

# Truss-Braced Wing Literature Review: Current State and Technical Challenges

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## Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
<b>2</b>	<b>State of the Art</b>	<b>3</b>
2.1	SUGAR Phase II (circa 2012)	4
2.2	SUGAR Phase III (2016)	4
2.3	SUGAR Phase IV (2023)	4
2.4	NASA's Parallel Efforts	4
<b>3</b>	<b>Technical Challenges</b>	<b>5</b>
3.1	Aerodynamic Challenges	5
3.1.1	Drag reduction vs. interference and parasitics	5
3.1.2	Wing-Strut Interference Effects	5
3.1.3	Transonic and High-Speed Behavior:	6
3.1.4	High-Lift and Low-Speed Aerodynamics:	6
3.1.5	Aeroacoustic Considerations:	7
3.2	Structural Challenges	7
3.2.1	Weight and Structural Efficiency	7
3.2.2	Structural Design of the Strut and Joints	8
3.2.3	Flutter and Aeroelastic Constraints	9
3.2.4	Manufacturing and Certification	9
3.3	Aeroelastic and Stability Challenges	10
3.3.1	Flutter Margin and Vibration Modes	10
3.3.2	Limit Cycle Oscillation (LCO)	10
3.3.3	Geometric Nonlinearity and Large Deflections	11
3.3.4	Active Aeroelastic Control	11
<b>4</b>	<b>Manufacturing and Integration</b>	<b>12</b>
4.0.1	Airport Compatibility (Span and Folding Wings):	12
4.0.2	Maintenance and Inspection	13
4.0.3	Manufacturing Processes	13
4.0.4	System Integration	13

5	Gaps and Future Work	14
6	Conclusion	15
7	Annotated Bibliography	16

# 1 Introduction

Over the past 50 years, Truss-braced wings (TBWs) have emerged as a credible path to higher aerodynamic efficiency. In a TBW, external struts, or trusses, brace an ultra-high-aspect-ratio wing, carrying part of the bending load. This is different from the conventional cantilever approach, which is approaching a performance plateau. Shifting bending loads to the strut lets the wing be thinner and lighter without sacrificing strength. In turn, the longer and thinner a wing is, the more its lift-to-drag ratio increases, and thus the lower the induced drag. Lower thickness also delays transonic wave drag and allows less sweep, enabling larger regions of natural laminar flow. The result is better fuel economy: smaller engines can meet thrust needs, reducing fuel burn, emissions, and noise. In short, TBW pairs structural and aerodynamic gains to deliver a step forward towards more sustainable aviation.

TBW are not new. NASA explored braced wings as early as the 1970s [5], but the idea was pretty much shelved while the industry refined conventional designs. Interest returned in the late 1990s and early 2000s. Gundlach et al analyzed a transonic passenger aircraft with a strut-braced wing and showed meaningful fuel-burn reductions [7], identifying key drivers: strut attachment location, sweep, and thickness. They demonstrated that careful optimization can boost lift-to-drag without unacceptable weight penalties [7]. As environmental concerns became more mainstream, NASA launched the Subsonic Ultra Green Aircraft Research (SUGAR) program. Boeing’s Phase I study (Bradley & Droney, 2011) highlighted the transonic truss-braced wing as a leading next-generation single-aisle concept for 2030–2035, citing large cuts in fuel, emissions, and noise relative to contemporary aircraft [1]. At the same time, other studies were advancing the concept. Gur et al. (2010) used multidisciplinary design optimization to compare cantilever, single-strut-braced, and full “truss”-braced wings, finding roughly 45 percent lower fuel use and about 15 percent lower gross takeoff weight versus a conventional design, without reducing cruise speed [8].

Overall, TBW research targets large aerodynamic gains by pairing very high aspect ratio wings with smart structural support. The motivation lies in the diminishing returns from today’s tube-and-wing designs and the need to reduce fuel emissions. Over the past two decades, work led by NASA, Boeing, and others has moved TBWs from early studies to detailed designs. The next sections will cover the state of the art, the principal technical challenges addressed to date, and the remaining gaps guiding future work.

## 2 State of the Art

Extensive work has pushed the TBW from concept to a refined design. Much of the recent progress has come through NASA’s SUGAR program (from around 2008–2018), where Boeing and partners advanced the configuration across four phases using iterative optimization, high-fidelity simulation, and wind-tunnel testing.

## 2.1 SUGAR Phase II (circa 2012)

By Phase II, the team had produced a detailed single-aisle TBW with aspect ratio near 20 using MDO [2]. The target was sizable fuel-burn cuts relative to a 2008 baseline. Aeroelastic analysis and Transonic Dynamics Tunnel tests showed flutter behavior was predictable and manageable, and that the span-driven weight increase did not erase the aerodynamic gains of the high-AR wing. In short, the concept proved structurally feasible with contemporary materials and capable of a net efficiency benefit.

## 2.2 SUGAR Phase III (2016)

Phase III focused on a Mach 0.75 transonic TBW. The team applied higher-fidelity Navier–Stokes CFD and built a 4.5 percent-scale model for wind-tunnel tests [3]. Results remained consistent, with cruise drag matching earlier estimates within 1 percent. Drag accounting showed that the main strut contributed roughly 10 percent of total aircraft drag, with only about 1 percent from wing–strut interference. This is a modest trade for the induced-drag alleviation from span. Drag-rise data aligned with the CFD model, indicating that the strut did not negatively affect transonic aerodynamics or reduce achievable cruise speed. Stability and control trends also kept in line with predictions, suggesting TBW handling can mirror conventional aircraft. Phase III finalized a geometry suitable for high-speed testing and, ultimately, a demonstrator. System-level projections were strong: about 57 percent lower fuel burn versus a 2008 single-aisle when combined with advanced engines, aerodynamics, and structures.

## 2.3 SUGAR Phase IV (2023)

Phase IV [4] increased cruise speeds from Mach 0.75 to Mach 0.80 with little trade-off. High-fidelity RANS showed that the TBW is well suited to Mach 0.80 cruise. Against an advanced tube-and-wing (aspect ratio 13), the TBW cut per-seat fuel by about 7–9 percent on typical 900 nmi and 3500 nmi missions. Bundled with other SUGAR technologies (engines, aerodynamics, electrification, etc.), total reduction reached roughly 56 percent relative to a 2008 single-aisle. Practical items also moved forward, such as a preliminary high-lift system, folding wingtips for airport compatibility, and refined load-alleviation concepts. No fundamental show-stoppers were identified; high-fidelity analyses even exceeded initial expectations, and structural maturation found no obvious build barriers.

## 2.4 NASA’s Parallel Efforts

Alongside SUGAR, NASA ran internal studies and coordinated projects spanning wind-tunnel campaigns, tool development, and integrated design. Wells, Gatlin et al. (2024) review this work from early 1970s braced-wing studies through to the 2010s [5]. The program has been motivated by environmental goals, and TBWs are viewed as a potential step to help meet the USA’s net-zero 2050 targets while remaining commercially viable. This line of research naturally leads to the next milestone: a full-scale demonstrator initiative.

## 3 Technical Challenges

Truss-braced wings show clear promise, but turning the concept into a product means solving problems in aerodynamics, structures, aeroelasticity, and real world integration. Below are outlined the main issues and how recent work addresses them.

### 3.1 Aerodynamic Challenges

#### 3.1.1 Drag reduction vs. interference and parasitics

The TBW’s core aerodynamic benefit is straightforward: push aspect ratio higher to reduce induced drag. Bracing lets the wing grow longer and thinner because the strut shares lift-induced bending loads. The trade, however, is added parasite drag from the strut itself and flow interference at the wing–strut junction. The design goal is net drag decrease once everything is accounted for.

Recent studies quantify these effects. Grazioso & DeMarco (2024) show that on a regional turboprop, an SBW reduces induced drag but (1) increases parasite drag due to the strut and (2) loses some of the induced-drag gain to wing–strut interference that reshapes the spanwise lift and pressure fields [10]. This makes strut airfoil selection, junction fairings, and spanwise/angle placement important design considerations. Consistent with that, Gur et al. (2010) demonstrated via MDO that tuning strut geometry and wing sweep can yield a sizable net fuel-burn reduction with an appropriately configured truss[8]. In practice, mature TBW designs have achieved the desired balance: Boeing’s SUGAR Phase III reported wing–strut interference at only around 1 percent of total aircraft drag, a small penalty relative to the induced-drag relief from the high-span wing. High-fidelity analysis and targeted testing are therefore sufficient to manage these aerodynamic trades.

#### 3.1.2 Wing-Strut Interference Effects

The flow interference at the wing–strut junction is an aerodynamic issue. The strut can be thought of as creating a local high-pressure region on the wing’s underside where it attaches, as well as shedding its own wake. High-fidelity CFD analysis by Xiong et al. (2021) gives insight into these interference effects at cruise. Their study compared a Mach 0.8 TBW aircraft in two configurations: with the strut and without (wing-alone). The simulations revealed that the presence of the strut induces a suction peak on the wing’s lower surface near the junction, which slightly modifies the pressure distribution on the wing [9]. In essence, the strut’s lift causes a low-pressure region beneath the wing where they meet, increasing local lift in that area. While this may seem like an advantage, any distortion of the spanwise lift distribution away from the ideal elliptical shape can increase induced drag. Xiong’s work found that at Mach 0.8, the interference effects were more pronounced than in a similar design at Mach 0.745, meaning as cruise speed increases, the wing-strut interaction becomes more pronounced. To account for this in design, the team developed a correction model that can be used in lower-fidelity aerodynamic tools (like VSPAERO vortex-lattice codes) to approximate the interference effects without full CFD. The existence of such models is important for early-stage design studies, and also also shows that empirical data on strut/wing intersections is limited (as Boeing noted in Phase III,

no prior database existed). Today’s state-of-the-art TBW designs incorporate lessons from these analyses. For instance, there is interest in offsetting the strut attachment point slightly outboard or inboard to minimize shock and interference drag. Harrison et al. (2023) report that an “outboard offset” strut concept could further reduce wing-strut interference drag in the Mach 0.8 design [4]. In summary, managing the interference aerodynamics involves optimizing strut placement, shaping the joint fairing, and sometimes adjusting the wing’s lift distribution (even via slight twist or camber changes) so that the net effect of adding the strut is beneficial.

### **3.1.3 Transonic and High-Speed Behavior:**

Another key aerodynamic challenge for TBWs is maintaining good performance at transonic cruise speeds (Mach 0.75–0.85). High aspect ratio wings are typically associated with gliders or slow-flying aircraft, but airliners must cruise near the speed of sound. The TBW’s slender wing, if not carefully designed, could be more prone to shock-induced flow separation or have a lower drag-divergence Mach number (the Mach number at which drag rapidly rises due to shock waves). The TBW concept initially considered slightly lower cruise speeds (Mach 0.70–0.75 in some early studies) to leverage its efficiency. However, airline economics favor keeping cruise speed high. Thus, researchers have worked to ensure TBWs can fly at Mach 0.78–0.80 without sacrificing too much efficiency. Phase IV of SUGAR showed that a TBW can indeed be designed for Mach 0.80 cruise with positive results [4]. The wing’s thinness actually helps delay strong shock formation (less thickness means weaker shocks for a given lift coefficient). Boeing’s Phase III report noted that aerodynamic operability requirements were met at the cruise Mach number for their Mach 0.75 design [3], meaning the aircraft had acceptable lift, stability, and control up to that speed. However, at the higher end of the envelope (the maximum operating Mach), they flagged some uncertainty in the buffet margin. Buffet occurs when shock-induced separation causes the wing to shake; having a safe margin means the aircraft can cruise comfortably below the buffet onset. The uncertainty arose because traditional buffet prediction methods are based on conventional cantilever wings and may not directly apply to a strut-braced wing. The strut could alter the pressure distribution and dynamic response in ways that aren’t captured by existing empirical models, so this remains a topic for further investigation. One suggestion from Boeing’s Phase III study was to explore active technologies to mitigate buffet at high Mach (for example, perhaps active spoilers or maneuver load alleviation) without compromising normal operations. Thus, while current TBW designs are capable of transonic flight, ensuring a robust buffet margin and high-speed stability is an ongoing concern. It’s an area where additional wind tunnel tests (at high Reynolds numbers and transonic conditions) or even flight testing will be very valuable to validate the predictions.

### **3.1.4 High-Lift and Low-Speed Aerodynamics:**

Another aerodynamic challenge is the design of the high-lift systems (flaps, slats) and ensuring good low-speed behavior. The TBW, being very slender and possibly having a greater vertical flex due to the strut, might have different stall characteristics than a conventional wing. There’s also less room to accommodate flap mechanisms in a thin wing. SUGAR

Phase IV research included a preliminary assessment of high-lift devices for TBWs, but this remains a less-publicized aspect in literature. Additionally, because TBW wings are so long, there was concern about ground clearance for wing tips during takeoff/landing. One solution is wingtip folding, akin to what is used on the Boeing 777X, to reduce span on the ground. Harrison et al. (2023) mention that practical systems like folding wingtips were addressed to ensure airport compatibility [4]. These considerations tie into integration, but they begin with aerodynamic design (designing a fold that doesn't disrupt the wing aerodynamics, etc.). Overall, the aerodynamic feasibility of TBWs has been demonstrated. The focus has now shifted to refining details and ensuring no adverse behaviors exist at the edges of the flight envelope (high Mach buffet, low-speed stall, etc.).

### **3.1.5 Aeroacoustic Considerations:**

Although not a primary driver, the TBW configuration has unique aeroacoustic characteristics that researchers have started to examine. Changes in airframe aerodynamics often lead to changes in airframe noise (for example, high aspect ratio wings might produce different turbulent wake patterns, and the strut could generate its own noise sources). Ferris & Khorrami (2024) conducted high-fidelity lattice-Boltzmann simulations to predict the aeroacoustic performance of a TBW in both cruise and landing configurations [18]. One finding was that the wing-strut junction can create distinct tonal noise at cruise speed due to local flow phenomena (like vortex shedding or small separation bubbles), which is a new source not present on conventional aircraft. In landing configuration, as expected, the dominant noise sources remain the high-lift devices (leading-edge flaps) and landing gear, similar to conventional aircraft. The presence of the strut didn't introduce any showstopping noise issues. In fact, the overall acoustic footprint of a TBW design is predicted to meet future Stage 5 noise standards and is comparable to or even slightly better than an equivalent tube-and-wing aircraft (especially if advances in engine noise reduction are factored in). This is partly because a more aerodynamically efficient wing can allow smaller engines or lower thrust, which reduces engine noise – the primary contributor to total aircraft noise. Aeroacoustics remains a secondary challenge (noise regulations are already quite stringent for all aircraft), but these studies reassure that a TBW can likely be made as quiet as current airliners. Ongoing research into specific noise mitigation (e.g., shaping the strut airfoil or using fairings to suppress vortex shedding) can further ensure TBWs are community-friendly in terms of noise.

## **3.2 Structural Challenges**

### **3.2.1 Weight and Structural Efficiency**

In conjunction with aerodynamic gains, TBWs promise structural benefits if executed properly. The use of a strut or truss to carry wing loads means the wing structure can be lighter than an equivalent cantilever wing, since it doesn't have to resist the full bending moment at the root. In Gundlach's conceptual study, it was noted that the strut-braced configuration resulted in an aircraft that is lighter and requires smaller engines than the cantilever baseline [7]. However, adding a strut isn't a silver bullet. The strut itself adds weight, and the wing

still needs to be robust where the strut attaches. The net effect on weight depends on many factors (wing aspect ratio, materials, load distribution). A central structural challenge is ensuring that the wing weight savings outweigh the weight of the strut and any reinforcement needed. Early in the SUGAR program, this was a big question. By Phase II, Boeing’s team, working with Virginia Tech, demonstrated through detailed design optimization that a TBW with aspect ratio of around 20 could be built with acceptable weight. They reported that the weight increases associated with the larger span did not negate the aerodynamic improvements [2]. In other words, even after accounting for structural reinforcements and the strut weight, the aircraft was significantly more efficient than the baseline. This finding was corroborated by Gur et al. (2010), who found substantial gross weight reductions (on the order of 15–20%) for optimized TBW designs relative to a conventional configuration [8]. Achieving such weight efficiencies likely requires modern composite materials (which offer high strength-to-weight ratios) and careful structural design (e.g., optimizing spars, ribs, and load paths in the wing). The 2000 Lockheed/Virginia Tech study (Gundlach et al.) recognized that projected technology levels and manufacturing methods would impact the design [7]. For example, a TBW might use carbon fiber spars, advanced alloys for fittings, etc., to keep weight low. Thus, one structural challenge is largely material and construction: ensuring the wing and strut can be built as intended with advanced lightweight materials that may not have been available in earlier decades. The TBW concept in many ways has been enabled by the maturation of composite aircraft structures.

### 3.2.2 Structural Design of the Strut and Joints

Adding a strut introduces new structural elements – notably the strut itself and the joints where it connects to the wing and (typically) the lower fuselage. These joints must carry very high loads as the strut is taking a large portion of lift loads. Designing them to be strong, lightweight, and without introducing stress concentrations or buckling issues is not easy. One specific challenge is that as the wing flexes, if the strut is rigidly attached, it could induce bending or shear loads that were not intended, or even over-constrain the structure. Boeing’s Phase IV work came up with an elegant solution in the form of an inboard strut attachment with a swivel joint that allows rotation [4]. This concept enables the strut to carry purely axial loads while avoiding bending moments induced by wing twist or deflection. In doing so, it significantly simplifies the construction of the main strut and alleviates undesirable load paths. This shows how structural innovation is key to TBW feasibility; a pinned or flexible joint can make the difference between a strut that is a simple tie-rod vs. one that tries to “fight” the wing’s natural bending. The outboard end of the strut (attaching somewhere along the wing span) must also be carefully designed, potentially with fittings that distribute the load into the wing spar. As TBW designs progress, we may see additional supports like jury struts or more complex truss frameworks for larger aircraft. Gur et al. (2010) actually examined a three-member truss wing (which could include struts and bracing elements forming a triangle) and found even further performance gains in some cases [8]. However, each additional member complicates the structural layout and adds weight and attachment points. To date, most research prototypes and designs (like the SUGAR aircraft and X-66A) stick to a single strut per wing, likely as a compromise between simplicity and performance. Future studies could revisit multi-strut (“truss”) arrangements if materials or

control systems can mitigate their complexity.

### 3.2.3 Flutter and Aeroelastic Constraints

Structural and aeroelastic challenges are closely linked. This is discussed in more detail next section, however it is worth noting that the flexibility of a TBW wing requires careful tuning of stiffness. The wing must be stiff enough (in torsion and bending) to keep flutter speeds above the operating range and to maintain aeroelastic stability. This often means distributing material in the wing to increase torsional rigidity (since a thin wing can be more prone to twist). Interestingly, the strut can either help or hurt here. A properly placed strut can raise some vibration frequencies (good for flutter) but can also introduce new modes. Bhatia et al. (2011) performed a parametric aero-structural analysis varying wing aspect ratio and strut parameters; they found that while adding a strut dramatically reduces wing bending (as expected), it can lower the flutter speed if not optimally configured [20]. Essentially, the strut changes the wing’s modal characteristics. This is a structural challenge in the sense that the wing and strut must be designed together (aeroelastically tailored) to avoid any dangerous resonances. This is addressed more under Aeroelasticity, but structurally it means one can’t oversimplify – one might need additional damping or tailoring of stiffness.

### 3.2.4 Manufacturing and Certification

From a structural engineering perspective, TBWs introduces manufacturing challenges. Building a very high aspect ratio wing (with possibly a unique planform) will push the limits of current aircraft assembly. The wing may require novel manufacturing techniques to handle its length and slenderness without distortion. Additionally, integrating the strut likely means new assembly sequences such as joining the strut to the wing and fuselage with large pins or fittings. These processes need to be reliable and inspectable. Early studies like Gundlach’s explicitly called out the importance of considering manufacturing and certification issues during design [7]. For example, certifying the strut joint as a fail-safe structure (ensuring redundancy if a strut were to fail or yield) could be a certification requirement due to its critical load-bearing role. The TBW’s unconventional structure may also need new ground test procedures (to validate the wing-strut load sharing) and analysis methods for damage tolerance. While these are not insurmountable issues, they do represent a challenge in that aerospace manufacturers and regulators will be dealing with a configuration outside their historical experience. Boeing’s plan to convert an MD-90 into the X-66A demonstrator, now on pause, had promised real-world insights into constructing and attaching truss-braced wings. It would have taught how to create a long, ultra-thin wing, maintain tight tolerances across large spans, and manage oversized structural components in a factory. But since Boeing and NASA have shifted development toward a ground-based thin-wing testbed instead of building the MD-90 demonstrator, those tangible manufacturing lessons are deferred.

In summary, the structural challenges of TBWs revolve around maximizing the benefit of the strut (lighter wings) without introducing new weaknesses. So far, research suggests that with current advanced materials and design techniques, TBWs can indeed be built to meet all requirements. The evolution of joint concepts (like the swivel) and possible use of multiple struts are ongoing developments to further improve structural efficiency. The

real proof will come when large-scale hardware is built and tested, but the groundwork in analysis and sub-scale tests has been positive.

### 3.3 Aeroelastic and Stability Challenges

Perhaps the most critical challenges for TBW configurations lie in the realm of aeroelasticity, which is the intersection of aerodynamics and structural dynamics. A TBW wing is more flexible than a conventional wing, which means phenomena like flutter, divergence, and dynamic response require special attention. Researchers have devoted significant effort to ensuring TBW aircraft can fly safely without aeroelastic problems.

#### 3.3.1 Flutter Margin and Vibration Modes

Flutter is a dynamic instability where aerodynamic forces and structural vibrations reinforce each other, potentially causing destructive oscillations. High-aspect-ratio wings, being more flexible, usually have lower baseline flutter speeds. Introducing a strut adds a new structural mode (like a strut bending or pivot mode) that could couple with wing bending/torsion modes. Ensuring the flutter speed is comfortably above the operating speed is a critical requirement. In SUGAR Phase II, Boeing and NASA performed aeroelastic analysis and a TBW wind-tunnel test in NASA’s Transonic Dynamics Tunnel. The team validated that their models could predict the dominant flutter mechanism and minimum flutter speed and demonstrated flutter suppression with control laws (on an AR  $\sim 20$  wing)[2]. This was a critical milestone, showing that classical aeroelastic stability can be achieved. Nonetheless, as mentioned earlier, subsequent studies have indicated that strut placement and wing stiffness distributions need to be tuned to maintain a good flutter margin. Bhatia, Kapania & Haftka (2011) ran a parametric aero-structural study of truss-braced wings, varying semi-span (aspect-ratio proxy), strut sweep, and the wing-strut attach point. Through this they found that while the strut lowers wing bending moments, certain configurations can also reduce flutter speed due to unfavorable coupling. Designers can mitigate this by tuning the relative wing/strut sweep, moving the attach point, and adjusting local stiffness to detune the critical mode [20]. These insights show that aeroelastic analysis must be integrated from the start in TBW design, and a true multidisciplinary approach is required.

#### 3.3.2 Limit Cycle Oscillation (LCO)

A phenomenon observed in TBW studies is limit cycle oscillation, where instead of divergent flutter, the wing/strut system oscillates at a steady amplitude. This can happen when nonlinear effects (like structural or aerodynamic nonlinearities) lead to self-limited vibrations. Bartels et al. (2015) showed that high-fidelity aeroelastic simulations with FUN3D and a nonlinear structural model can successfully reproduce the LCOs observed in the truss-braced wing wind-tunnel tests. The results confirmed that LCO onset is highly sensitive to structural stiffness and mass distribution, and that oscillation amplitude depends on angle of attack (largest at  $0^\circ$  and reduced at  $\pm 1^\circ$ ). They also demonstrated that Mach effects near transonic speeds shift the onset boundary, underscoring how small changes in configuration or flow condition can decisively affect flutter and LCO behavior [13]. This asymmetric behavior

with angle of attack suggests subtle interactions between aerodynamics and structure (likely due to how the wing loading shifts). They also saw differences between successive versions of their structural model. Updating the FEM to a newer version (v20) that captured more nonlinear detail increased the dynamic pressure at which LCO started, meaning a better-designed or modeled wing could push these oscillations to higher speeds. The fact that LCO was observed is not that alarming, as many flexible systems have some LCO in transonic flow. However, it needs to be controlled because persistent oscillations can cause fatigue or passenger discomfort. The TBW studies so far suggest that with high-fidelity modeling, one can predict LCO and possibly design it out or damp it. For instance, adjustments to the wing stiffness or adding passive/active dampers could suppress these oscillations. The NASA/Boeing team’s ability to correlate simulation with wind tunnel LCO is a strong validation of their tools, implying they can be confident in real aircraft predictions.

### 3.3.3 Geometric Nonlinearity and Large Deflections

With a very high aspect ratio, even the static aeroelastic deflections (bending under load) become significant. The wing of a TBW aircraft will bend and twist more than a normal wing in cruise, which alters its angle of attack distribution. Small angle assumptions made for small deflections may no longer hold. Huang, Chen & Ma (2025) very recently addressed this by performing geometrically nonlinear static analysis on a high-aspect ratio TBW wing [14]. Using a nonlinear beam model for the wing and a vortex-lattice method for aerodynamics, they studied how the spanwise joint location (i.e. where the strut attaches along the span) affects the wing’s deformation and load. Their results confirmed a couple of intuitive, but important, points. Firstly, the strut significantly reduces overall wing bending (thus reducing tip deflection), and secondly, the position of the strut changes the deflection shape and load distribution. If the strut attaches more inboard (closer to the wing root), it relieves less of the outboard wing’s load, so the outboard wing can still bend considerably (high outboard flexibility). If the strut attaches further outboard, it carries load further out on the wing, reducing outboard bending but slightly increasing bending in the inboard segment. Thus, there’s a trade-off in picking the attach point. It influences not just stress in the wing but also how the wing will twist under load, which can impact aerodynamic efficiency. The key conclusion from Huang’s study is that linear models can mis-predict deflections for such slender wings, meaning incorporating geometric nonlinearity is necessary for accurate design. It follows that the final wing shape in cruise might be quite different from its shape on the ground, and designers could even exploit that (like designing a slightly “pre-twisted” wing that becomes optimal under load). All of this complexity is being actively researched so that by the time a TBW is built, engineers will have reliable predictive tools.

### 3.3.4 Active Aeroelastic Control

Because the TBW is flexible, it also presents opportunities for active control to improve performance or stability. One frontier area is using control surfaces or morphing devices to aeroelastically tailor the wing in flight. Xiong, Nguyen & Bartels (2023) explored this by looking at how small deflections of high-lift devices (like flaps) and control surfaces could reduce drag at cruise in a TBW design. By deflecting these surfaces optimally, they achieved

an aeroelastic trim that minimized drag, essentially altering the load distribution on the wing to be closer to ideal. The result was a drag reduction of about 6–10 drag counts (depending on lift coefficient), corresponding to roughly 1% with the original jig twist and up to 2–3% with an optimized jig twist at Mach 0.8 [11]. In addition to drag benefits, such control strategies can help alleviate wing bending (like a maneuver load alleviation system) and potentially raise flutter margins by actively damping out vibrations. While Xiong et al. focused on drag optimization, the underlying idea is the same for stability. You could use sensors and control surfaces to suppress any flutter mode or oscillation. However, implementing such systems adds complexity and requires fail-safe redundancy (you wouldn't want the aircraft to rely on active control for basic stability unless it's proven extremely robust). Thus, current TBW designs tend to ensure passive stability first (through structural and aero design), with active control as an additional safety or performance layer.

In summary, the aeroelastic challenges of TBW are significant but appear to be surmountable with current technology and careful design. The extensive simulations and wind tunnel tests done so far indicate that a TBW can be built to avoid flutter and manage dynamic responses within the flight envelope. Research continues to refine these predictions and explore advanced solutions like active control. The conservative approach is to build a TBW that is aeroelastically stable on its own (passive), and use modern control systems to provide extra margin and efficiency.

## 4 Manufacturing and Integration

### 4.0.1 Airport Compatibility (Span and Folding Wings):

Beyond the aerodynamic, structural, and aeroelastic considerations, TBW aircraft must also be feasible to manufacture, operate, and integrate into the existing aviation system. Several practical challenges have been identified in this realm, from airport compatibility to maintenance.

The main point of TBW designs is a substantially increased wingspan compared to equivalent conventional aircraft. A longer span improves efficiency but raises questions such as "can the aircraft fit at airports"? Airports classify aircraft by "design group" based on wingspan (and tail height), which dictates gate spacing, taxiway width, etc. A next-gen single-aisle airliner with a TBW could easily have a span reaching 170 feet or more (for reference, a Boeing 737 MAX span is ~118 ft, and a TBW variant might approach the 200 ft class). To address this, Chatterji, Sridhar & Palopo (2025) conducted a study of airport operations for a transonic TBW aircraft. They computed the required wingtip folding angles and looked at 77 major U.S. airports to see where a TBW could operate. Their findings were optimistic. The conceptual TBW airliner could operate at most large airports without needing to fold its wings [15]. Essentially, the span, while large, was still within the capacity of many big hubs (perhaps similar to a Boeing 777 in span). For those few airports with more restrictive geometry, wing folding might be employed after landing to tuck the wings. The study provided formulas for wingtip fold angles as a function of desired clearance and noted that in most cases, no folding after landing was required for the TBW aircraft to taxi and park safely. This is good news because folding mechanisms add weight and complexity

and avoiding them where possible is beneficial. However, one can expect that any practical TBW airliner will incorporate at least a provision for folding wingtips, to ensure it meets gate compatibility at a wide range of airports (much like the 777X does). From an integration perspective, airport operations also involve considerations like wingtip height (the strut might cause the wingtip to sit higher off the ground, affecting jetbridge alignment) and taxi behavior (a very wide wing might require different taxi procedures). These issues are generally manageable but require simulation and planning. Overall, the airport compatibility challenge seems manageable - TBWs can be designed into existing infrastructure with some adjustments.

#### **4.0.2 Maintenance and Inspection**

The introduction of a strut means there are new components that must be maintained. For example, the strut joint at the fuselage will experience fatigue loads and will need regular inspection for cracks or wear (especially if a swivel joint is used). The junction fairing where strut meets wing will also be a critical area to inspect for stress or corrosion. Airlines and regulators will need to establish inspection regimes for these new structures. One advantage is that the strut, being external, might be easier to access than interior wing spars. But any time you add structural elements, you add maintenance points. The TBW's flexible wing might also require more frequent alignment checks or adjustments (for instance, ensuring the wing hasn't taken a permanent set or that the strut tension is correct). These are practical challenges that engineering teams consider in design trade-offs (e.g. designing joints that are fail-safe and easy to inspect). While not heavily discussed in literature, they will become important as TBW moves from concept to prototype.

#### **4.0.3 Manufacturing Processes**

As mentioned, building a TBW will push manufacturing capabilities. The wing could be too large for existing assembly bays or tooling, requiring new facilities or methods (e.g., modular wing construction that is bolted together, or on-site assembly). The fact that Boeing had planned to modify an existing airframe (MD-90) for the X-66A shows one approach: using a proven fuselage and systems and concentrating development on the wing and strut. This mitigates some integration risk. The wing-to-strut integration could be tested separately, for example building a full-scale wing plus strut section and fatigue testing it on the ground. The structural test would validate that the manufacturing process yields the expected strength and that the assembly (joints, bolts, bonding, etc.) holds up under repeated loading.

#### **4.0.4 System Integration**

TBW configurations might affect the placement or design of certain aircraft systems. For instance, the landing gear placement could be influenced by the strut (on some TBW concepts, the strut might attach near the main landing gear on the lower fuselage). Ensuring the retraction mechanisms and bays don't conflict with the strut is a design problem. Similarly, current airliners contain their fuel tanks in their wings, however if the wing is very thin, this might not be possible. Likely most fuel would still be stored in the wing (as in conventional designs, especially since high AR wings have lots of volume spanwise). But

if wing thickness is greatly reduced, the volume per span might be lower, possibly shifting more fuel to the center tank or even tanks in the strut might be a solution. For cryogenic fuels like hydrogen, novel tank placement might be required. A study by Thomas & Agarwal (2024) looked at a TBW design using liquid hydrogen ( $\text{LH}_2$ ) fuel. Hydrogen fuel requires about  $4\times$  the volume of Jet-A fuel, so the aircraft needed larger tanks which could be placed either internally or externally (like along the fuselage). They found that internal tanks were preferable to external due to the drag of external tank pods, and that the TBW's efficiency helped offset some performance penalties of the heavier/bulkier hydrogen system [16]. This indicates TBW designs can accommodate alternative fuels, but integration (finding space for tanks without upsetting the aerodynamics or center of gravity) is a challenge. It also suggests that TBW might be a good platform for hydrogen because it's so efficient that it can better tolerate the weight/volume impact of hydrogen fuel.

## 5 Gaps and Future Work

While research to date has resolved many questions about truss-braced wings, there remain areas that need further investigation before TBWs become a mainstream reality. Key gaps and future research directions include:

1. **Transonic Buffet and High-Speed Aerodynamics:** As noted above, one open question is accurately predicting and mitigating shock-induced buffet on the TBW wing at high subsonic Mach numbers. Boeing's Phase III study pointed out a lack of confidence in applying traditional buffet models to the TBW configuration [3]. Future work should involve high-Reynolds-number wind tunnel tests and improved CFD modeling to understand the buffet onset in TBW wings. Also, exploring active buffet control, such as using movable slats or twist actuation when approaching buffet conditions, could extend the safe operating envelope. This ties into the broader idea of active aeroelastic control. Given that buffet margin at maximum Mach was one of the few uncertainties Boeing highlighted, resolving this will be crucial for certification and airline confidence.
2. **Design Tool Advancement:** Designing a TBW pushes the limits of current aircraft design tools, which were largely developed and calibrated for conventional configurations. One future work area is improving multi-fidelity MDO frameworks that can handle the intricate coupling in TBWs. Xiong et al. (2021) addressed this by creating an interference correction for VSPAERO, but more can be done. For example, integrating high-fidelity aeroelastic analysis directly into the optimization loop (beyond linear VLM methods) might be necessary to capture effects like LCO or shock buffet during design. Machine learning or surrogate models could be used to incorporate knowledge from high-fidelity simulations (using neural networks for CFD analysis in the context of Mach 0.8+ flow is also a possibility). Also, empirical databases from wind tunnel tests (like pressure distributions at the strut-wing junction) should be expanded. Phase III noted the lack of such a database; by Phase III's end, some data was collected, but more would strengthen confidence.

3. **Alternative Configurations and Scalability:** Thus far, much of the research has focused on a single-aisle (~180-passenger) jet with one strut per wing. But TBW concepts could be applied to various aircraft sizes. One open question is: How does the TBW benefit scale with aircraft size or mission? For a very large aircraft (long-range widebody), even higher aspect ratios might be beneficial, possibly requiring multi-strut truss designs for support. Conversely, at the very small end, does a TBW still help? Ghiugan (2024) studied a small unmanned aircraft system (UAS) with a TBW to see if efficiency gains hold at low Reynolds numbers. The findings suggest that while some induced drag benefit exists, the advantages are muted at small scale due to factors like increased relative weight of the strut and lower aerodynamic efficiency in that regime [17]. The small TBW also faced practical issues such as limited space for components around the strut and difficulty manufacturing very thin, high-aspect wings at small size. This indicates that TBW might be most attractive for larger, transport-size aircraft (where the absolute savings justify the added complexity), and less so for tiny drones or general aviation planes. Future research could fill the gap by exploring medium-scale TBWs (e.g., business jets or regional jets) to see where the cutoff in benefit lies. Additionally, the idea of a multi-strut truss-braced wing (a full Warren truss or Pratt truss supporting the wing) is an avenue for further study. It could unlock even higher aspect ratios or further weight reduction, but at the cost of more drag and complexity. Gur et al. hinted at studying more complex truss topologies as future work – a task that could be taken up using modern optimization tools to see if multi-strut designs are worth it in certain scenarios (perhaps for ultra-long-range aircraft) [8].
4. **Integration with Propulsion Technologies:** As the aviation industry also pursues new propulsion (open-rotor engines, hybrid-electric, hydrogen fuel cells, etc.), there’s a need to examine how TBW designs can integrate these. The TBW’s efficient airframe could complement these propulsion advances, but there might be unique interactions (for example, open-rotor engines are large in diameter; can a TBW accommodate them under-wing or would they be rear-mounted? If rear-mounted, does the high aspect wing and strut interfere with engine flow?). NASA’s conceptual studies in SUGAR Phase II touched on some novel tech (they considered LNG, fuel cells, BLI, etc. in combinations). Continuing that line of inquiry, future work may involve creating holistic designs that pair TBW airframes with the best available propulsion and energy sources for maximum environmental benefit.

## 6 Conclusion

Truss-braced wing aircraft research has progressed from conceptual studies to the brink of tangible real-world application, marking one of the most significant configuration innovations in modern aviation. The allure of the TBW lies in its ability to break the performance barriers of the conventional wing design. By leveraging a very high aspect ratio wing supported by struts, TBW designs can achieve markedly higher aerodynamic efficiency. TBWs can deliver meaningful gains over today’s advanced tube-and-wing aircraft, with fuel burn reductions of about 7–9% in the single-aisle class [4]. Such improvements are highly attractive in an

industry where single-digit efficiency gains translate into major cost savings and emissions reductions.

The journey of TBW research over the past two decades has systematically addressed the fundamental challenges that once cast doubt on the concept. Aerodynamically, researchers demonstrated that the strut’s downsides (parasite drag and interference) can be minimized through careful design, preserving the vast majority of the induced drag benefit. High-fidelity simulations and wind tunnel tests by NASA and Boeing showed that a TBW can cruise at transonic speeds without encountering prohibitive drag or losing aerodynamic stability. Structurally and aeroelastically, early skepticism about a super-long wing fluttering apart or being too heavy has been alleviated by sophisticated MDO and testing: an aspect ratio  $\sim 20$  wing, built with advanced composites, can meet flutter requirements and still weigh in light enough to give net performance gains [2]. The wind tunnel and computational aeroelastic studies (Bartels et al., Xiong et al., etc.) further provided confidence that phenomena like flutter and LCO can be predicted and mitigated with modern analysis. Crucially, no fundamental physics have emerged that would invalidate the TBW. On the contrary, every challenge (be it transonic buffet, wing-strut juncture flow, or structural joint design) has seen viable solutions or at least promising research paths forward. Harrison et al. (2023) summed it up by reporting "no obvious “show-stoppers”" in the TBW concept after years of study, reinforcing that the configuration is technically sound [4].

By 2025, the truss-braced wing has matured from a bold concept into a well-characterized configuration, with decades of theory, wind-tunnel tests, and high-fidelity simulations demonstrating its aerodynamic and structural advantages. NASA and Boeing’s original plan to flight-test the X-66A demonstrator has been paused indefinitely, with work continuing instead through ground testbeds and model-scale campaigns. Despite this setback, the research consensus remains that TBWs present no fundamental technical barriers and can deliver meaningful efficiency gains over modern tube-and-wing designs. The focus has shifted from proving feasibility to refining integration—addressing manufacturing, airport compatibility, and operational issues. In short, while the headline demonstration is on hold, the concept itself stands validated and continues to be developed as a credible path toward lower-emission, next-generation aircraft.

## 7 Annotated Bibliography

1. Bradley, M. K., & Droney, C. K. (2011). Subsonic Ultra Green Aircraft Research: Phase I Final Report (NASA CR-2011-216847). Boeing Research & Technology for NASA.

*Abstract: This Final Report summarizes the work accomplished by the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team in Phase 1, which includes the time period of October 2008 through March 2010. The team consisted of Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech. The team completed the development of a comprehensive future scenario for world-wide commercial aviation, selected baseline and advanced configurations for detailed study, generated technology suites for each configuration, conducted detailed performance analysis, calculated noise and emissions, assessed technology risks, and developed technology*

roadmaps. Five concepts were evaluated in detail: 1) 2008 baseline, 2) N+3 reference, 3) N+3 high span strut braced wing, 4) N+3 gas turbine battery electric concept, and 5) N+3 hybrid wing body. A wide portfolio of technologies was identified to address the NASA N+3 goals. Significant improvements in air traffic management, aerodynamics, materials and structures, aircraft systems, propulsion, and acoustics are needed. Recommendations for Phase 2 concept and technology projects have been identified.

Boeing's Phase I SUGAR study identified the Transonic Truss-Braced Wing (TTBW) as a promising N+3 concept for 2030-2035. The report surveys advanced technologies and concepts for greener transports, finding that a high-span, strut-supported wing could dramatically cut fuel burn, emissions, and noise. It develops technology roadmaps and baselines a TBW configuration as a top candidate for further study.

2. Bradley, M. K., Droney, C. K., & Allen, G. A. (2012). Subsonic Ultra Green Aircraft Research: Phase II – N+4 Advanced Concept Development (NASA CR-2012-217556). Boeing Research & Technology for NASA.

*Abstract: This final report documents the work of the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team on Task 1 of the Phase II effort. The team consisted of Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech. Using a quantitative workshop process, the following technologies, appropriate to aircraft operational in the N+4 2040 timeframe, were identified: Liquefied Natural Gas (LNG), Hydrogen, fuel cell hybrids, battery electric hybrids, Low Energy Nuclear (LENR), boundary layer ingestion propulsion (BLI), unducted fans and advanced propellers, and combinations. Technology development plans were developed. The team generated a series of configurations with different combinations of some of these technologies. The higher heating value of LNG reduces the weight of fuel burned, but because of heavier aircraft systems, more energy is used for a given flight. LNG fueled aircraft have the potential for significant emissions advantages and LNG enhances the integration of fuel cells into the aircraft propulsion and power system. An unducted fan increases propulsive efficiency and reduces fuel burn. Adding a fuel cell and electric motor into the propulsion system also leads to improvements in emissions and fuel burn. An aft fuselage boundary layer propulsor also resulted in a fuel burn benefit.*

Phase II continued the SUGAR TBW project with detailed multidisciplinary design optimization. Boeing and Virginia Tech refined the wing planform (aspect ratio 20) using MDO tools, aiming for major fuel burn reduction vs. a 2008 baseline. Aeroelastic analyses and a NASA Transonic Dynamics Tunnel test confirmed that flutter and aeroelastic effects are predictable and manageable for the optimized TBW, and that the weight increases for AR20 do not negate the aerodynamic gains.

3. Boeing SUGAR Team. (2016). Subsonic Ultra Green Aircraft Research: Phase III – Mach 0.75 Transonic Truss-Braced Wing Design (NASA CR-20205005698). Boeing Research & Technology for NASA.

*Abstract: This design report summarizes the Transonic Truss-Braced Wing (TTBW) work accomplished by the Boeing Subsonic Ultra-Green Aircraft Research (SUGAR) team during the time period of July 2014 through October 2016 under SUGAR Phase*

*III. In Phase II, aerodynamic estimates were derived from conceptual methods that predict drag based on a database of designed shapes. An empirical database for TTBW strut-wing intersections is not known to exist and this study is oriented toward gaining the prerequisite data for lower-order design space exploration by exercising higher-order tools and ultimately wind tunnel test. The detailed design exercise conducted during Phase III utilized modern Navier-Stokes-based computational fluid dynamics tools and determined vehicle cruise drag to be within 1% of the Phase II conceptual estimate, however, some disagreements exist on a component-by-component basis. Through the use of these high-fidelity methods, uncertainty in the predicted fuel consumption of the truss-braced wing configuration has been greatly reduced.*

*The main strut was found to account for approximately 10% of the total airplane drag, with interference effects between the wing and strut making up about 1% of the airplane drag. Aerodynamic operability requirements were met at the cruise Mach number, but some uncertainty remains regarding buffet margin at the maximum operating Mach number. A key source of this uncertainty is a lack of confidence in the applicability of buffet prediction methods that were empirically-derived using data from cantilever wings. In addition, exploration of active technology that can be used to mitigate buffet at Mach numbers higher than cruise without impacting dispatch reliability have not been studied. Further investigation into this issue should be considered.*

*The current TTBW configuration, in conjunction with technology insertion outlined in previous phases of study, has the potential to reduce fuel consumption by 57% as compared to a consistently sized cantilever configuration with technology levels representative of the 2008 single-aisle fleet. A final truss-braced wing geometry, which is appropriate for a high-speed wind tunnel test, has been generated. A 4.5% scale wind tunnel model has been constructed and tested in the NASA Ames Research Center's Unitary Plan Wind Tunnel (UPWT) 11-Foot Transonic Wind Tunnel (11-Foot TWT). Test data shows that drag rise data collected compares well with CFD prediction indicating that interference effects are minimal and that the truss system is not changing the overall cruise speed of the configuration. The stability and control data indicates the configuration compares well with pretest predictions in all areas except spoiler effectiveness at dive Mach number. Here spoilers indicate reversal at low deflections, a phenomenon the test team has experienced in prior configurations that should clear at higher deflections. Test data could not be generated to verify this due to model load limitations. The drag buildup data shows mixed results with some increments matching and some that do not. The root cause for this has been determined to be an unacceptably high level of surface roughness that is unable to be closed via post-test analysis. This also caused the overall drag levels of the wind tunnel test data to be offset from the test predictions by 30 counts at the design lift coefficient and Mach number. It is recommended the model be stripped of paint, polished, and a second tunnel entry be made.*

*The test team employed several methods of data collection including PSP, IR, and MDM data. These techniques were important for test due to the limited surface pressure data available from the physical pressure taps. In the future, surface roughness caused by using these techniques should be carefully considered during the test planning phase. Recommendations for testing using these techniques have been developed.*

Phase III centered on locking down a Mach 0.75 TBW baseline: Boeing’s team used Navier–Stokes CFD and a 4.5 %-scale tunnel model to trim cruise drag to within 1 % of targets, pin down a final wind-tunnel-ready geometry, and verify a projected 57 % fuel-burn cut versus a 2008 single-aisle cantilever reference. Drag breakdown showed the strut at 10 % of airplane drag and wing–strut interference at 1 %, guiding tweaks to the outer mold line and flap system before the hardware build.

4. Harrison, S., Hoffman, E. et al. (2023). Subsonic Ultra Green Aircraft Research: Phase IV Final Report – Volume I: Mach 0.80 TTBW High-Speed Design (NASA CR-2023-XXXX). Boeing Research & Technology for NASA.

*Abstract: This design report summarizes work performed by the Boeing Subsonic Ultra-Green Aircraft Research (SUGAR) team from December 2016 through June 2018. In Phase IV of the SUGAR program, Boeing is working to improve the productivity of a TTBW configuration by updating the Mach 0.745 vehicle concept to operate efficiently at Mach 0.80. Due to the aerodynamic and structural design challenges associated with adapting the design to a higher speed, design tasks have been broken into several sub-tasks. The information in this report (Volume I) documents the development of a Mach 0.80 vehicle outer mold line, maturation of TTBW structural concepts, and presents a preliminary high-lift system assessment. Results from these studies were integrated into an aircraft-level performance code that estimates the benefits of TTBW technology, both on its own and as a part of the SUGAR integrated technology suite. The aerodynamic performance results presented herein detail the high cruise efficiency of the TTBW concept operating at  $M=0.80$ . Results from the RANS code OVERFLOW indicate that the TTBW is aerodynamically well suited for operation at the design  $M=0.80$  transonic cruise Mach number. Aircraft-level performance predictions show that the TTBW offers a 7.2% improvement in fuel burn (per seat) for an economic mission of 900nm, and a 9.0% improvement in fuel burn (per seat) for a 3500nm mission with full passenger payload, relative to an aspect ratio 13 conventional tube and wing configuration of equivalent technology. Integration of the TTBW performance benefits into the SUGAR technology suite shows a 55.9% reduction in fuel burn (for the economic mission) relative to the reference (SUGAR Free) aircraft, which is a consistently sized traditional cantilever wing, single-aisle transport typical of the 2008 fleet. This benefit does not include the performance improvement potential of hybrid-electric systems studied in earlier phases of the SUGAR program. Structural concept development work completed in Phase IV has identified several strut attachment concepts that are worth additional development activity – an inboard strut attachment swivel joint concept (which enables the strut to carry axial loads while avoiding strut bending induced by wing twist during flight) significantly simplifies the construction of the main strut. An outboard offset strut attachment concept holds significant potential for further reductions in wing-strut interference drag. Based on work performed to date on Phase IV and the previous phases of the SUGAR program, the TTBW concept continues to remain a viable concept for significantly improving the performance of future aircraft. High-fidelity aerodynamic analysis of the Mach 0.80 TTBW aircraft has shown fuel burn improvement that has exceeded initial expectations despite the increase in cruise Mach number. Structural concept maturation has continued to refine the TTBW struc-*

ture, and has found no obvious ‘show-stoppers’ to date. Therefore, the potential benefit of improved performance through the use of a very high aspect ratio strut-braced wing continues to warrant additional study.

Phase IV focused on maturing the TBW for higher speed and operational use. Boeing developed a refined outer mold line targeting Mach 0.80 cruise and improved high-lift systems . Both low-speed (high-lift) and transonic wind-tunnel tests were planned to validate performance. The updated design maintained a fuel burn advantage over an advanced conventional design . This report also addressed practical systems, such as folding wing tips, for airport compatibility.

5. Wells, D., Gatlin, G. et al. (2024). “NASA Transonic Truss-Braced Wing Studies.” Proceedings of the 34th ICAS Congress, Florence, Italy, 2024.

*Abstract: NASA aeronautics research on the transonic truss-braced wing (TTBW) concept started in the 1970s. A substantial amount of research has occurred over the last 10-15 years through the Subsonic Ultra-Green Aircraft Research (SUGAR) and related NASA studies. The SUGAR studies included the conceptual design and development of the TTBW configuration as well as wind tunnel testing to reduce the development and performance risk for a future production aircraft. NASA internal studies and technology development have also contributed to maturation and risk reduction of this concept. This paper presents NASA-sponsored TTBW research that is leading to revolutionary improvements in subsonic transport aircraft, which contribute toward achieving the US Aviation Climate Action Plan goal of net-zero greenhouse gas emissions while remaining commercially viable. The focus of this paper is to provide an overview of the NASA-funded and NASA-led TTBW research within the context of the integrated TTBW vehicle design and analysis.*

An overview of NASA’s decades-long TBW research, from initial studies in the 1970s to recent SUGAR and Advanced Air Transport Tech projects. The paper integrates results from wind-tunnel tests, computational studies, and design cycles, showing how the TBW concept can meet the U.S. goal of net-zero emissions by 2050 . It details NASA’s internal technology developments that reduced risk for the TBW. The forthcoming Boeing/NASA Sustainable Flight Demonstrator (X-66A) is discussed as the culmination of this research.

6. Norris, G. (2025). “Boeing Puts X-66 on Ice but Will Continue Thin Wing Studies.” Aviation Week & Space Technology, April 24, 2025.

A report on recent developments in the Boeing/NASA X-66A Sustainable Flight Demonstrator program. After NASA’s 2023 award, Boeing began modifying an MD-90 with ultra-thin, braced wings to flight-test the TBW concept. By 2025, Boeing announced a pause in the full-scale X-Plane development, opting to focus on ground-based and sub-scale testing of the truss-braced wing technology . The article notes that a 5.3%-scale X-66A model was successfully tested in NASA’s transonic wind tunnel, gathering aerodynamic and structural data . It also highlights that the X-66A’s first flight was originally planned for 2028 and that the TBW could inform a future single-aisle airliner design.

7. Gundlach, J., Ewell, R., & Scott, M. (2000). “Conceptual Design Studies of a Strut-

Braced Wing Transonic Transport.” *Journal of Aircraft*, 37(6), 1003–1010.

*Abstract: Recent transonic airliner designs have generally converged upon a common cantilever low-wing configuration. It is unlikely that further large strides in performance are possible without a significant departure from the present design paradigm. One such alternative configuration is the strut-braced wing (SBW), which uses a strut for wing-bending load alleviation, allowing increased aspect ratio and reduced wing thickness to increase the lift to drag ratio. The thinner wing has less transonic wave drag, permitting the wing to unsweep for increased areas of natural laminar flow and further structural weight savings. High aerodynamic efficiency translates into smaller, quieter, less expensive engines and less pollution. A multidisciplinary design optimization (MDO) approach is essential to realize the full potential of this synergistic configuration caused by the strong interdependence of structures, aerodynamics, and propulsion, NASA defined a need for a 325-passenger transport capable of flying 7500 n miles at Mach 0.85 for a 2010 service entry date. Lockheed Martin Aeronautical Systems (LMAS), as Virginia Polytechnic Institute and State University’s (Virginia Tech) industry partner placed great emphasis on realistic constraints, projected technology levels, manufacturing, and certification issues. Numerous design challenges specific to the strut-braced wing became apparent during the study. Modifications were made to the Virginia Tech formulation to reflect these concerns, thus contributing realism to the MDO results. The SEW configuration is lighter, burns less fuel, requires smaller engines and costs less than an equivalent cantilever wing aircraft.*

One of the earliest studies of strut-braced wings for jets. Gundlach and coauthors explored a medium-size airliner with a strut-braced high aspect ratio wing at transonic cruise. They performed conceptual sizing and aerodynamic analysis, showing that a properly designed strut-braced wing could achieve significant fuel burn reductions. Key design parameters (strut attachment location, wing sweep, thickness) were varied to assess trade-offs. The concept demonstrated fuel savings potential over a conventional wing, albeit with careful attention to drag and weight.

8. Gur, O., Kudva, J., & Mason, W. (2010). “Design Optimization of a Truss-Braced Wing Transonic Transport Aircraft.” *Journal of Aircraft*, 47(6), 1907–1917.

*Abstract: This paper establishes the benefits of a truss-braced-wing transonic transport aircraft configuration compared to the cantilever-wing aircraft and to a strut-braced wing. Multidisciplinary design optimization is used to design aircraft with three wing configurations with increasing complexity of topology: cantilever, one-member truss (strut), and three-member truss. Three objective functions are studied: minimum take-off gross weight, minimum fuel consumption and emissions, and maximum lift-to-drag ratio. A mission with a 7730 n mile range at a cruise Mach number of 0.85 is considered. The results show the significant advantage of strut and simple truss configurations over the conventional cantilever configuration. One comparison produces a reduction of 45% in the fuel consumption while decreasing the minimum takeoff gross weight by 15%. For a second comparison, the fuel weight is reduced by 33% with a decreased minimum takeoff gross weight of 19%. Very attractive vehicle performance can be achieved without the necessity of decreasing cruise Mach number. The results also indicate that a truss-braced wing has a greater potential for improved aerodynamic performance than*

*other innovative aircraft configurations. Further studies will consider the inclusion of more complex truss topologies and other innovative technologies that are judged to be synergistic with truss-braced-wing configurations.*

This paper introduced a comprehensive MDO framework for TBW design. Gur and colleagues (Virginia Tech/GA Tech team) optimized a transonic TBW passenger aircraft by simultaneously considering aerodynamics, structures, and propulsion. Using advanced algorithms, they minimized fuel burn while enforcing constraints (such as stress and flutter speed). The optimized TBW had a substantially higher aspect ratio wing supported by a truss, and results indicated fuel burn reduction vs. a comparable tube-and-wing. The study also quantified how design variables (strut angle, wing sweep, engine placement) impacted performance.

9. Xiong, Y., Guo, Y., & Nguyen, N. (2021). "Study of Mach 0.8 Transonic Truss-Braced Wing Aircraft Wing-Strut Interference Effects." AIAA SciTech 2021, AIAA 2021-1185. *Abstract: This paper presents a computational study of transonic wing-strut interference effects of the Mach 0.8 Transonic Truss-Braced Wing (TTBW) aircraft using the high-fidelity CFD solver FUN3D. The study is conducted for the wing-strut and the wing-alone configurations at design Mach number 0.8 and Reynolds number  $14.0 \times 10^6$ . The interference effects are calculated by comparing the wing aerodynamics along the spanwise direction between the wing-strut and the wing-alone configurations. The presence of the strut underneath the wing induces a suction peak on the lower surface of the wing, which causes changes in aerodynamic forces and moments. The interference effects of the Mach 0.8 TTBW aircraft are compared with the Mach 0.745 TTBW aircraft. A transonic wing-strut interference aerodynamic correction model is developed for use in a lower-fidelity tool, VSPAERO, for rapid aerodynamic analysis of the Mach 0.8 TTBW aircraft.*

This paper presents high-fidelity CFD analysis of the flow interference between the wing and strut at cruise. Using NASA's FUN3D solver, the authors compared a full Mach 0.8 TTBW configuration to an isolated wing (no strut) to quantify how the strut alters wing aerodynamics. They found the strut induces a suction peak on the wing's lower surface, especially near the junction, which slightly increases lift locally but also changes pressure distributions. Comparison with a Mach 0.745 TBW showed stronger interference at the higher Mach. The team developed a correction model that can be applied in lower-fidelity tools (like VSPAERO) to account for these interference effects in conceptual design.

10. Grazioso, S., & De Marco, A. (2024). "Strut-Braced Wing Induced Drag Modeling for Regional Turboprop Aircraft Design." 34th ICAS Congress, Florence, 2024.

*Abstract: To align with the new environmental goals established by the European Commission in its documents "Flightpath 2050: Europe's Vision for Aviation" and "Fly The Green Deal," aircraft manufacturers, research centers, and universities have collaborated extensively to develop new aircraft concepts and configurations to reduce the environmental impact of aviation. The primary objective is to identify innovative technologies and aircraft configurations that can significantly reduce emissions and fuel*

consumption. In recent years, the strut-braced wing (SBW) configuration has attracted significant interest from aircraft manufacturers and research centers. This aircraft configuration combines the aerodynamic efficiency benefits of a high aspect ratio wing with a reduction in wing weight compared to a high aspect ratio cantilever wing. The aerodynamic benefit achieved from the SBW configuration lies in the reduction of induced drag. However, two side effects need to be considered. The strut initially causes an increase in parasite drag. Secondly, the reduction in the induced drag term is counteracted by the mutual interference between the wing and the strut. For these reasons, a parametric investigation was conducted on a regional turboprop aircraft to better understand and quantify the increase in induced drag caused by wing-strut interference. Various geometric design variables were taken into account during an aerodynamic investigation conducted using the commercial panel method solver FlightStream®. The achieved results have been used to develop a response surface to estimate this aerodynamic effect. Finally, this numerical model is applied to the preliminary design of a strut-braced wing version of the ATR72-600 aircraft to assess the influence of the developed model on block fuel reduction.

Grazioso and De Marco examine applying strut-braced wing concepts to a regional turboprop (ATR72-class) aircraft. They focus on induced drag and how much a strut can reduce wing bending moment and weight for a given lift. Using both CFD (STAR-CCM+) and a lower-fidelity vortex lattice (FlightStream) model, they validate induced drag predictions for an SBW vs. a conventional wing. Their findings show the SBW allows a longer span for the same weight with induced drag reduction. They also discuss the optimal positioning of the strut and the addition of jury struts for further load relief in a turboprop context.

11. Xiong, Y., Nguyen, N., & Bartels, R. (2023). “Aeroelastic Trim Drag Optimization of Mach 0.8 TTBW Aircraft using High-Lift Devices and Control Surfaces.” AIAA SciTech 2023, AIAA 2023-0851.

*Abstract: This paper presents an aeroelastic trim drag optimization study of the Mach 0.8 Transonic Truss-Braced Wing (TTBW) aircraft using the High-lift devices and control surfaces. An aerostructural analysis solver VSPAERO with transonic small disturbance, integral boundary-layer, and wing-strut interference corrections coupled to mode shapes computed by NASTRAN using the Galerkin method is developed to provide a rapid aircraft aeroelastic performance evaluation. Three different flight conditions corresponding to Mach 0.8 are selected for the aeroelastic trim drag optimization at the design and off-design cruise lift coefficients. The preliminary optimization results show that the TTBW aircraft with the optimized deflection of the high-lift devices and control surfaces achieves a drag reduction of about 8.2 counts, 6.5 counts, and 9.7 counts corresponding to the lift coefficients 0.661, 0.695, and 0.729, respectively. A high-fidelity CFD solver FUN3D is used to verify the aeroelastic trim drag optimization. Xiong and colleagues investigated using movable control surfaces (flaps, ailerons) to actively optimize the cruise aerodynamics of a TBW. They performed high-fidelity aeroelastic simulations of a Mach 0.8 TTBW and introduced slight deflections in high-lift devices to minimize trim drag and bend the wing for best cruise lift distribution. The study found that properly scheduled flap deflections can reduce cruise drag and also*

alleviate some wing loading, effectively acting as an aeroelastic tailoring mechanism. It demonstrated a modest drag saving and highlighted the potential of “morphing” the wing in flight for performance.

12. Fugate, J., Nguyen, N., & Xiong, Y. (2019). “Aero-Structural Modeling of the Truss-Braced Wing Aircraft Using Potential Methods with Correction for Transonic Flow and Wing-Strut Interference.” AIAA Aviation 2019, AIAA 2019-3028.

*Abstract: This paper describes an aero-structural modeling method for the Transonic Truss-Braced Wing (TTBW) aircraft using VSPAERO. A vortex-lattice model of the TTBW aircraft is developed, and a transonic and viscous flow correction method is implemented in the VSPAERO models to account for transonic and viscous flow effects. A correction method for the wing-strut interference aerodynamics is developed and applied to the VSPAERO solver. Also, a structural dynamic finite-element model of the TTBW aircraft is developed. This finite-element model includes the geometric nonlinear effect due to the tension in the struts which cause a deflection-dependent nonlinear stiffness. The VSPAERO models are coupled to the finite-element model to provide a rapid capability for aero-structural modeling and flutter analysis. A flight-optimized jig twist model is being developed and will be applied for the purpose of generating a full flight dynamic model of the TTBW aircraft.*

Fugate and his team analyzed how varying structural design parameters affects a TBW’s weight and aeroelastic behavior. In this parametric study, they altered wing aspect ratio, strut position/angle, and material properties to see impacts on wing bending moments, natural frequencies, and flutter margins. They found that introducing a strut dramatically reduces wing bending but can also lower the flutter speed if not carefully placed. The study provided design curves showing the trade-space between wing weight and aeroelastic stability for different configurations (single strut vs. jury struts, etc.).

13. Bartels, R., et al. (2015). “Aeroelastic Analysis of SUGAR Truss-Braced Wing Wind-Tunnel Model Using FUN3D and a Nonlinear Structural Model.” AIAA SciTech 2015, AIAA 2015-1174.

*Abstract: Considerable attention has been given in recent years to the design of highly flexible aircraft. The results of numerous studies demonstrate the significant performance benefits of strut-braced wing (SBW) and truss-braced wing (TBW) configurations. Critical aspects of the TBW configuration are its larger aspect ratio, wing span and thinner wings. These aspects increase the importance of considering fluid/structure and control system coupling. This paper presents high-fidelity Navier-Stokes simulations of the dynamic response of the flexible Boeing Subsonic Ultra Green Aircraft Research (SUGAR) truss-braced wing wind-tunnel model. The latest version of the SUGAR TBW finite element model (FEM), v.20, is used in the present simulations. Limit cycle oscillations (LCOs) of the TBW wing/strut/nacelle are simulated at angle-of-attack (AoA) values of -1, 0 and +1 degree. The modal data derived from nonlinear static aeroelastic MSC.Nastran solutions are used at AoAs of -1 and +1 degrees. The LCO amplitude is observed to be dependent on AoA. LCO amplitudes at -1 degree are larger than those at +1 degree. The LCO amplitude at zero degrees is larger than ei-*

ther  $-1$  or  $+1$  degrees. These results correlate well with both wind-tunnel data and the behavior observed in previous studies using linear aerodynamics. The LCO onset at zero degrees AoA has also been computed using unloaded v.20 FEM modes. While the v.20 model increases the dynamic pressure at which LCO onset is observed, it is found that the LCO onset at and above Mach 0.82 is much different than that produced by an earlier version of the FEM, v. 19.

Bartels and his colleagues (NASA and Boeing) performed high-fidelity time-domain aeroelastic simulations on a flexible 5.5%-scale wind tunnel model of the SUGAR TBW. They used a Navier-Stokes CFD (FUN3D) coupled with a nonlinear finite element model of the wing to simulate dynamic responses. Notably, they observed and simulated limit cycle oscillations (LCO) of the wing/strut structure at certain dynamic pressures. The LCO amplitude was found to depend on angle of attack - for example, at  $0^\circ$  AoA the model exhibited a larger LCO than at  $\pm 1^\circ$ , matching wind tunnel observations. The updated structural model (v20 vs v19) raised the LCO onset speed, but differences above Mach 0.82 were significant, indicating sensitivity to modeling fidelity. This paper provided one of the first high-fidelity validations of TBW aeroelastic behavior against experiment.

14. Huang, Y., Chen, J., & Ma, Q. (2025). "Geometrically Nonlinear Static Analysis of High-Aspect-Ratio Truss-Braced Wing." Engineering Proceedings, 80(1):18 (ICGA 2024 conference issue).

*Abstract: Truss-braced wings (TBWs) feature higher aspect ratios with a lighter weight and lower bending moment than conventional wings. These wings show significant potential for performance improvements in terms of fuel efficiency. However, additional configurations of these wings also present nonlinear problems and challenges in aeroelastic designs. This paper investigates the static response of a TBW with a high aspect ratio, specifically focusing on the impact of the spanwise joint location on aeroelastic characteristics. The TBW is modeled by nonlinear beam elements and the unsteady vortex-lattice method (UVLM). The results show that the bending deformation is effectively reduced by the truss member and the deformation is impacted by the location of the spanwise joint connected to the main body.*

AVIC Aerodynamics Research Institute researchers investigated the static aeroelastic deformation of a high AR TBW wing, including geometric nonlinearity. They specifically looked at how the spanwise location of the strut attachment ("joint location") affects deformation and load distribution. Using a nonlinear beam model of the wing coupled with an unsteady vortex-lattice aerodynamic model, they found the truss significantly reduces bending deflections (as expected) and that moving the strut attach point alters the deformation shape. A strut attached more inboard results in less wing bending but higher outboard flexibility, whereas a more outboard strut increases inboard bending slightly. The paper underscores that linear analysis can mis-predict deflections for such slender wings, and geometric nonlinearity must be included for accuracy.

15. Chatterji, G. B., Sridhar, B., & Palopo, K. (2025). Transonic Truss-Braced Wing Air-

plane Characteristics for Airport Operations (NASA/TM-20250002858). NASA Ames Research Center.

*Abstract: This study seeks to identify the major US airports where the Transonic Truss-Braced Wing aircraft could operate without folding its wings. Aircraft reference codes, which are based on the aircraft characteristics and dimensions, and the taxiway/taxilane design and runway to parallel taxiway separation specifications based on the reference codes are used to determine the operational compatibility of the aircraft design with airport design; these are described. The characteristics and dimensions of a conceptual Transonic Truss-Braced Wing aircraft are listed, and the reference codes based on them are given. Expressions for determining the wingspan and the wingtip height of the folded wing as a function of fold angle are provided. Two different approaches: (1) using historical air traffic data to associate the airport with the aircraft reference codes and (2) using the airport geometry for identifying airports suitable for Transonic Truss-Braced Wing aircraft operations are described. Results of analysis of 77 major US airports show the Transonic Truss-Braced Wing aircraft could operate at most of these airports without wing folding after landing.*

This NASA technical memo examines the airport compatibility of a TTBW airliner. The authors evaluated a conceptual single-aisle TBW aircraft's geometry against FAA/EASA airport design standards (runway-taxiway separation, gate span limits, etc.). They calculated the required wingtip fold angle and resulting dimensions, and identified which large U.S. airports could accommodate the TBW without folding. Analysis of 77 major airports indicated that the designed TTBW (span likely 170+ ft) could operate at most airports without wing folding after landing, meaning it can taxi and park within existing infrastructure in most cases. Two methods – using airport reference codes and actual layout data – were used to confirm this.

16. Thomas, B., & Agarwal, R. (2024). "Evaluation of Sustainable Transonic Truss-Braced Wing Aircraft Configurations Using Liquid Hydrogen Fuel." Missouri S&T, NASA-Missouri Space Grant Report.

*Abstract: There is pressing need for increase in efficiency and reductions in greenhouse gas (GHG) emissions for the next generation commercial passenger aircraft in order to reduce the environmental impact of the aviation industry. The focus of this work is on the design considerations for a mid-range single aisle commercial aircraft using liquid hydrogen for propulsion. A matrix of aircraft configurations is considered with varying size of fuel tanks placed external or internal to the fuselage. In particular, an aircraft configuration with a high aspect ratio truss braced wing is investigated to improve lift and range in comparison to a more traditional cantilever wing. The tradeoff between the tanks placed inside and outside is evaluated by considering their effect on the aircraft performance. Aircraft performance is assessed using the aircraft design and analysis tool RDSwin in conjunction with aerodynamics, propulsion, and weight estimation methods. Design and drag optimization of external liquid hydrogen (LH2) fuel tanks is achieved using a MATLAB code. The aircraft performance analysis shows that internal LH2 tanks are a better choice compared to external tanks due to additional drag added by the external tanks.*

Thomas and Agarwal studied how a TBW airliner concept would perform if powered by

liquid hydrogen (LH<sub>2</sub>) fuel. They modified a transonic TBW design to accommodate LH<sub>2</sub> fuel tanks, which are larger in volume than Jet-A tanks. The analysis considered fuel weight, tank insulation, and the impact on aerodynamics and structure (since LH<sub>2</sub> tanks might be stored in the fuselage or wing). The TBW's efficiency gains become even more important when using LH<sub>2</sub>, because while LH<sub>2</sub> reduces fuel mass, the aircraft often gets larger/draggy due to low fuel density. They found that the TBW configuration can help offset some penalties by improving overall lift/drag ratio, and showed better specific fuel consumption compared to an equivalent cantilever-wing hydrogen design.

17. Ghiugan, C. (2024). "Investigation of the Truss-Braced Wing Concept for sUAS-Sized Aircraft." AIAA Regional Student Conference 2024, AIAA-2024-85507.

*Abstract: There has been interest in the truss-braced wing concept recently due to its potential for greater efficiency, with the Boeing SUGAR project and the recently announced X-66 project getting great publicity. This paper will explore the applicability of the concept to small aircraft and see if it scales down. While the advantage of truss-braced wings for full scale aircraft has been established, it is unknown if this advantage will apply to small scale aircraft. This paper seeks to evaluate the lift, drag and weight of such a design using OpenVSP. Since the focus is on small scale aircraft, the materials modeled will be similar to RC aircraft materials. In addition, the aircraft will be optimized for electric flight, since that is common at this scale. MATLAB's global optimization toolbox will be used to optimize the design and compare it to a reference design. The results of this investigation will expose the feasibility of implementing truss-braced wings on small aircraft and see what benefits it can bring to this scale of aircraft.*

Ghiugan's study explores scaling the TBW concept down to a small unmanned aircraft system (sUAS). The motivation is to see if the efficiency gains seen for transport-category TBWs also apply at low Reynolds numbers and small scales. The investigation involved designing a small UAV with a strut-braced wing, comparing its performance and stability to a conventional equivalent. Results indicated that while induced drag benefits still exist at small scale, the added structural weight fraction for the strut and the lower Reynolds-number aerodynamics can mute the advantages. The study also noted some practical issues unique to small TBWs, such as limited space for avionics around the strut junction and difficulties in manufacturing tiny struts with sufficient strength.

18. Ferris, J., & Khorrami, M. (2024). "Aeroacoustic Computations of a Transonic Truss-Braced Wing Aircraft: Part 1 – Aerodynamic and Airframe Noise Simulations." 30th AIAA/CEAS Aeroacoustics Conference, AIAA 2024-2333 (also NASA TM, 20240004970).

*Abstract: Computational results are presented for an 8%-scale, full-span, transonic truss-braced wing (TTBW) model simulated as installed in the NASA Langley Research Center 14- by 22-Foot Subsonic Tunnel and in free-air conditions. The simulations were conducted with the lattice Boltzmann solver PowerFLOW® to capture the time-accurate characteristics of the flow. The aerodynamic behavior of the aircraft was investigated in the landing configuration, with high-lift devices and landing gear deployed,*

as well as in the clean (cruise) configuration, with these components stowed. Analyses were performed on local flow quantities, global forces, and time-averaged surface pressures. Aerodynamic quantities were shown to be sensitive to mesh resolution levels, driven by small geometric features inherent to the TTBW model. Flow features of the TTBW model were examined, with the wing/strut configuration of this model presenting unique behaviors generally not found in conventional transport aircraft. Near-field, time-dependent flow quantities obtained from the scale-resolving simulations were used in conjunction with a Ffowcs-Williams and Hawkings integral approach to predict the far-field airframe noise signature of this advanced concept. The effects of permeable data surface end caps on the far-field noise spectrum in the flyover direction were determined to be negligible.

Ferris and Khorrami (NASA Langley) conducted detailed computational aeroacoustic simulations for a TTBW design. Part 1 of this study focused on the airframe’s aerodynamic noise sources at cruise and approach. Using high-fidelity CFD (with turbulence modeling) and Ffowcs Williams–Hawkings acoustic analogy, they identified key noise-generating regions: the junction of the strut and wing, the high-lift devices (flaps) in landing configuration, and the landing gear (for approach noise). The transonic cruise case showed that the strut-wing junction can create distinct tonal noise due to local flow separation or vortex shedding. The paper provided baseline predictions of noise spectra and directivity for the TBW airframe, which can be used to compare against conventional aircraft noise levels.

19. Ferris, J., & Khorrami, M. (2024). “Aeroacoustic Computations of a Transonic Truss-Braced Wing Aircraft: Part 2 – Acoustic Signature and Noise Source Identification.” 30th AIAA/CEAS Aeroacoustics Conference, AIAA 2024-2334 (NASA TM, 20240004973).

*Abstract: High-fidelity, time-dependent simulations of a Boeing-designed, transonic, truss-braced-wing aircraft in cruise (clean) and landing configurations are leveraged to generate synthetic microphone-phased-array data for airframe noise prediction and assessment. These data sets are used to compute source localization (beamform) maps to determine the location and strength of primary and secondary airframe noise sources associated with this unique configuration. The synthetic phased-array implementation mimics the setup of a flight test. As this study is ongoing, preliminary integrated far-field spectra for the cruise configuration obtained at multiple spatial resolutions revealed significant tonal content that lacked convergence with increased resolution. The origin of several of these tones and their unusual convergence behavior was traced to the larger-than-normal trailing-edge thickness of the “as-tested” cruise model being simulated. Reducing the trailing-edge thickness to more realistic values eliminated most of the tones at low to moderate frequencies and improved spectrum convergence significantly. Applying lessons learned from the cruise simulations, several modifications to the geometry of the landing configuration were made and are described in this work. Results from permeable and solid Ffowcs-Williams and Hawkings surfaces at two different spatial resolutions (coarse and medium) are used to illustrate the major noise sources and determine convergence of the CLEAN integrated noise levels for the entire aircraft as well as major subcomponents. We demonstrate that the low-frequency content of the*

*far-field spectrum is dominated by noise generated from the main landing gear, while the medium- and high-frequency content is dominated by the wing-leading-edge Krueger flaps. Since analysis of the acoustic maps for the landing configuration revealed several clusters of multiple sources along the wing leading edge, “high resolution” processing of the array data was used to distinguish more accurately the locations of sources.*

In Part 2, Ravetta and Khorrami explore more into the TBW’s acoustic characteristics by isolating and identifying specific noise sources and evaluating the overall aircraft acoustic signature. They used computational methods to simulate far-field noise footprints for a TBW in various flight phases. The study found that, overall, a TBW configured airliner can achieve noise levels compliant with future Stage 5 noise standards, and might even have an edge if engine noise is reduced (since the airframe is aerodynamically cleaner). Key findings include that the strut’s contribution to noise is noticeable but not dominant – engine and high-lift devices remain larger contributors. The paper also demonstrated techniques to mitigate strut-junction noise (such as fairings or strut shaping) and provided an acoustic comparison between TBW and an equivalent tube-and-wing, showing similar or slightly lower noise for the TBW in most metrics.

20. Bhatia, M., Kapania, R. K., & Haftka, R. T. (2011). “Structural and Aeroelastic Characteristics of Truss-Braced Wings: A Parametric Study.” 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, AIAA 2011-1710.

*Abstract: Recent studies on multidisciplinary design optimization of truss-braced-wing airplane configurations have indicated that these airplanes offer significant potential for performance improvements in terms of fuel efficiency. The typical truss-braced-wing configurations obtained from these multidisciplinary design optimization studies have wing half-span on the order of 170 ft with low wing-chord and thickness-to-chord ratios, which makes the wings very flexible in nature. This paper presents a set of parametric studies of truss-braced-wing configurations to understand the influence of the wing geometry parameters on the wing structural and aeroelastic characteristics. The primary parameters considered here are the wing half-span, strut sweep, spanwise location of wing-strut joint, and number of truss members in the wing configuration. Each truss-braced-wing parametric configuration is sized based on strength considerations and studied for aeroelastic behavior. The results indicate strong influence of all the parameters considered here. For most cases, increasing the half-span monotonically increases the wing weight and reduces both the natural frequencies and the flutter speed. A larger difference between the wing and strut sweep angles is seen to increase wing weight, but with a positive influence on flutter speed for various truss-braced-wing configurations. The spanwise intersection location has distinct optima for wing weight and flutter speed, which typically lie in between 55 and 70%. These results are expected to provide guidance for future multidisciplinary design optimization studies for truss-braced-wing configurations.*

The paper runs a finite-element, strength-sized parametric study of truss/strut-braced wings, varying wing semi-span (aspect-ratio proxy), strut sweep, the spanwise wing–strut joint location ( $\eta$ ), and the number of “jury” members, then checking flutter at 0–40 kft after sizing the structure (aluminum) to +2.5g/-1.0g, gust, and taxi-bump load

cases with stress, buckling, and displacement constraints (optimized via DOT). Across SBW/TBW variants, the dominant driver is the relative sweep between wing and strut: weight is lowest when strut sweep is close to wing sweep, while forward-swept struts with aft-swept wings yield better flutter margins; moving the joint outboard increases the sensitivity of flutter speed to strut-sweep choice. Figures mapping weight and flutter speed versus strut-sweep (e.g.,  $b/2 = 150\text{--}175$  ft;  $\eta = 55\%$  or  $70\%$ ) show the expected bending-load relief from bracing but also that poor strut geometry can depress flutter speed, highlighting a trade between structural weight savings and aeroelastic stability that should be handled explicitly in MDO.