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Structural Configuration Analysis of Advanced Flight Vehicle Concepts with Distributed Hybrid-Electric Propulsion

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Structural configuration analysis of two advanced aircraft concepts with distributed hybrid-electric propulsion is presented. These concepts are characterized by multiple wing-mounted electric propulsors, which are powered by turbo-generators. Based on lessons learned from previous structural analysis of unconventional concepts, high-fidelity finite element models of the aircraft wing with embedded electric propulsors are developed. Although a hybrid-electric propulsion system has noise and emission benefits, it also adds electrical power system weights. Hence, efficient structural integration of the wing and propulsors is investigated for design improvement, structural analysis, and weight reduction. Wing structural weights of the two designs are compared with a baseline conventional transport aircraft wing for benefit assessment. In one design, the wing structural weight reduction partially compensates for the additional weight associated with the distributed electric propulsion system.

I. Introduction

Under the NASA Aeronautics Research Mission Directorate (ARMD) Advanced Air Transport Technology (AATT) project, performance, noise and emission benefits of distributed turbo-electric propulsion are being investigated. Felder, *et al.*[1] reported the impact of boundary layer ingestion on the design of a Turbo-electric Distributed Propulsion (TeDP) system integrated into a hybrid wing body (HWB) aircraft. Jensen, *et al.*[2] discussed key performance parameters of turbo-electric aircraft. Turbo-electric distributed propulsion benefits on the hybrid-wing-body type vehicle were presented by Kim, *et al.*[3] Wick, *et al.*[4] studied the integration challenges and potential benefits of distributed propulsion systems on next generation commercial and military transports. Schiltgen, *et al.*[5] described a 150-passenger Environmentally Conscious tube-and-wing regional airliner concept (ECO-150), which is characterized by a turbo-electric distributed propulsion system embedded within the inboard section of the wing. A novel conceptual design of a single-aisle turbo-electric commercial transport with fuselage boundary layer ingestion was described by Welstead and Felder.[6] Gerald[7] discussed weights and efficiencies of electric components for a turbo-electric hybrid-wing-body aircraft propulsion system. A large set of advanced hybrid-electric propulsion concepts was investigated by Bradley, *et al.*[8,9] at the Boeing Company. Jensen, *et al.*[10] have conducted extensive systems analysis to evaluate the risks and benefits of a conversion from an all fuel high by-pass turbofan to a hybrid-electric turbofan engine concept. Jensen also described NASA Electrified Aircraft Propulsion (EAP) research to improve the fuel efficiency, emissions, and noise levels in commercial transport aircraft. Turbo-electric, partially turbo-electric, and hybrid-electric propulsion systems are the primary EAP configurations being evaluated for regional jet and larger aircraft. The goal is to show that one or more viable EAP concepts exist for narrow-body aircraft.

Although a hybrid-electric propulsion system has potential performance benefits, electric generators, motors, and power distribution system add to the overall weight compared to an aircraft with conventional propulsion. The objective of this paper is to investigate wing structural designs of distributed hybrid-electric propulsion vehicles that would compensate for this additional system weight compared to a conventional aircraft wing. This paper will present structural design and weight analysis of two concepts referred to as Single-Aisle Turbo-electric Aircraft with Leading Edge Embedded Distribution (STARC-LEED) concept-I and STARC-LEED concept-II. The wing-embedded propulsors in these concepts significantly impact the wing structural design. The weight of this type of unconventional wing structure cannot be determined from historical low-order weight estimation methods. Predicting the weight requires higher order analysis such as the structural finite element analysis. Based on lessons learned from previous structural analysis of unconventional concepts, such as the hybrid-wing-body fuselage section[11] and large double-bubble fuselage section,[12] high-fidelity finite element models (FEM) of the aircraft wing with embedded electric fans

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have been developed. Wing structure and propulsor integration is investigated to seek an efficient design. Structural sizing and stress analyses of vehicle components are applied for design improvement and weight reduction. The wing FEM weights of the two STARC-LEED concepts are compared with the baseline conventional transport aircraft, to assess the benefits.

II. Analysis Approach

Figure 1 illustrates a range of structural analysis work performed by the author for evaluation of NASA advanced transport concepts. Much of the past work has focused on unconventional fuselages structures. Figures 1a-1d show finite element models of a hybrid-wing-body vehicle fuselage section,[11] a conventional cylindrical section fuselage, a comparable ND8 double-bubble and double-D section fuselage section,[12] and a double-bubble type vehicle. Note that in evaluating new structural concepts it is important to establish a relevant baseline, such as the cylindrical fuselage shown in Figure 1b. Although fuselage structural concepts are not the focus of the current effort, the analysis approach developed in these previous activities has been adopted for the current work. Figure 1e shows the "N+3" technology advanced conventional configuration (N3CC) research vehicle model with high by-pass turbofan engines. This conventional configuration serves as the baseline for evaluation of the STARC-LEED concepts analyzed in this paper. These vehicles have the same general configuration, except for the wing and propulsion system. Figure 1f shows an initial STARC-LEED concept with turbo-electric distributed propulsion. This initial concept uncovered several integration challenges for the wing embedded propulsion system that were addressed in subsequent iterations of the design. Figures 1g and 1h show the two final STARC-LEED TeDP concepts, concepts I and II, which are the subject of this paper.

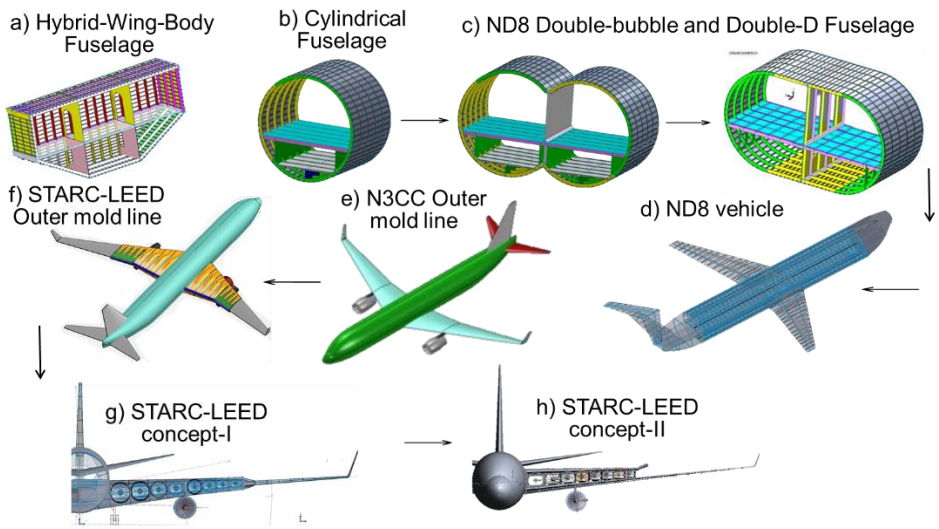


Figure 1. Structural configuration development for advanced air transport vehicle concepts.

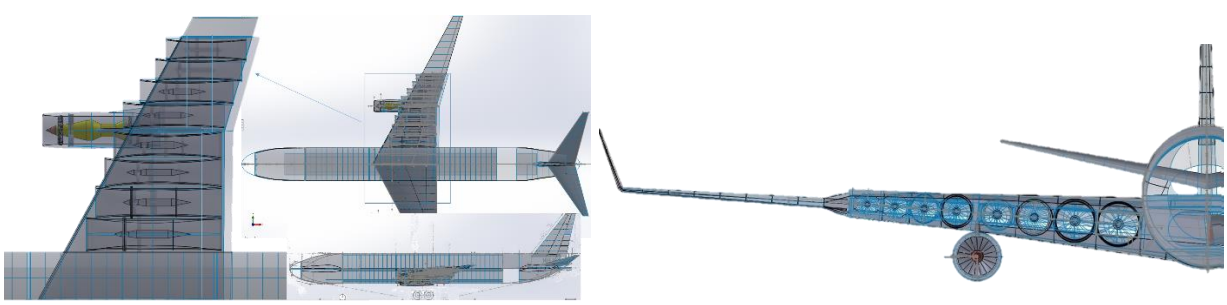


Figure 2. STARC-LEED concept-I with hybrid-electric distributed propulsion integrated into the wing.

The initial STARC-LEED vehicle outer mold line (OML) was developed using the OpenVSP[14,15] software. However, the wing, fuselage, engine and propulsor models did not have sufficient details, so parasolid models of all internal structure were created using SolidWorks, as shown in Fig. 2. Detailed finite element models of the N3CC and the two final STARC-LEED concepts are analyzed in this paper for structural design and weight prediction using SolidWorks Sim[12] simulation software. Figure 2 also shows the full vehicle assembly of the STARC-LEED concept-I

with sixteen electric fans, which are embedded in the wing. Two underwing turbine engines drive electric generators that power the distributed electric propulsors. Figure 3 shows a second distributed concept (STARC-LEED concept-II) in which the electric fans are integrated between the main wing and an upper wing, that has a shorter span. Multiple airfoil-shaped chordwise pylons in-between the fans attach the upper wing with the main wing.

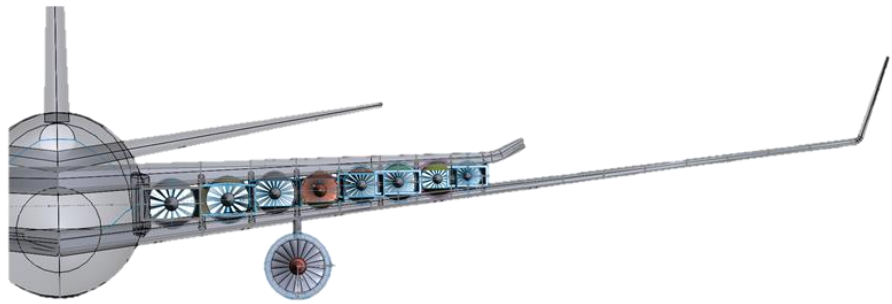


Figure 3. STARC-LEED concept-II with electric fans integrated between the main wing and an upper wing.

The general structural analysis process starts with development of the detailed geometry, parts, and assembly within SolidWorks. This is followed by assignment of material properties, component thicknesses, and design loads. After successful meshing and finite element analysis, the stress and displacement results are plotted and the safety factors are checked. Component skin thicknesses are selected and additional structural elements are inserted or redesigned for better stress distribution and displacement reduction. The design steps are as follows:

1. Develop detailed geometry and finite element model of parts and assembly.
2. Apply material properties, loads, and boundary conditions.
3. Generate a finite-element mesh and perform FEM analyses of parts and assembly.
4. Plot stress, strain, displacement, and safety factor distributions.
5. Resize and redesign for stress and deformation reduction.
6. Repeat steps 1 through 5 for design feasibility and improvement.
7. Compute structural weight of each component and assembly.
8. Compare the computed weights with existing empirical estimates.

Several analysis cycles are often necessary for both components and the whole assembly before a reasonable engineering design is obtained that meets design constraints and exhibits weight reduction from the previous design.

III. Results

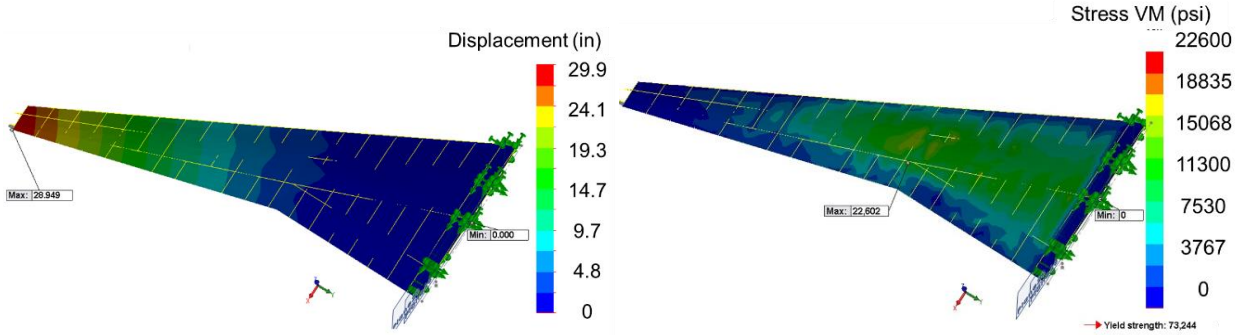


Figure 4. Deflection and stress distribution of N3CC wing with ultimate design load.

The conventional wing of the N3CC configuration (Fig. 1e) serves as the structural baseline for evaluation of the unconventional wing structural concepts. The structural weights of the N3CC and STARC-LEED wings will be compared to determine the structural weight benefits (if any) of the STARC-LEED wing concepts. Figure 4 shows structural deflection and stress distributions for the conventional N3CC wing at the 2.5g pull-up lift load with 160,000 lb takeoff gross weight and a safety margin of 1.5. This ultimate design load is simulated with a spanwise elliptic pressure distribution on the upper wing surface. The material assumed is 7075-T6 aluminum alloy. For this analysis,

all skin, rib, and spar thicknesses are assumed to be 0.2 inch. The maximum deflection is 30 inches and the maximum von Mises stress is 22,600 psi. For this conventional N3CC wing, the computed FEM weight is 3979 lb per side.

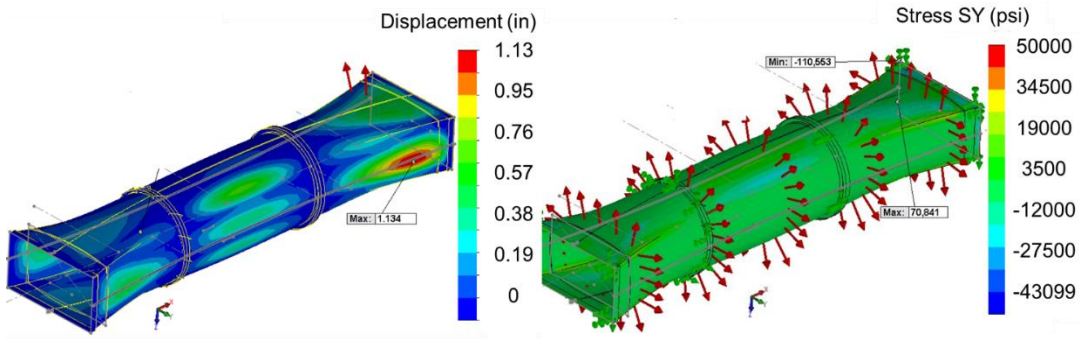


Figure 5. A fan duct displacement and stress analysis example with 2 psi internal pressure.

A unique aspect of the STARC-LEED wing structure is the internal propulsion ducting. Figure 5 shows deflection and stress distribution from initial finite element analysis of the first inboard fan duct with an internal design pressure of 2 psi and advanced composite material properties.[12] The displacement analysis shows 1.13 inch deformation near the rectangular outlets, which required additional reinforcement supports in addition to lengthwise ribs. The circular mid-section of the ducts is reinforced with two blade containment hoops to reduce overall stresses, which are generally below 50,000 psi. However, there are certain high stress areas, which will require local reinforcements. From the FEM analysis, the total fan duct weight of the four inboard ducts is estimated to be 505 lb. For the four outboard fan ducts, total weight is estimated to be 255 lb. Duct weights includes the outer shell, reinforcements at the rectangular inlets and outlets, blade containment hoops, and chord-wise ribs. The total 760 lb weight of eight ducts do not include the internal rotary components or motors. The entire hybrid-electric propulsion system concept along with detailed geometry of each propulsor was developed and evaluated at NASA Glenn. The total weight of the propulsion system was estimated with the NPSS/WATE++ code.[16]

Figures 6 and 7 show the STARC-LEED concept-I wing model internal structure development, assembly, and initial analysis results. In this initial configuration, four fans are placed inside the wing, inboard of the turbo-generator, and four fans are placed outboard. Figure 6 also shows the internal spar and rib structure. The inboard ribs are placed between the propulsors. In the finite element model, the upper and lower skins at the inboard section cover the entire propulsors to form chordwise and spanwise streamlined wing surfaces.

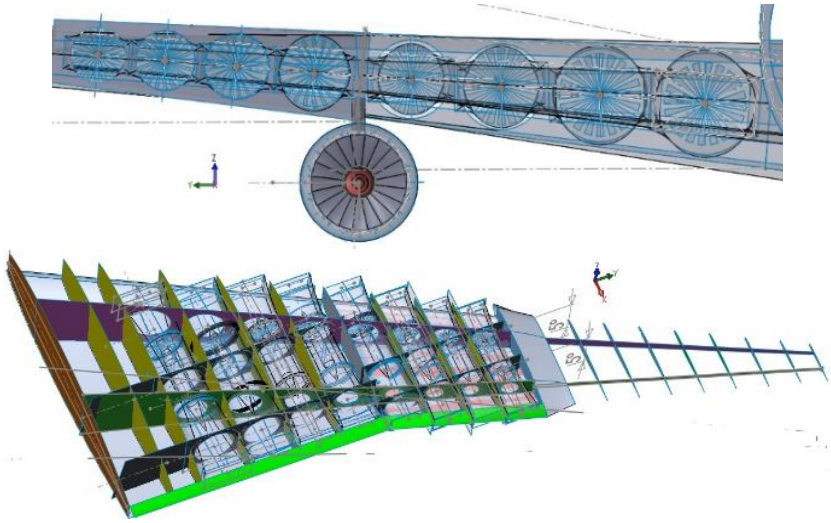


Figure 6. STARC-LEED concept-I wing and fan duct internal structure development.

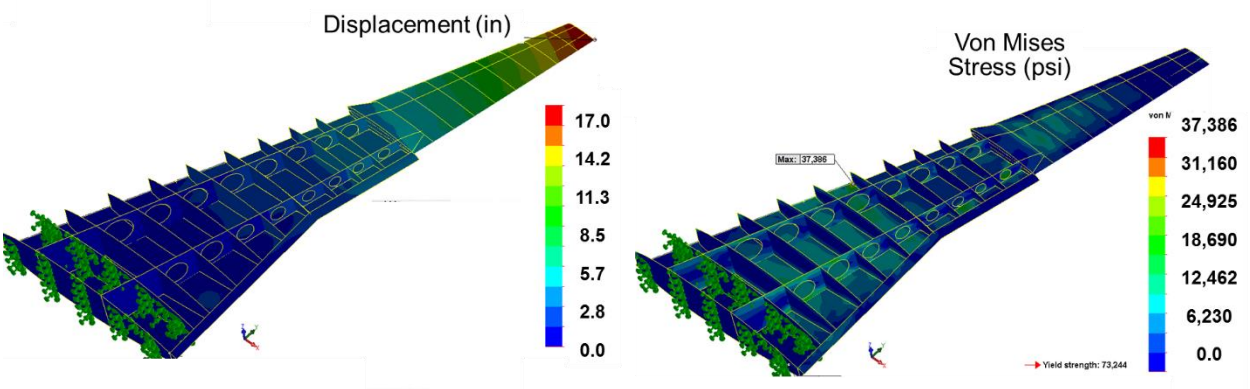
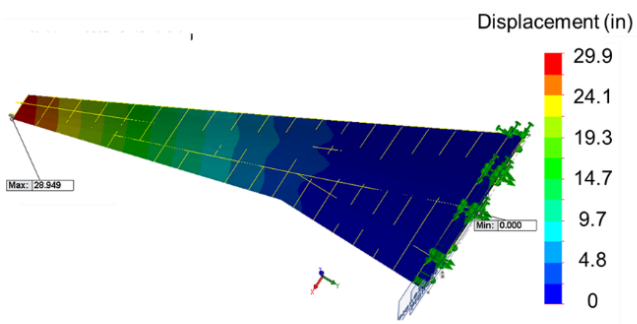
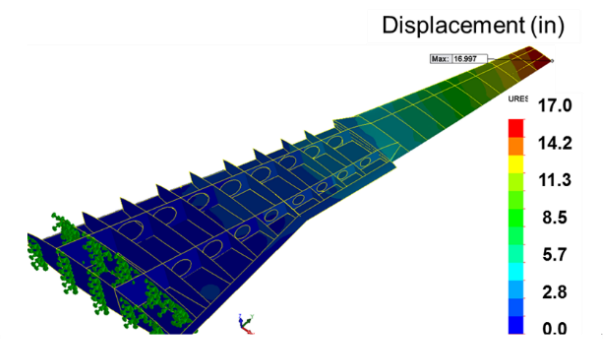


Figure 7. Deflection and stress distribution of STARC-LEED concept-I wing with ultimate design load.

The STARC-LEED concept-I wing has higher bending stiffness at the inboard section than that of the N3CC wing. The higher bending stiffness of the wing is due to the higher rib and spar heights. The upper and lower skins on the inboard wing are farther apart to enclose the embedded fan ducts. This wing and airfoil cross-section geometry increases the bending stiffness. Therefore, a smaller skin thickness of 0.05 inch can be used. The wing has a rib thickness of 0.1 inch, and spar thickness of 0.2 inch. At the mid-wing transition fairing area, skin thickness is 0.1 inch. Figure 7 shows the wing deflection and von Mises stress distributions at the 2.5g ultimate design load condition. This wing has lower deflection than that of the N3CC wing (Fig. 4) for the same wing load. The maximum von Mises stresses are higher, but within the allowable limits. In Fig. 7, the upper cover of the inboard section of the wing is removed to show the internal rib and spar arrangement for accommodating the fan ducts. The inboard front and rear spars have large cutouts for this purpose. Large stresses occur near these cutouts and will require local reinforcements. The STARC-LEED concept-I wing has a maximum deflection of 17 inches at the wing tip. The maximum von Mises stress is ~37,000 psi at the mid-wing transition area and spar cutouts, but this value is well within the allowable limits of the 7075-T6 aluminum alloy material (~73,000 psi).



N3CC Conv One wing	surf area (in^2)	thickness (in)	density (lb/in^3)	weight (lb)
Inner Wing skin (upper+lower)	65170	0.2	0.1	1303
outerwing skin (upper and lower)	38912	0.2	0.1	778
wing rib average area x 20	70440	0.2	0.1	1409
front spar	14129	0.2	0.1	283
rear spar	10320	0.2	0.1	206
Total weight				3979



STARC-LEED-I One wing w/o fan ducts	surf area (in^2)	thickness (in)	density (lb/in^3)	weight (lb)
inner wing skin (upper+lower)	117560	0.05	0.1	588
mid wing skin (upper+lower)	39039	0.05	0.1	195
outerwing skin (upper+Lower)	41247	0.05	0.1	206
inner wing average rib area (7)	78141	0.1	0.1	781
mid wing average rib area (5)	18775	0.1	0.1	188
outer wing average rib area (10)	4760	0.1	0.1	48
front spar with holes	17375	0.2	0.1	348
rear spar with holes	15432	0.2	0.1	309
flaps+mid skin fairing	12027	0.1	0.1	120
Total weight				2782

Figure 8. Comparison of the N3CC and STARC-LEED-I wing deflections and FEM weights (one side).

Figure 8 shows a comparison of the deflections for the baseline N3CC wing (from Fig 4) and the STARC-LEED concept-I wing (from Fig. 7) and the corresponding FEM weight estimates of one (right or left) side wing. The FEM weight of the N3CC conventional wing is estimated to be 3979 lb (one side). The wing FEM weight of the STARC-LEED concept-I is 2782 lb per side, which is 1197 lb (or 30%) less than that of the N3CC wing. But this ~2400 lb

weight saving (for two wings) is only a fraction of the additional propulsion system weight associated with the distributed electric propulsion system. The weight of 8 ducts will add 760 lb per side. Although the STARC-LEED concept-I wing design results in a structural weight savings compared to the N3CC wing, this only partially offsets the additional weight associated with the distributed electric propulsion system. The 16 electric motors alone add an additional propulsion system weight of almost 4000 lb to STARC-LEED. Therefore, the STARC-LEED concept as a whole has a weight disadvantage compared to the N3CC. The aerodynamic drag differences will also affect overall performance.

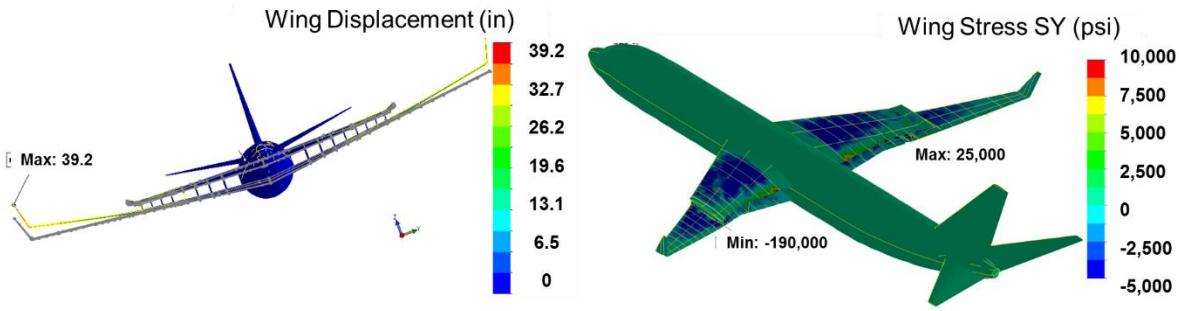


Figure 9. STARC-LEED concept-II wing deflection and stress with ultimate design load.

Integration of the propulsors into the concept-I wing led to a number of compromises in the wing planform and airfoil geometry. Concept-II was developed as an alternative approach to avoid some of the geometric integration challenges faced with concept-I. This arrangement facilitates better access to the electric-propulsors for maintenance, and perhaps results in cleaner aerodynamic flow. Figure 9 shows the wing displacement and stress analysis results for the alternative STARC-LEED Concept-II (Fig. 3). In the initial analysis with 7075-T6 aluminum alloy, using all skin and rib thicknesses of 0.1 inch and all spar thicknesses of 0.5 inch, the wing tip deflection is 39.2 inch at the 2.5g ultimate design load. There are still some design and modeling issues at the wing-pylon junctions, which exhibit large local stresses. But, in general, the tensile and compressive stresses on the wing skin in the spanwise direction are fairly low, indicating this might be an over-design. Based on this single ad-hoc design, the right upper and lower wing weight are 2193 lb and 2666 lb, respectively. The total weight of nine pylons between the eight propulsors is 1061 lb. Total wing weight is 5920 lb. The deflection are higher than those for the N3CC conventional wing (Fig. 4) and the STARC-LEED concept-I wing (Fig. 7). Although, this configuration is very innovative, additional high fidelity structural design optimization of the wing is necessary to reduce the structural weight.

IV. Conclusions

The emission, noise, propulsion, and aerodynamic performance enhancements associated with distributed hybrid-electric propulsion come at the cost of additional weight from the electric power distribution system, generators, and electric propulsors. It has been postulated that the greater structural depth associated with a wing embedded propulsion approach would provide a structural weight advantage over conventional configurations. Detailed finite element models of two such concepts have been developed and analyzed. The structural integration of the electric propulsors embedded inside the wing or between a partial bi-wing are key factors in these wing designs. A number of design scenarios have been examined through a knowledge-based iterative analysis process to arrive at a wing structural configuration and weight estimation. The initial finite element model analysis of one hybrid-electric propulsion wing concept shows a potential reduction in the structural weight when compared to that of the conventional wing. This reduction, however, will only partially compensate for the additional weight associated with the distributed electric propulsion system. A second concept was developed to address some of the propulsion integration challenges encountered with the first. Initial structural analysis of this design indicates that the wing structural weight is actually higher than that of the baseline conventional wing. This particular concept, therefore, does not appear to offer any structural weight advantage to offset the higher propulsion system weight. The result of this work shows this distributed hybrid-electric propulsion concept has a net weight disadvantage that will have to be offset by aerodynamic and propulsion efficiency advantages in order for the concept to have a system level fuel consumption benefit. Although these initial weight results are not favorable, additional follow-up structural and aerodynamic analyses are necessary for the two hybrid-electric propulsion concepts in order to assess their overall system level performance.

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