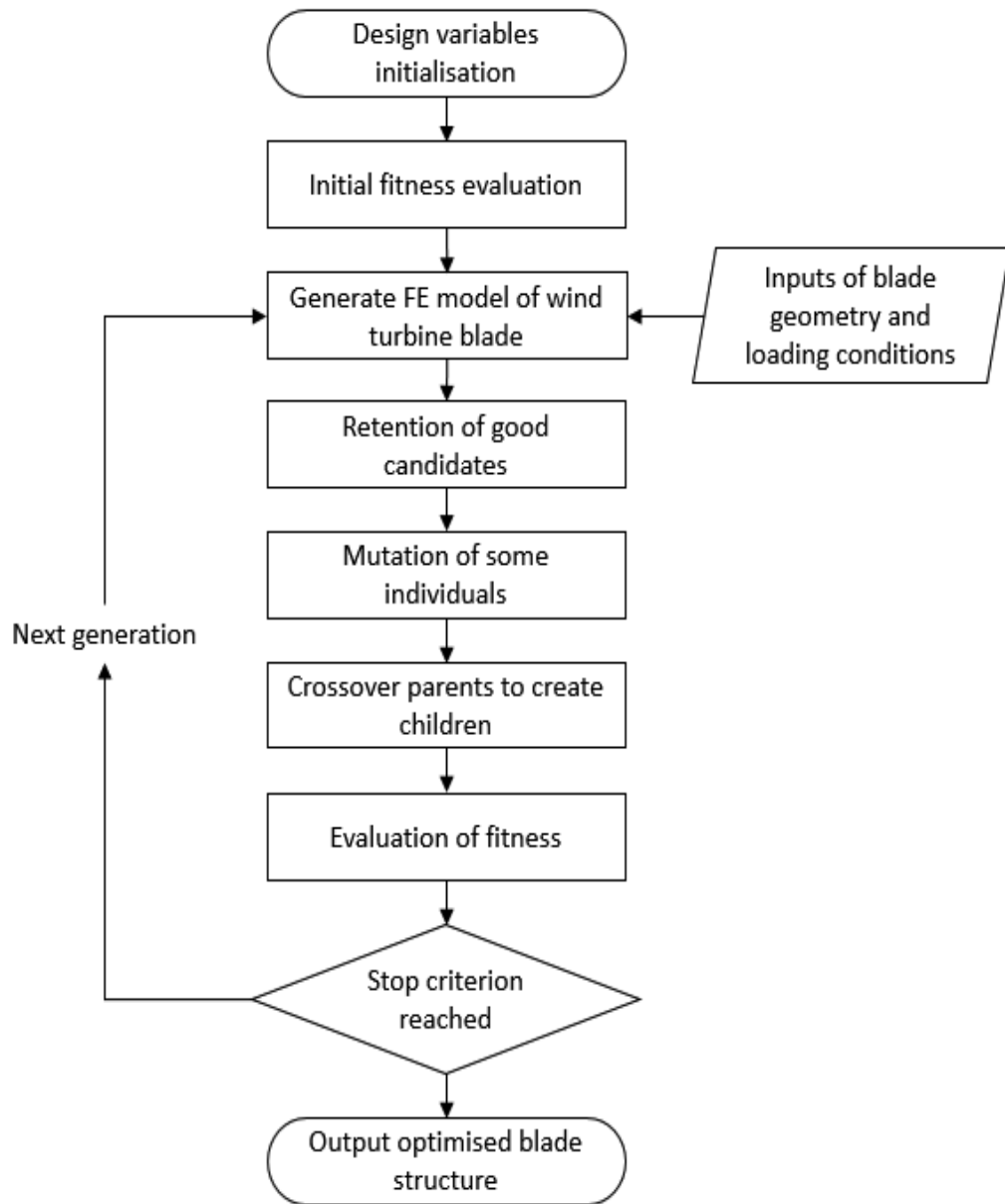


Figure 4. Flowchart describing the genetic algorithm's functions.

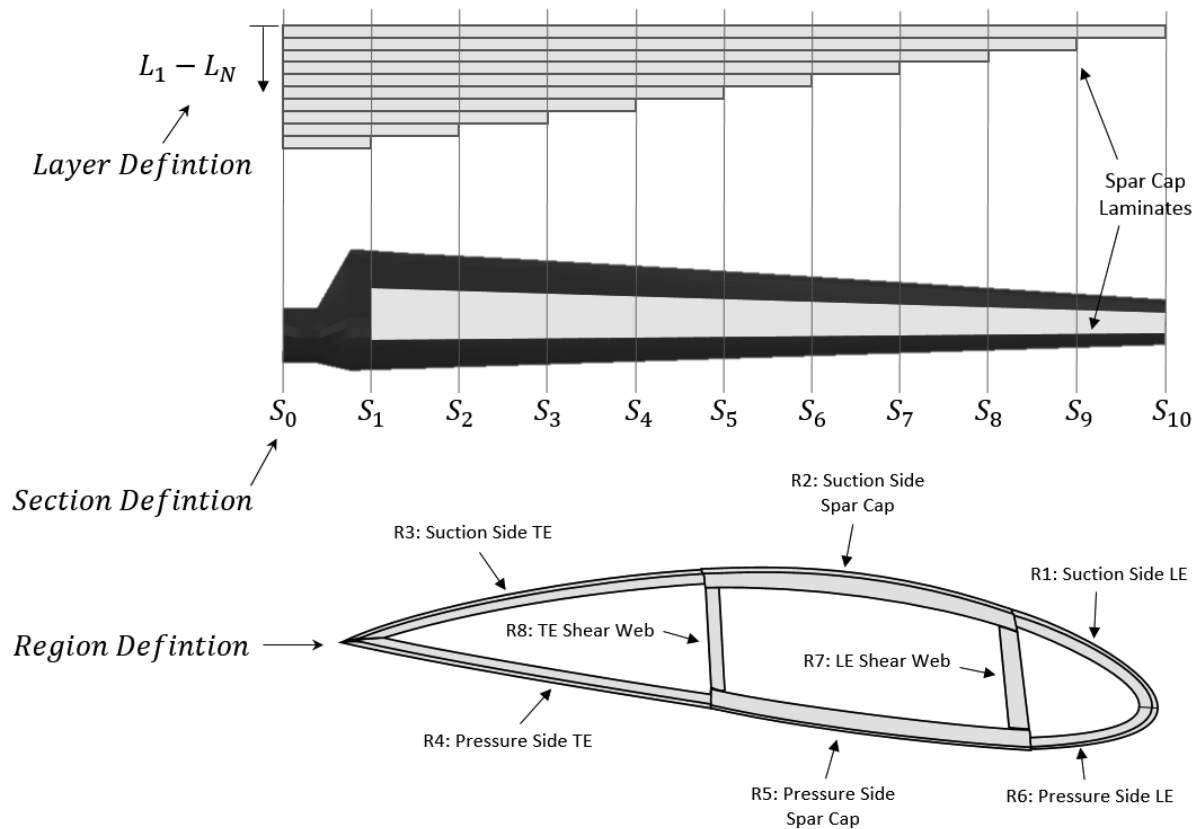


Figure 5. Overview of the naming/numbering convention for processing the results of the FE analysis. TE = trailing edge, LE = leading edge. Sections are labelled radially along the blade from root to tip, regions are labelled counter-clockwise from the leading edge of the blade for each section and layers are labelled from the top surface of the laminate down for each region.

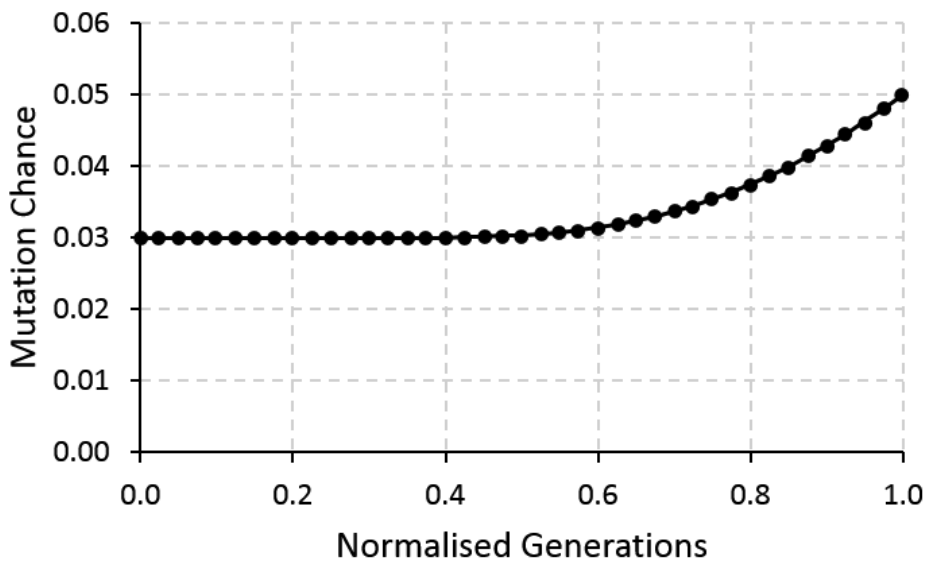


Figure 6. Variation in the chance of mutation for the design variables over the course of the genetic search (generations are normalised).

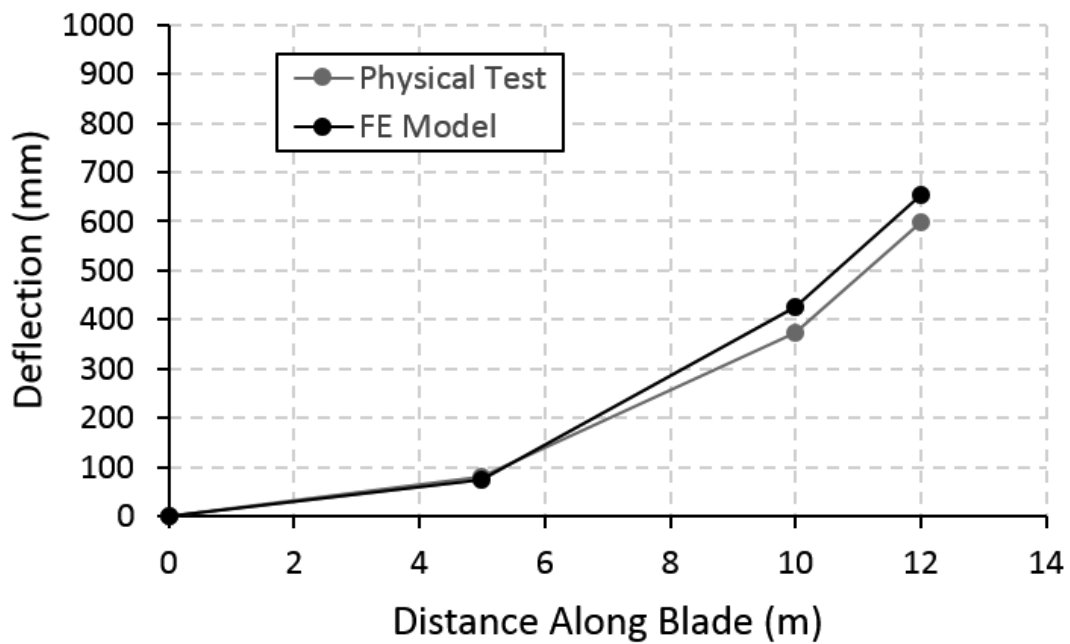


Figure 7. Blade deflection results from the static test and numerical model.

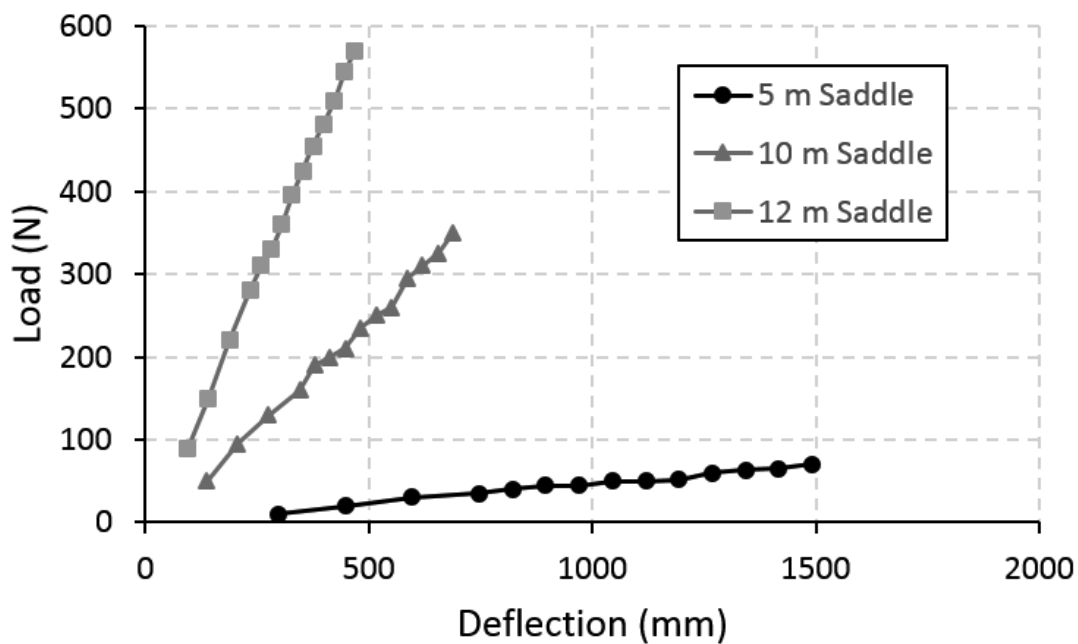


Figure 8. Load versus deflection curve for the three load saddles measured in the physical test of the blade.

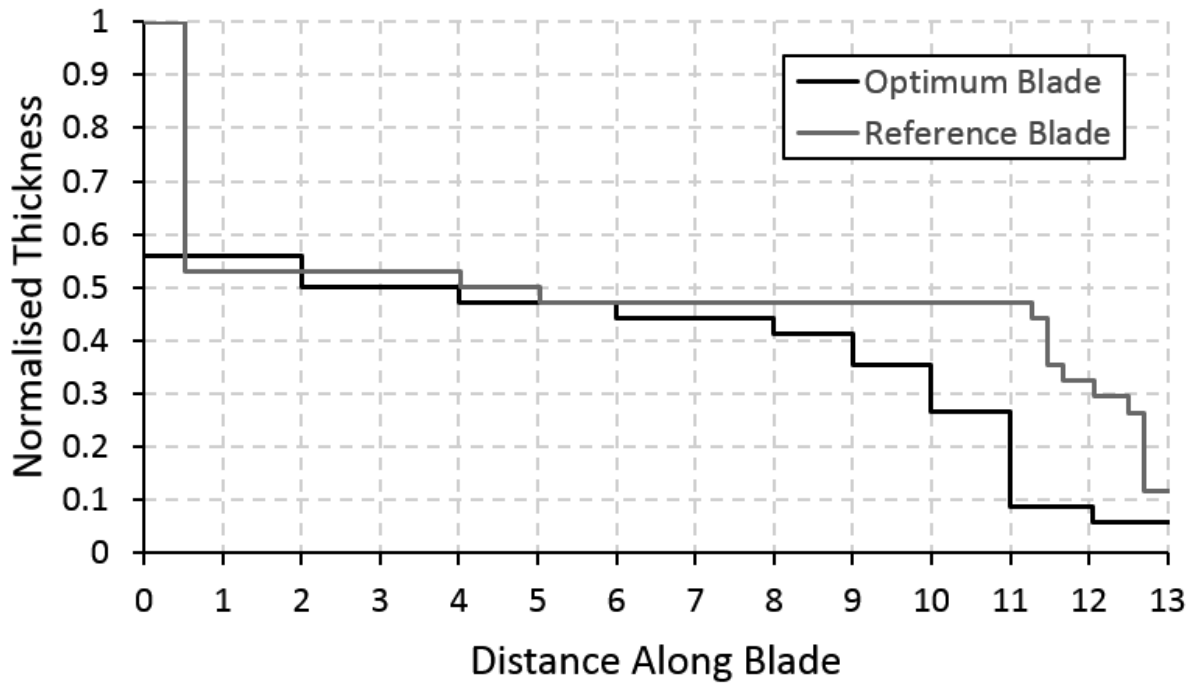


Figure 9. Comparison of the thickness distribution in the spar caps along the length of the blades between the reference blade and the optimum blade design found by the GA.

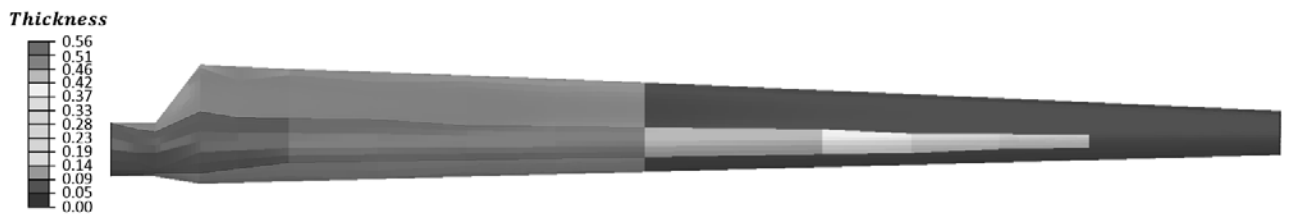


Figure 10. Thickness distribution of the laminates in the optimum blade.

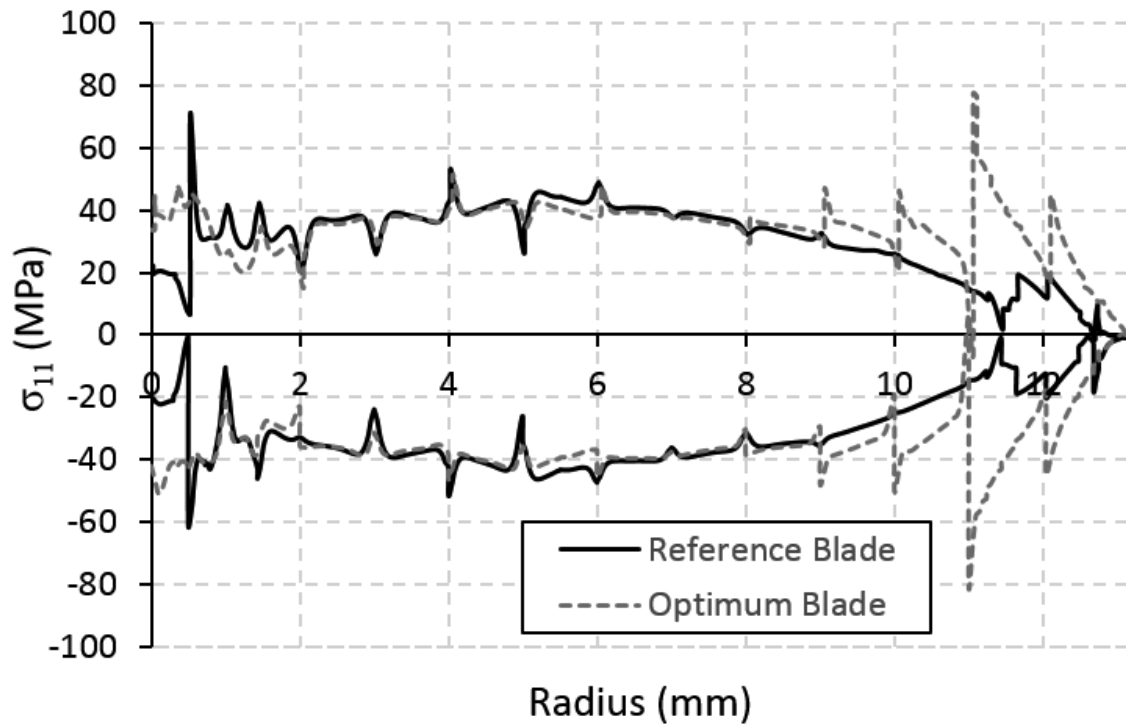


Figure 11. Fibre direction stress (σ_{11}) distribution along the centreline of the spar caps of the optimum and reference blades.

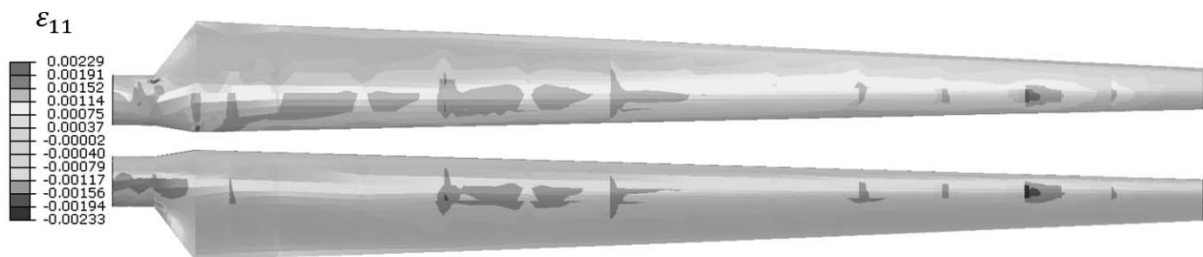


Figure 12. Contour plot of the fibre direction strain (ϵ_{11}) distribution on the outer surface of the blade at the extreme wind load.



Figure 13. Contour plot of the stress exposure values for inter-fibre failure Mode A ($f_E(IFF)^A$) on the outer surface of the blade at the extreme wind load.

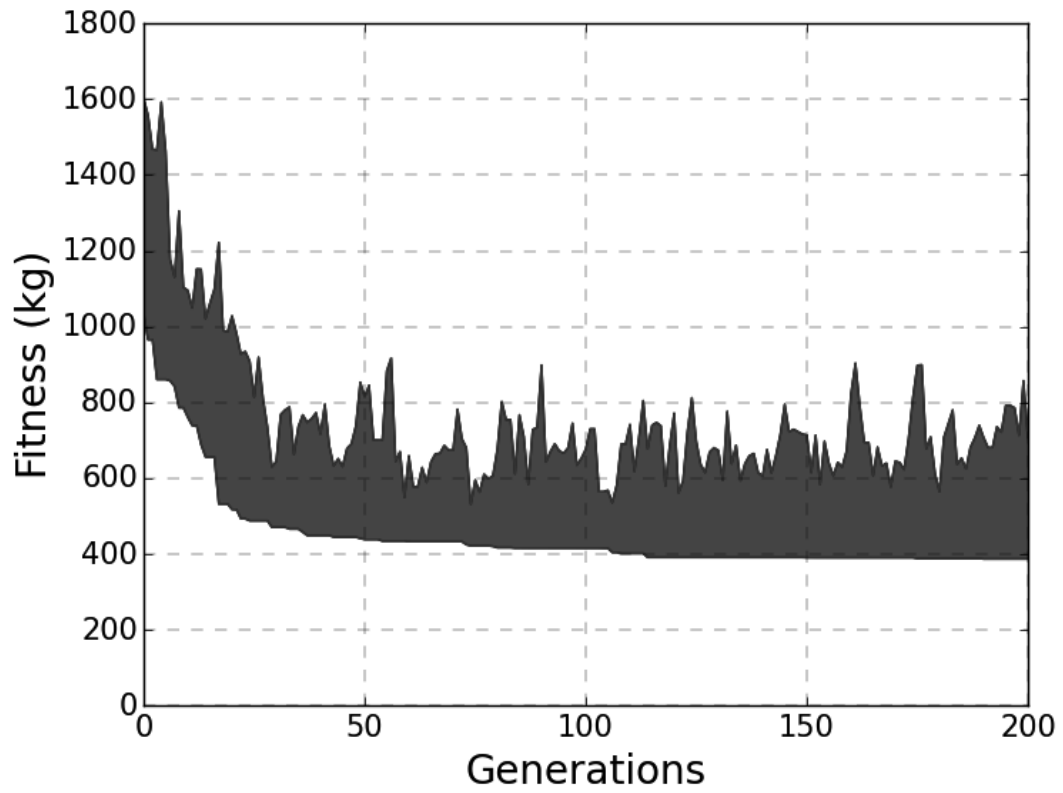


Figure 14. Results from the GA search. The bounds for the minimum and maximum values of the objective function for each individual in the population are shown.

Tables

*Table 1. Mechanical properties of the various materials used in the blade models. * Triaxial layers were assumed to consist of three layers of UD material. The density of a single triaxial layer is slightly lower than a UD layer. ** Values for the mechanical properties of the gelcoat and core/balsa layers were obtained from [24].*

	UD *	Gelcoat **	Balsa **
E_1 (MPa)	35000	0.00001	10
E_2 (MPa)	11000	0.00001	10
G_{12} (MPa)	4000	0.000001	0.2
ν_{12}	0.2	0.3	0.3
Density (kg/m ³)	1900	1830	80

Table 2. Details of the composite layups for the three main sections of the blade: the spar caps, outer aerodynamic shells and the shear webs.

	Spar Caps			Outer Shells			Webs		
0.00	UD x 32	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	UD x 4	TRIAX x 10
1.00	UD x 16	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	UD x 3	TRIAX x 10
2.00	UD x 16	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	UD x 2	TRIAX x 10
3.00	UD x 16	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	UD	TRIAX x 10
4.00	UD x 16	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	UD	TRIAX x 10
5.00	UD x 15	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	UD	TRIAX x 10
6.00	UD x 14	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
7.00	UD x 14	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
8.00	UD x 14	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
9.00	UD x 14	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
10.00	UD x 14	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
11.00	UD x 14	TRIAX x 2	Gelcoat	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
12.00	UD x 2	TRIAX x 2	Core	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
12.50	UD	TRIAX x 2	Core	TRIAX	Core	TRIAX	Gelcoat	TRIAX x 4	
13.00	TRIAX x 4	Gelcoat	Gelcoat	TRIAX x 4	Gelcoat	TRIAX	Gelcoat	TRIAX x 4	
13.15	TRIAX x 4	Gelcoat	Gelcoat	TRIAX x 4	Gelcoat	TRIAX	Gelcoat	TRIAX x 4	

Table 3. The distributions along the length of the blade of some of the key geometric (and structural) data, including: chord length, twist angle, blade thickness and aerodynamic profiles [26]. Note: Some of the quantities have been normalised. *** The thickness distribution of the blade along its length is determined by the chord length and the designation of NACA profile applied at each section.

Radius (m)	Chord (m)	Twist (°)	Profiles ***	Thickness (%)
0.00	0.600	0.00	Circular	100
0.50	0.600	0.00	Circular	100
1.00	1.366	12.4	NACA 63-240	40
2.00	1.294	13.2	NACA 63-235	35
3.00	1.223	11.4	NACA 63-230	30
4.00	1.151	9.68	NACA 63-230	30
5.00	1.079	8.05	NACA 63-225	25
6.00	1.008	6.53	NACA 63-225	25
7.00	0.936	5.13	NACA 63-222	22
8.00	0.864	3.87	NACA 63-220	20
9.00	0.793	2.77	NACA 63-220	20
10.00	0.721	1.85	NACA 63-218	18
11.00	0.649	1.12	NACA 63-216	16
12.00	0.574	0.59	NACA 63-216	16
13.00	0.505	0.32	NACA 63-215	15
13.15	0.494	0.29	NACA 63-214	14

Table 4. Radial distribution of the out of plane loads on the wind turbine blade applied in the optimisation study [26].

Radius (m)	Load (N/m)
1	3710
2	3510
3	3320
4	3120
5	2930
6	2730
7	2540
8	2340
9	2150
10	1960
11	1760
12	1570
13	1370

Table 5. Outline of the design variables and their limits.

Variable	Description	Lower Limit	Upper Limit
x_1	Triaxial plies $S_0 - S_{10}$	3	5

x_2	Triaxial plies $S_0 - S_9$	0	5
x_3	Triaxial plies $S_0 - S_8$	0	5
x_4	Triaxial plies $S_0 - S_7$	0	5
x_5	Triaxial plies $S_0 - S_6$	0	5
x_6	Triaxial plies $S_0 - S_5$	0	5
x_7	Triaxial plies $S_0 - S_4$	0	5
x_8	Triaxial plies $S_0 - S_3$	0	5
x_9	Triaxial plies $S_0 - S_2$	0	5
x_{10}	Triaxial plies $S_0 - S_1$	0	5
<hr/>			
x_{11}	UD plies $S_0 - S_{10}$	1	10
x_{12}	UD plies $S_0 - S_9$	0	10
x_{13}	UD plies $S_0 - S_8$	0	10
x_{14}	UD plies $S_0 - S_7$	0	10
x_{15}	UD plies $S_0 - S_6$	0	10
x_{16}	UD plies $S_0 - S_5$	0	10
x_{17}	UD plies $S_0 - S_4$	0	10
x_{18}	UD plies $S_0 - S_3$	0	10
x_{19}	UD plies $S_0 - S_2$	0	10
x_{20}	UD plies $S_0 - S_1$	0	10
<hr/>			
x_{21}	Biaxial plies $S_0 - S_{10}$	1	5
x_{22}	Biaxial plies $S_0 - S_9$	0	5
x_{23}	Biaxial plies $S_0 - S_8$	0	5
x_{24}	Biaxial plies $S_0 - S_7$	0	5
x_{25}	Biaxial plies $S_0 - S_6$	0	5
x_{26}	Biaxial plies $S_0 - S_5$	0	5

x_{27}	Biaxial plies $S_0 - S_4$	0	5
x_{28}	Biaxial plies $S_0 - S_3$	0	5
x_{29}	Biaxial plies $S_0 - S_2$	0	5
x_{30}	Biaxial plies $S_0 - S_1$	0	5
x_{31}	Balsa core drop off	0	9
x_{32}	Number of shear webs	1	2

Table 6. Parameters required for Puck failure criterion.

Material Parameter	Value
Tensile failure strain, ε_{1T} (%)	2.807
Compressive failure strain, ε_{1C} (%)	-1.754
Mean stress magnification factor, $m_{\sigma f}$	1.3
In-plane shear strength, S_{12} (MPa)	73
In-plane transverse tensile strength, Y_T (MPa)	-145
In-plane transverse compressive strength, Y_C (MPa)	40
Failure envelope shape parameters, $p_{\parallel\perp}^{(+)}, p_{\perp\parallel}^{(+)}$	0.3
Failure envelope shape parameters, $p_{\parallel\perp}^{(-)}, p_{\perp\parallel}^{(-)}$	0.25

Table 7. Information on the set-up of the genetic algorithm.

Population Size	Total Generations	Retained Individuals	Chance of Mutation
25	200	5	0.03 - 0.05

Table 8. The optimum values for each of the design variables from the genetic search algorithm.

Variable	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
x_1	3	3	3	3	3
x_2	0	0	0	0	0
x_3	0	0	0	0	0

x_4	0	0	0	0	0
x_5	0	0	0	0	0
x_6	0	0	0	0	0
x_7	1	1	1	1	1
x_8	0	0	0	0	0
x_9	0	0	0	0	0
x_{10}	0	0	0	0	0

x_{11}	2	2	2	2	2
x_{12}	6	6	6	6	6
x_{13}	3	3	2	2	3
x_{14}	2	2	3	3	2
x_{15}	1	1	1	1	1
x_{16}	0	0	0	0	0
x_{17}	1	1	1	1	1
x_{18}	0	0	0	0	0
x_{19}	1	1	0	0	1
x_{20}	2	2	2	2	2

x_{21}	1	1	1	1	1
x_{22}	1	1	1	1	1
x_{23}	0	0	0	0	0
x_{24}	0	0	0	0	0
x_{25}	0	0	0	0	0
x_{26}	0	0	0	0	0
x_{27}	0	0	1	1	1
x_{28}	0	0	0	0	0
x_{29}	0	0	0	0	0
x_{30}	0	0	0	0	0

x_{31}	1	7	0	1	0
x_{32}	1	1	1	1	1

Table 9. Details of the composite layups for Solution 1 optimum blade for the three main sections of the blade: the spar caps, outer aerodynamic shells and the shear webs.

	<i>Spar Caps</i>			<i>Outer Shells</i>		<i>Web</i>		
0.00	UD x 18	TRIAx x 4	Gelcoat	TRIAx x 4	Gelcoat	BIAX	Core	BIAX
1.00	UD x 18	TRIAx x 4	Gelcoat	TRIAx x 4	Gelcoat	BIAX	Core	BIAX
2.00	UD x 18	TRIAx x 4	Gelcoat	TRIAx x 4	Gelcoat	BIAX	Core	BIAX
3.00	UD x 18	TRIAx x 4	Gelcoat	TRIAx x 4	Gelcoat	BIAX	Core	BIAX
4.00	UD x 16	TRIAx x 4	Gelcoat	TRIAx x 4	Gelcoat	BIAX	Core	BIAX
5.00	UD x 15	TRIAx x 4	Gelcoat	TRIAx x 4	Gelcoat	BIAX x 2		
6.00	UD x 15	TRIAx x 4	Gelcoat	TRIAx x 4	Gelcoat	BIAX x 2		
7.00	UD x 14	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX x 2		
8.00	UD x 14	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX x 2		
9.00	UD x 13	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX x 2		
10.00	UD x 11	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX x 2		
11.00	UD x 8	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX x 2		
12.00	UD x 2	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX		
12.50	UD x 2	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX		
13.00	UD x 2	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX		
13.15	UD x 2	TRIAx x 3	Gelcoat	TRIAx x 3	Gelcoat	BIAX		

Table 10. Breakdown of the results of the optimum designs found by the genetic algorithm.

	<i>Solution</i> <i>1</i>	<i>Solution</i> <i>2</i>	<i>Solution</i> <i>3</i>	<i>Solution</i> <i>4</i>	<i>Solution</i> <i>5</i>	<i>Reference</i> <i>Blade</i>
<i>Fitness (kg)</i>	387.2	387.9	388.3	388.4	389.3	497.0
<i>Mass (kg)</i>	383.1	383.7	377.0	377.2	386.0	497.0
<i>Mass Saving (%)</i>	22.9	22.8	24.1	24.1	22.3	-
<i>Cost Savings (%)</i>	15.5	15.4	16.3	16.3	15.1	-
δ_{tip} (mm)	809	809	824	823	807	800
<i>Tip Rotation (°)</i>	10.6	10.6	10.7	10.7	10.6	7.9
$Max f_E(FF)^+$	0.081	0.081	0.081	0.081	0.081	0.197
$Max f_E(FF)^-$	0.148	0.147	0.147	0.147	0.148	0.254
$Max f_E(IFF)^A$	0.730	0.731	0.742	0.743	0.720	0.745

$Max f_E(IFF)^B$	0.238	0.238	0.238	0.238	0.238	0.136
$Max f_E(IFF)^C$	0.234	0.234	0.234	0.234	0.234	0.200
<i>Radial Location of Centre of Mass (m)</i>	4.38	4.38	4.41	4.41	4.37	4.25
<i>Generation Determined</i>	190	195	192	175	176	-
