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ADAPTIVE REUSE OF FRP COMPOSITE WIND TURBINE BLADES FOR CIVIL INFRASTRUCTURE CONSTRUCTION

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ABSTRACT

The rapid growth in wind energy technology has led to an increase in the amount of thermosetting FRP composite materials used in wind turbine blades that will need to be recycled or disposed of in the near future. Calculations show that 16.8 million tons of waste from wind blades will need to be managed globally by 2030, increasing to 39.8 million tons by 2050. Three waste management route are possible: disposal, recycling or reusing. Currently, most FRP composites taken out of service are disposal of in landfills or are incinerated. Recycling options consist of reclamation of the constituent fibers or the resins by thermo–chemical methods or recycling of small pieces of granular FRP material as filler material by cutting, shredding or grinding. Reuse options consist of reusing the entire FRP blade or large parts of the blade in new structural applications.

This paper reports on the potential for reusing parts of wind turbine blades in new or retrofitted architectural and civil infrastructure projects. The paper introduces the geometry, materials, and laminates typically used in wind blades and provides a snapshot of the sizes of wind blades likely to be available from the inventory of active turbines. Because the materials and manufacturing of commercial wind blades are proprietary, generic blade geometries and materials are discussed. These come from the Sandia National Laboratory and National Renewable Energy Laboratory, in the United States, and from OPTIMAT in the European Union. The paper presents an example of the geometry and material properties of structural elements cut from wind blades, using the Numerical Manufacturing and Design Tool (NUMAD), published by the Sandia National Laboratory.

KEYWORDS

Recycling of FRP Composites, Adaptive Reuse, Design of FRP Structures, Composite Wind Turbine Blades

INTRODUCTION

Wind turbine blades, also known simply as blades or rotors, are propeller-shaped cantilevering structures that convert the movement of air into rotation to drive wind turbines. The typical horizontal-axis wind turbine uses three of these blades arrayed around a central hub to spin a generator. The material properties of FRP composites: high strength-to-weight and stiffness-to-weight ratios, proven environmental durability, and ability to be manufactured in complex shapes, make them an ideal material for wind turbine blades. The 100 kW wind turbines produced in the 1980's in United States used an 8-meter blade constructed of hand-laid glass-fiber composite with a polyester resin (Johnson 1985). The largest wind turbines available currently are rated for around eight MW and use 80-meter blades, constructed with glass and carbon fibers, typically with an epoxy resin (Marsh 2011). The FRP blades in new wind turbines are designed for a 20-year service life. Many existing operators are opting to 'repower' their wind farms with new turbines (often prior to the 20 years of operation) in order to take advantage of technical innovations to improve energy yield and reliability. In the next two decades, the on–shore repowering market is expected to grow in the mature wind energy markets of Europe and North America, while new off–shore farms are constructed (DOE 2015; SEAI 2015). The repowering and subsequent decommissioning of older on–shore wind farms will begin in earnest in about 2025 and continue to 2050, whereas decommissioning of off–shore wind farms will only begin in earnest after 2045 (SEAI, 2015).

Discussion of the key issues related to the end of life of wind turbines (blades as well as all other parts) can be found in Cherrington et al. (2012) and Ortegon et al. (2013). A typical 2.0 MW turbine with three 50 m blades contains approximately 20 tonnes of FRP material and an 8 MW turbine has approximately 80 tonnes of FRP material that will need to be disposed of when its end of life is reached (1 MW equals approximately 10 tonnes of FRP composites). Calculations show that a global total of wind blades of 16.8 million tonnes to be disposed of by 2030 and 39.8 million tonnes by 2050 (Bank et al. 2018). These estimates are based on wind power growth rates from 2000–2015, which are likely to be conservative.

In recent years there has been an increased interest in the end of life and recycling of FRP composites (Yang et al. 2012; Job 2013; Bank and Yazdanbakhsh 2014; Oliveux et al. 2015). Two options to dispose of FRP composites at the end of life are used at the present – disposal in landfills and incineration (with or without energy recovery and subsequent disposal of the residual ash or reuse as a precursor for cement production in a cement kiln). Recycling options consist of reclamation of the constituent fibers or the resins by thermo–chemical methods (Oliveux et al. 2015) or recycling of small pieces of granular FRP material as filler material in concrete or other composites by cutting, shredding or grinding (Yazdanbakhsh and Bank 2016; Ribeiro et al. 2016)). Efforts to commercialize shredding and grinding of GFRPs for the filler market or for use in cement-kilns have not been commercially successful (Job et al. 2016).

This paper introduces a recently initiated project to develop load-bearing structural systems and materials from decommissioned wind blades – either whole blades or large sections cut from blades. In the first section, the paper discusses the geometry and materials used in windblades. The paper goes on to introduce a methodology to create sub-structure geometric and finite element models from windblades, as a first step in designing potential applications for use of composite materials cut from the blades. The paper uses the prototype 100 m blade designed as part of the NUMAD initiative completed at the Sandia National Laboratory and identified as SNL-100-00 (Griffith et al. 2012). The NUMAD program provides a means to generate geometric and structural analysis models from airfoil cross-sections and composite laminate data (Berg and Resor 2012). As the project presented in this paper progresses, it is expected that models will be generated for a wide range of blades that are nearing the end of their service life. These models will be used as the basis for the design of structures built from the repurposed wind blades.

GEOMETRY AND LOAD BEARING STRUCTURES IN WIND BLADES

Though wind blades vary widely in terms of material and manufacturing techniques, they all have roughly the same geometry. Blades are hollow, closed-sections and at most, cross-sections have one or more webs that span across the outer skins. The general configuration of wind blades is depicted in Fig. 1. Specific details of the geometry are taken from the SNL-100-00 blade. At the root of the blade, where the blade connects with the hub of the wind turbine, the cross-section of the blade is circular and the skins are made of thick, solid composites. An array of steel bolts, made integrally with the FRP composite, join the blade to the hub at the root. Moving away from the hub, the shape of the blade transitions rapidly from round to an airfoil shape. These airfoil shapes vary along the length of the blade, with the maximum chord dimension occurring at around 20% of the overall blade length and tapering continuously to the blade top (see Fig. 2).

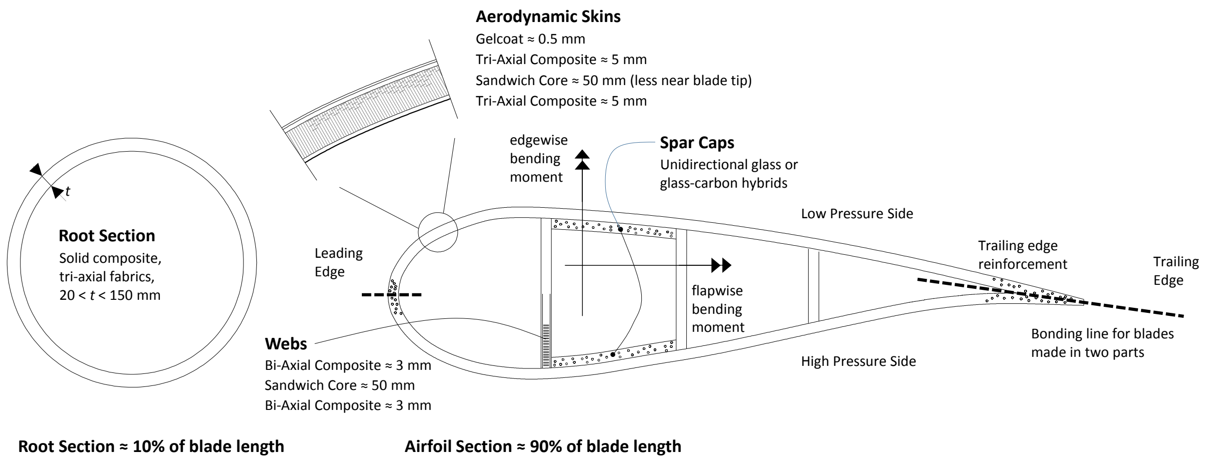

Figure 1: Cross-sections of wind blades showing internal structures and composite materials.

At the root of the blade, the aerodynamic flexural bending is carried in the outer skins of the root, and the skins are thus quite thick. For the SNL-100-00 blade, the root skins are 160 mm at the hub tapering to zero over the first 15 m of the blade (see Fig. 2). As the blade begins to transition into an airfoil shape, the flapwise (weak axis) bending moments begin to be carried by the spar caps and this load bearing element increases in thickness as the you move away from the hub. The flapwise bending moments produce the largest normal stresses due to the relatively low section modulus of the airfoil about this axis. For blades longer than 30 meters, longitudinal forces and edgewise (strong axis) bending moments, induced by inertial actions on the blades, become quite significant, leading to the need for additional strengthening about the edgewise axis (Schubel and Crossley 2012).

One or more webs are generally used to carry shear in the blade and to provide stability to the relatively thin blade skins. The webs are constructed of sandwich composites (materials described below). The webs are discontinued near the root and tip of the blade. It is uncommon for blades to have three webs as shown in Fig. 1 for the SNL-100-00 blade. For small and mid-size blades, a single web is generally sufficient.

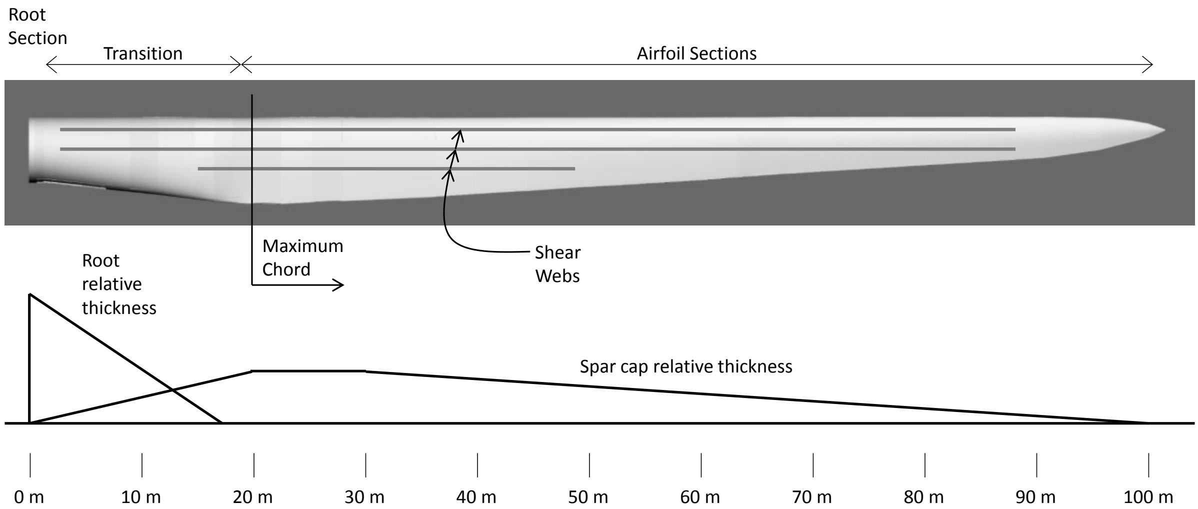

Figure 2: Planform of the SNL-100-00, 100 m wind blade and location of load bearing structures.

Two outer skins, known as the high and low pressure skins due to the differential aerodynamic pressures applied to them, form the load bearing surface of the wind blades. These skins wrap the entire surface of the blades, encapsulating the spar caps and webs. The aerodynamic skins are typically sandwich constructions, but gradually become solid composites in the transition region and into the root.

MATERIALS IN WIND BLADES

Early wind blades were made primarily of glass fiber composites, with polyester resins. These blades were produced by hand-layup in open molds. Most blades today are produced using resin infusion technologies, typically VARTM, with fiber volume fractions around 55%. A few manufacturers use prepreg techniques to manufacture blades and some use filament winding to produce the longitudinal spars. These filament wound sub-structures, which encompass both the spar caps and webs (Fig. 1) are then bonded into the aerodynamic skins.

The spar caps are made from unidirectional laminates, thickest near the root with decreased thickness (and laminate ply drops) toward the tip of the blade (Brondsted and Mikkelsen 2012). In the SNL-100-00 blade, for example, the spar cap thickness ranges from 50 mm near the maximum chord down to 2 mm at the blade tip (Griffith et al. 2012). About one-half of the weight of the given blade will be unidirectional composites, most of these in the spar cap. Consequently, the spar cap is a focus of structural optimization and material substitution, and many of the large wind blades use a glass/carbon hybrid spar cap for weight reduction and increased stiffness.

Because of the proprietary nature of commercial wind blades, the fiber architectures of blades are not generally public information. The OPTIMAT program in Europe designated two standard materials, which are representative of the materials used in blades. The OPTIMAT unidirectional material was a stitched mat, supplied by PPG, with an areal density of 1250 g/m^2, constructed of PPG 2002 rovings. Material properties for the unidirectional material were assessed on a $[0^o]^4$ laminate with a thickness of 3.6 mm and a fiber volume fraction of 54% (Nijssen 2006).

The root section and aerodynamic skins bear a more complex set of stresses compared to the spar cap, and are typically constructed of tri-axial fabrics (see Fig. 1). The root section is solid composite and the aerodynamic skins are sandwich structures. The OPTIMAT tri-axial material consists of N layers of a $\pm 45^o$ stitched bi-directional fabric, with an areal weight of 810 g/m^2, alternating with (N - 1) layers of the 1250 g/m^2 zero-degree fabric. Material properties of the OPTIMAT tri-axial material were assessed based on a $[\pm 45^o, 0^o]^4 \pm 45^o$ laminate, with a thickness of 6.5 mm and a fiber volume fraction of 54% (Nijssen 2006).

The webs of wind blades do not carry significant forces, as their role in the overall structure is to provide stability to the blade cross sections and thus prevent buckling of the aerodynamic skins. The webs are also sandwich constructions, with relatively thin skins that do not vary in thickness along the length of the blade. Following the spirit of the OPTIMAT material examples provided above, a $0/90^{o}$ or $\pm45^{0}$ bi-directional fabric, with an areal weight of 810 g/m^2 would be appropriate for the skins of the webs. Note that the web laminate is not described in Nijssen (2006) but appears in a later work by Nijssen et al. (2007). For the 3 mm thick skins used in the SNL-100-00 blade, three or four layers of this fabric would be required to create the skins.

The material properties from the three OPTIMAT laminates are provided in Table 1 as taken from Nijssen et al. (2007). The significant figures in the table are exactly as taken from the reference and represent mean property data extracted from the OPTIDAT database.

Table 1: Representative material properties from the OPTIDAT database (after Nijssen et al. 2007)

Material	E_{11} MPa	E_{22} MPa	G_{12} MPa	ν_{12}	ρ Kg/m^3	F_t^0 MPa	F_c^0 MPa
Uni-axial	38,887	9,000	3,600	0.249	1,869	810	507
Tri-Axial	24,800	11,500	4,861	0.416	1,826	436	349
Bi-Axial	11,700	11,700	9,770	0.501	1,782	180	144

Sandwich Core Materials

The potential for reuse of the web and aerodynamic skins of blades will depend on the properties of the sandwich composites that make up these structures – and the core materials used can have substantial impact on the stiffness and durability of these elements. For sandwich structures that were designed for uniform out-of-plane loading from wind, the performance under concentrated transverse or edgewise loadings in a repurposing application will depend to a great degree on the performance of the core. From the blade design perspective, the primary core property of interest is the shear modulus (Brondsted and Toftegaard 2009). In regions with low shear stiffness demand, PVC foams with a density of around 60 kg/m^3 and a shear modulus of around 21 MPa is commonly used. In regions with higher stiffness demands, "wind grade" end-grain balsa with an average density of 130 kg/m^3 and a shear modulus of around 160 MPa is used. A number of competing core materials are becoming available for blades, including low-density foams with 3D woven fiberforms. The foam limits the volume of resin infused into the core, but the fiberforms are the primary means of shear transfer.

GEOMETRIC MODELING OF WINDBLADES FOR REUSE DESIGN AND ANALYSIS

The NUMAD model for the SNL-100-00 blade uses a series of 25 cross sections to describe the shape of the blade. Each cross section describes the outer geometry of the blade, but does not capture the material thicknesses or internal structures (e.g., spar caps, webs). At the root, the cross section is a circle and at the tip, the cross section is a point. In the transition region, the intermediate cross sections morph from circular to elliptical to vaguely airfoil shaped (Fig. 2). In the airfoil region, which makes up 80% of the blade, the cross sections reference industry standard airfoil data, which are extracted from libraries of airfoil shapes. Between the cross-sections the blade geometry is linearly interpolated.

To provide 3D CAD geometry for designers, the same approach applied in NUMAD has been implemented in the Rhinoceros program. Figure 3 shows the 25 cross sections and the 24 segments generated for the SNL-100-00 blade. At the current stage of the research, the blade geometry has been modeled manually. As the project progresses, we anticipate building a library of blade models using design automation tools similar to those described by Charalampous et al. (2015), using Grasshopper, a design scripting tool integrated with Rhinoceros.

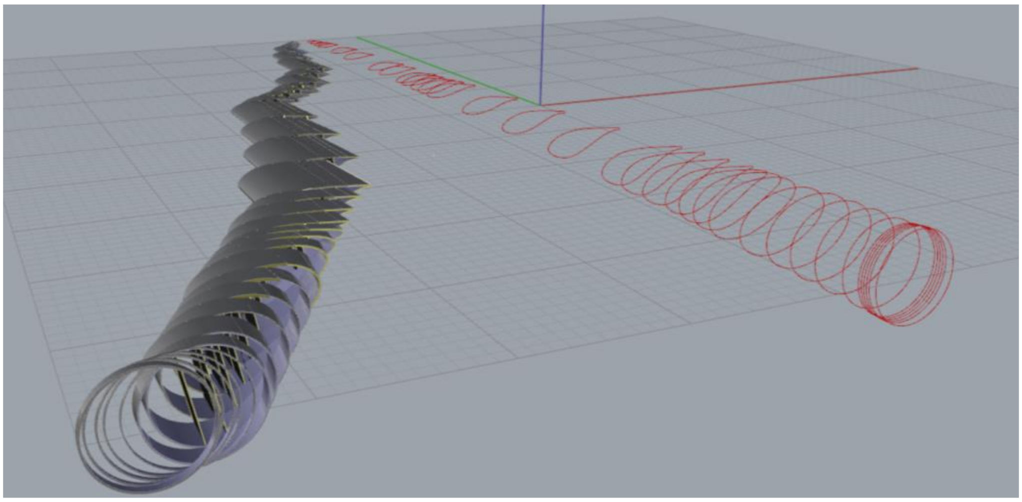

Figure 3: SNL-100-00 cross sections and segments in Rhinoceros.

CAD models often provide surface geometry, but often neglect material thickness and makeup. For comprehensive structural design, it is necessary that both overall and local geometries are captured. To this end the process used to model the windblades has mapped the laminates and sandwich data from the NUMAD database file into the Rhinoceros model (Fig. 4).

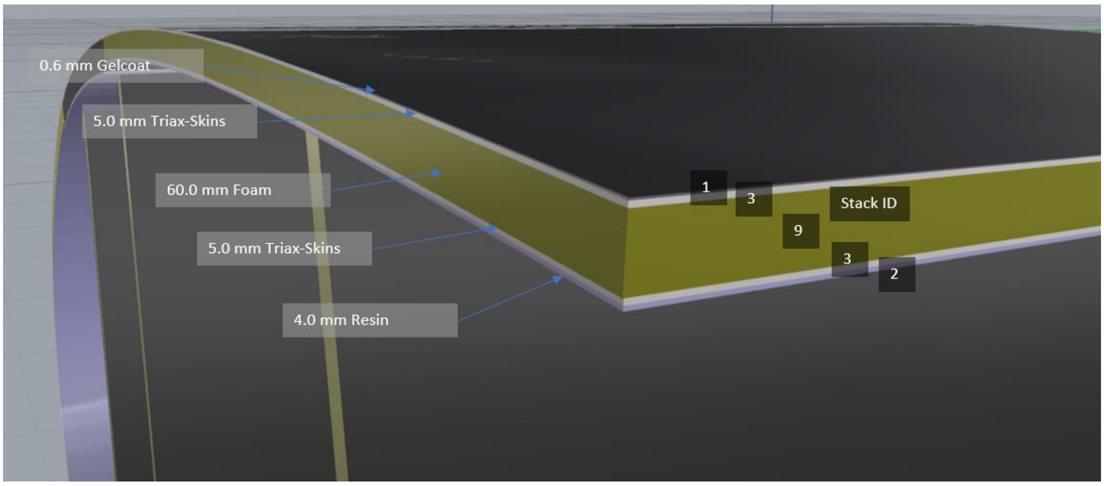

Figure 4: Section of SNL-100-00 from Rhinoceros.

EXAMPLE APPLICATION

An example of a housing application, serving as a roof for a small house typical of that found in the Yucatan Peninsula, Mexico, and composed of a section of the SNL-100-00 wind blade, is shown in Fig. 5. In this case the spar cap and trailing edge of the low pressure skin is cut from the blade, near the point of the maximum chord (see Fig. 2). One-half of the three webs remain in the section, and each web act as a deep beam, spanning approximately 5 meters between load bearing concrete masonry walls.

The example represents a proposal for a structural application. The adequacy of the proposition must be assessed through structural analysis, and design of additional reinforcements necessary for local conditions, connections, etc. For this example the following conditions have been identified for structural analysis and subsequent detailed design (see keynotes in Fig. 5):

1. In-plane flexure of the webs carrying the self-weight and superimposed roof loads.
2. Bearing of the webs at six locations on the masonry walls.
3. Continuous connection to the trailing edge to the roof along one masonry wall.
4. Stability of the web-to-skin interface and ability to resist inadvertent bending at this interface.
5. Concentrated loading on the roof causing out-of-plane bending of the sandwich panel

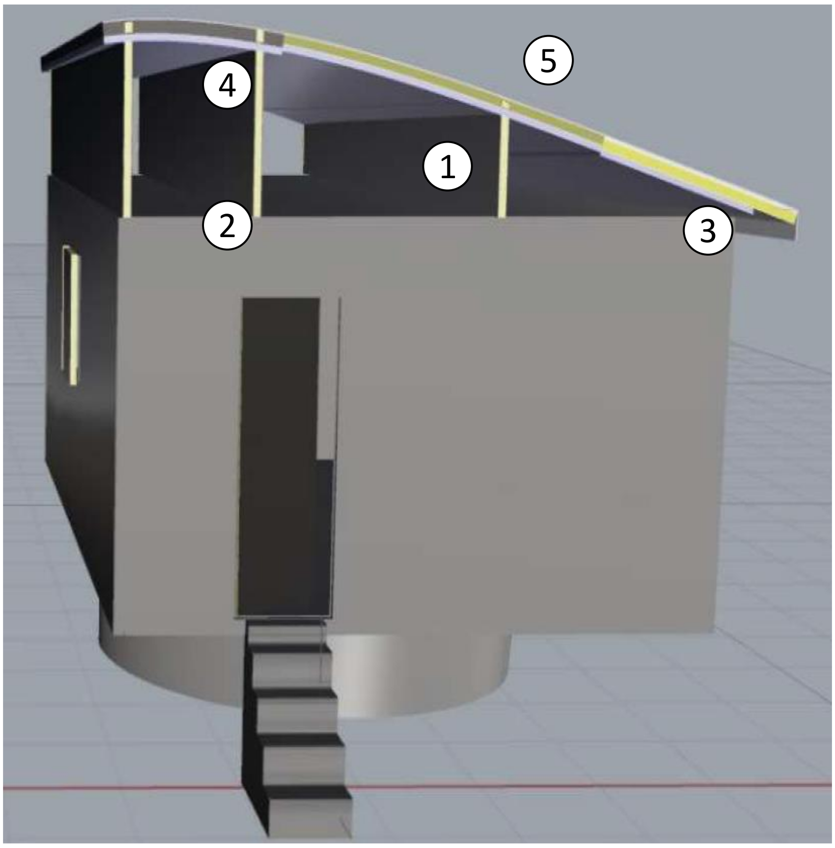

Figure 5: Housing roof concept using blade section from the SNL-100-00 blade (after Bank et al. 2018).

Future work on this project is expected to generate a large number of similar reuse proposals along with a methodology to analyze, assess, and design the retrofits.

CONCLUSIONS

The advantages of FRP composite materials are widely recognized, but at this point no economically-viable methods for recycling FRP materials have been developed. Most decommissioned FRP materials end up in landfills or incinerators. Wind blades show a tremendous potential for reuse applications because of the high quality of the composite materials used in blades. The complex geometry of blades hinders the design of potential reuse applications. Future work by the research team will develop a library of 3D blade geometries, available for architects and structural engineers, as a starting point for design explorations with decommissioned blades. Additional work on the residual properties of composite materials, taking into account the fatigue history of the composite materials, is expected to extend the work and provide design stress allowables for the reuse design process.

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