Civil Aircraft Materials: Selection

New Monetary Trade-Off Method

Present: Low Fuel Price
→ Aluminum Alloys, not CFRPs

Decision Making: Trade-Off

- Weight/Fuel saving but expensive materials?
- Saved fuel cost?

Near Future: Higher Fuel Price?
→ Low Cost CFRPs, instead of Aluminum Alloys

MECHANICAL ENGINEERING | RESEARCH ARTICLE

A new cost/weight trade-off method for airframe material decisions based on variable fuel price

Tetsuya Morimoto, Satoshi Kobayashi, Yosuke Nagao and Yutaka Iwahori

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Abstract: This paper presents a simple method for analyzing the monetary trade-off between rising airframe material cost and reduced jet fuel cost for supporting the decision-making in designing lightweight but expensive new materials. The method considers the weight growth factor, Breguet range equation, specific strength, material cost, fuel price, and aircraft range. A model analysis reveals that rising fuel price can drastically change the optimum airframe materials from legacy aluminum alloys to carbon fiber-reinforced plastics.

Keywords: decision support systems; design; airframe materials; trade-off analysis; carbon fiber reinforced plastics (CFRPs); aluminum alloys

1. Introduction

The prices of crude oil and jet fuel peaked in 2008 and remained high until the middle of 2014 due to the monetary surplus and spreading of unrest across crude oil production areas. Engineers were thus motivated to develop an airliner that guarantees excellent fuel efficiency by changing airframe materials from legacy aluminum alloys, such as Al-2024 and Al-7075, to new lightweight but more expensive ones such as CFRP.

ABOUT THE AUTHORS

The authors “A new cost/weight trade-off method for airframe material decisions based on variable fuel price” constitute a research group focused on the optimization of CFRP applications. The corresponding author, Tetsuya Morimoto, is a senior research engineer at aeronautical technology directorate of Japan Aerospace Exploration Agency (JAXA). He holds Dr. of Engineering degree from the University of Tokyo.

PUBLIC INTEREST STATEMENT

Lightweight but expensive new materials, such as carbon fiber reinforced plastics (CFRPs), are widely applied for the newest fuel-save jet liners such as Boeing B787 and Airbus A350. However, under the low fuel price condition after the middle of 2014, steady sales are reported for lower-priced, older, and less efficient legacy aluminum liners.

Therefore, the authors have set a question if selecting new materials contributed the business pay-off, and have proposed a new monetary trade-off method combining the fuel price, aircraft range, material strength, and material cost, for the decision-making of civil aircraft materials.

A model analysis with the method reveals that legacy aluminum alloys are favorable more than CFRPs for present condition, however, higher fuel price, CFRPs of lowered cost, and improved additive manufacturing (AM) technology can bring about drastic advantage for CFRPs in future aircraft projects.
expensive materials, such as carbon fiber-reinforced plastics (CFRPs) (United States Governmental Accountability Office, 2014; U.S. Energy Information Administration, 2016a, 2016b) (Figure 1).

However, the return of investment has come into question for some CFRP airframes since the prices of crude oil and jet fuel crashed in the middle of 2014 to approach the levels before 2005 (Dominic, 2015; Kevin, 2015). Therefore, the success of investment in airframe business projects is dependent on timely decision-making through a complex trade-off between rising airframe cost when using these expensive materials and the reduction in fuel costs they permit. For example, Mitsubishi Aircraft Corporation launched the Mitsubishi Regional Jet (MRJ) project in 2008 during the fuel price peak assuming a CFRP wing would be used; however, an aluminum-based wing was finally selected in 2009 during the fuel price downfall after a cost/weight trade-off study (Mitsubishi Aircraft Corporation, 2009; Mitsubishi Heavy Industries, 2008). Thus, a simple trade-off method could have saved at least one year of development before the 2014 rollout and the maiden flight in 2015. In addition, the method must be simple and applicable for investment for the funding sections and be independent of the engineering section, which tends to be optimistic regarding radical and innovative design but ignores the risk of business pay-off. Therefore, we performed a cost estimation study for legacy aluminum structures and CFRP structures, assuming mass production, and showed that a
weight reduction of 1 kg requires a cost rise of at least 170,000 Yen in the modeled vertical stabilizer structure (Morimoto, 2010). Next, we modeled the lean production of CFRP airframes by extending the Wright learning curve model and the Cobb-Douglas production function for the variable human-capital fraction while explaining deviations in the real delivery rate from the ideal case as stagnation resulting from excessive work using an asymmetric simple exclusion process (ASEP) cell automaton model (Morimoto, Kobayashi, Nagao, & Iwahori, 2016).

Additive manufacturing (AM) is a technology that helps to solve the stagnation problem by controlling excessive work as well as providing the potential of design freedom, no necessity of time taking machining process, and on-demand operations to enable less idle time. Systematic reviews (Costabile, Fera, Fruggiero, Lambiase, & Pham, 2017; Fera, Fruggiero, Lambiase, & Maccharoli, 2016) and standardization (ASTM, 2012) are active for the wide fields of potential AM applications including CFRPs (Kliftk, Koga, Todoroki, Ueda, Hirano, & Matsuzaki, 2016), implying that the drastic reduction in CFRP-made airframe life cycle cost (LCC) lowered the cost of production as well as that of maintenance, repair, and overhaul (MRO). The typical maintenance cost of a CFRP airframe has been estimated at seven percent of the total operating cost, with intervals of three years for the base inspection (C-Check) and 12 years for heavy maintenance (D-Check) (Khwaja, 2006). Such maintenance will not be needed in the near future because of AM-based, on-demand maintenance during the routine post-flight-check. Thus, the trade-off analysis method for selecting airframe materials must be flexible in considering the cost benefit of the rapidly evolving new technologies relating to AM.

In this work, we study the trade-off between the saved fuel cost $\Delta C_{\text{fuel}}$ and the rise of structural cost $\Delta C_{\text{structure}}$ assuming a change in airframe structural material from legacy metals to new materials while keeping the legacy design concept. This has been called the “Black Metal” approach, in which airframe components have been changed to typically black CFRPs while keeping the design concept of silver-colored aluminum metal. New design concepts such as “blended wing body” (BWB) craft may fully realize the excellence of CFRPs in airframe innovation beyond the conventional “tube and wing” design. Thus, use of the Black Metal approach may be a milestone in aircraft design history. However, we deduce that the Black Metal concept will continue with mainstream airliner design for the next few decades as the duration of developing commercial jetliners using the black metal concept is long. Starting with small subcomponents in the 1970s, such as landing gear bay doors, control surfaces, and tailplanes, the concept has progressed in the 2010s to the main components of long-range aircraft, such as main wings and fuselage.

The change from legacy metals to new materials while keeping the legacy design concept is analyzed as follows. First, the growth factor is used to estimate the saving of take-off gross weight $\Delta W_{\text{TOGW}}$ by changing the material of an imaginary component from a legacy aluminum alloy to a new, lightweight material. Next, the Breguet range equation is modified to estimate the fuel weight saving $\Delta W_{\text{fuel}}$ for a given range $R$ and $\Delta W_{\text{TOGW}}$. Finally, a new cost trade-off tool modified from $\Delta C_{\text{fuel}} - \Delta C_{\text{structure}}$ is proposed to analyze the cost superiority of new materials under the given conditions of unit weight cost, specific strength, aircraft range, and fuel price.

2. Methodology

2.1. Growth factor

The importance of controlling structural weight has become well known through the lesson that adding even the slightest fixed weight leads to larger wings, more powerful but heavier engines, and the need for more fuel. This loops back to the need for stronger and, thus, heavier structures to sustain the increment of weight factors. The “snowball effect” of weight growth thus leads to a drastically larger ratio between the added fixed structural weight and the increment of take-off gross weight. The growth factor ratio $G.F.$ is defined in the articles (Ando, 1958a, 1958b, 1958c; Driggs, 1952; Yamana, 1953) as follows.
The take-off gross weight, $W_{\text{TOGW}}$, is defined for civil airliners as follows:

$$W_{\text{TOGW}} = W_{\text{structure}} + W_{\text{propulsion}} + W_{\text{fuel}} + W_{\text{payload}} + W_{\text{systems}} \quad (1)$$

where the subscripts represent, respectively, the structure, propulsion or engine, fuel, payload, and systems including oil and auxiliary fuel supply. Equation (1) is modified as follows:

$$W_{\text{TOGW}} = \frac{W_{\text{payload}} + W_{\text{systems}}}{1 - \frac{W_{\text{structure}} + W_{\text{propulsion}} + W_{\text{fuel}}}{W_{\text{TOGW}}}} \quad (2)$$

The payload and system weights are fixed parameters; the structure, propulsion, and fuel weights concern design and operation, and so these weights are variable parameters as follows:

$$\begin{cases} 
W_{\text{payload}} + W_{\text{systems}} \equiv W_{\text{fixed}} \\
W_{\text{structure}} + W_{\text{propulsion}} + W_{\text{fuel}} \equiv W_{\text{variable}}
\end{cases} \quad (3)$$

Equations (2) and (3) lead to the following expression:

$$W_{\text{TOGW}} = \frac{W_{\text{fixed}}}{1 - \frac{W_{\text{variable}}}{W_{\text{TOGW}}}} \quad (4)$$

Equation (4) shows that fixed weight affects the take-off gross weight at the rate of $(1 - W_{\text{variable}} / W_{\text{TOGW}})^{-1}$. Therefore, the growth factor $G.F.$ is defined as

$$G.F. \equiv \frac{1}{1 - \frac{W_{\text{variable}}}{W_{\text{TOGW}}}} \quad (5)$$

When the fixed structure weight is reduced by changing from a legacy aluminum alloy to a new material, the take-off gross weight reduction is expressed by combining Equations (4) and (5) as follows:

$$\Delta W_{\text{TOGW}} = G.F. \times \Delta W_{\text{fixed}} \quad (6)$$

The typical growth factor values are $G.F. >> 1$; thus, design engineers can expect the impact of weight savings to be drastically higher than that of the direct saving of a component weight alone. For example, the typical case of $W_{\text{propulsion}} / W_{\text{TOGW}} \approx 1.0 \times 10^{-1}$, $W_{\text{fuel}} / W_{\text{TOGW}} \approx 3.5 \times 10^{-1}$ and $W_{\text{structure}} / W_{\text{TOGW}} \approx 3.0 \times 10^{-1}$ provides the growth factor $G.F. \approx 4.0$, implying that the fixed weight reduction using a new material is rewarded by a fourfold reduction in take-off gross weight.

### 2.2. Aircraft range description

A case of “cruise-climb” is assumed with fixed engine throttle and variable altitude above 11 km, where the atmospheric temperature is approximately constant. Thus, jet engine thrust $T$ is approximately proportional to air density, and lift-drag ratio $C_L / C_D$, single-engine-specific fuel consumption (SFC) $E_{\text{SFC}}$, and true air speed $V_{\text{TAS}}$ are also approximately constant. A unit weight of fuel provides a single-engine run time of $1 / (E_{\text{SFC}} \times T)$; thus, the range increment $\Delta R$ is $V_{\text{TAS}} / (E_{\text{SFC}} \times T)$, or

$$\Delta R = \left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right) \times \left( \frac{1}{W_{\text{cruise}}} \right) \quad (7)$$

as the aircraft’s weight at cruise $W_{\text{cruise}}$ is equal to $T \times C_L / C_D$. Therefore, the range $R$ with a fuel weight $W_{\text{fuel}}$ is expressed as follows:

$$R = \left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right) \times \ln \left( \frac{1}{1 - W_{\text{fuel}} / W_{\text{cruise}}} \right) \quad (8)$$

Equation (8) is known as the Breguet range equation. In the twin-engine case, $E_{\text{SFC}}$ in Equation (8) becomes $2 \cdot E_{\text{SFC}}$, as a unit weight of fuel provides the twin-engine run time of $1 / (2E_{\text{SFC}} \times T)$. 

$$\Delta W_{\text{TOGW}} = G.F. \times \Delta W_{\text{fixed}} \quad (6)$$

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$$\Delta R = \left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right) \times \left( \frac{1}{W_{\text{cruise}}} \right) \quad (7)$$

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$$R = \left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right) \times \ln \left( \frac{1}{1 - W_{\text{fuel}} / W_{\text{cruise}}} \right) \quad (8)$$

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2.3. Fuel cost reduction using lightweight material

The case of long-range flight enables the approximation $W_{\text{cruise}} \gg (W_{\text{TGW}} - W_{\text{cruise}})$ or $W_{\text{TGW}} \approx W_{\text{cruise}}$. Thus, the Breguet range Equation (8) is modified as follows:

$$R \approx \left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right) \times \ln \left( \frac{1}{1 - \frac{W_{\text{fuel}}}{W_{\text{TGW}}}} \right).$$  \hspace{1cm} (9)

Rearranging Equation (9) yields

$$\Delta W_{\text{fuel}} \approx \Delta W_{\text{TGW}} \times \left[ 1 - \exp \left\{ \frac{-R}{\left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right)} \right\} \right].$$ \hspace{1cm} (10)

The reduction of fuel cost $\Delta C_{\text{fuel}}$ is thereby given by combining Equations (6) and (10), the fuel price of unit weight $P_{\text{fuel}}$, and number of flights $N$ as follows:

$$\Delta C_{\text{fuel}} \approx N \times P_{\text{fuel}} \times G.F. \times \Delta W_{\text{structure}} \times \left[ 1 - \exp \left\{ \frac{-R}{\left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right)} \right\} \right].$$ \hspace{1cm} (11)

When $W_{\text{structure}}$ is modified because of the strength condition, $\Delta W_{\text{structure}}$ is given as follows:

$$\Delta W_{\text{structure}} = W_{\text{structure}} \times \left( 1 - \frac{S_{\text{Al}}}{S_{\text{NM}}} \right),$$ \hspace{1cm} (12)

where $S_{\text{Al}}$ and $S_{\text{NM}}$ are the specific strengths of legacy aluminum alloy and the new material, respectively. Specific rigidities, instead of specific strengths, are applied in Equation (12) for rigidity conditioned components such as wing panels of flutter-sensitive sections. Equations (11) and (12) lead to the following expression:

$$\Delta C_{\text{fuel}} \approx N \times P_{\text{fuel}} \times G.F. \times \Delta W_{\text{structure}} \times \left[ 1 - \exp \left\{ \frac{-R}{\left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right)} \right\} \right] \times \left( P_{\text{NM}} \times \frac{S_{\text{Al}}}{S_{\text{NM}}} - P_{\text{Al}} \right).$$ \hspace{1cm} (13)

2.4. Monetary benefit of using new materials

The cost rise of the structure $\Delta C_{\text{structure}}$ is given as follows:

$$\Delta C_{\text{structure}} = W_{\text{structure}} \times \left( P_{\text{NM}} \times \frac{S_{\text{Al}}}{S_{\text{NM}}} - P_{\text{Al}} \right),$$ \hspace{1cm} (14)

where $P_{\text{Al}}$ and $P_{\text{NM}}$ are the unit weight prices of legacy aluminum alloy and the new material, respectively. Thus, the cost benefit of using the new material $\Delta C_{\text{fuel}} - \Delta C_{\text{structure}}$ is expressed as

$$\Delta C_{\text{fuel}} - \Delta C_{\text{structure}} = W_{\text{structure}} \times \left[ N \times P_{\text{fuel}} \times G.F. \times \left( 1 - \frac{S_{\text{Al}}}{S_{\text{NM}}} \right) \right] \times \left[ 1 - \exp \left\{ \frac{-R}{\left( \frac{V_{\text{TAS}}}{E_{\text{SFC}}} \right) \times \left( \frac{C_L}{C_D} \right)} \right\} \right] \times \left( P_{\text{NM}} \times \frac{S_{\text{Al}}}{S_{\text{NM}}} - P_{\text{Al}} \right).$$ \hspace{1cm} (15)

2.5. A new trade-off method for material selection

Investment in using a new material is rational only when $\Delta C_{\text{fuel}} - \Delta C_{\text{structure}} > 0$; thus, a relationship is obtained by modifying Equation (15) as follows:
Equation (16) represents the trade-off of cost benefit between using the legacy aluminum alloy and a new material under given specifications of aircraft and fuel price, as illustrated in Figure 2. Legacy aluminum alloy is superior to the new material when cost surpasses the strength benefit, as shown in region “I.” The case of Equation (16) is shown in region “II,” where the new material is superior in cost-strength benefit to the legacy aluminum alloy. Region “III − A” is a safer-side subset of Equation (16) such that \( \frac{P_{NM}}{P_{Al}} < \frac{S_{NM}}{S_{Al}} \), that is, \( \frac{P_{Al}}{S_{Al}} > \frac{P_{NM}}{S_{NM}} \).

Region “III − B” is trivial, as here the new material is superior both in strength and cost than the legacy aluminum alloy. Higher fuel price, longer range flight, etc., may enlarge quantity \( F \) to expand region II as shown in Figure 3. Large \( N \) also leads to large \( F \); thus, the long duration of investment recovery also improves the profitability of new material. Therefore, a low interest rate, which prolongs the recovery duration, is also an important factor in selecting new materials.

![Equation (16)](image)

\[
\begin{align*}
\frac{P_{NM}}{P_{Al}} &< (1 + F) \times \frac{S_{NM}}{S_{Al}} - F \\
F & = N \times G \times \left(1 - \exp \left(\frac{-P}{(V_{c,t} / E_{c,t} + V_{c,t} / \cos \theta)}\right)\right) \times \frac{P_{NM}}{P_{Al}}.
\end{align*}
\]

Figure 2. Trade-off diagram for selection of aircraft materials.
3. Discussion

Typical development programs for jetliners are set to assess whether CFRP is a material worth investment instead of the present aluminum alloys.

(a) Use of CFRPs has been expanding to a larger share of aircraft components from control surfaces and fairings to primary structures in long-range commercial jetliners such as Boeing B787 and Airbus A350. The following example of typical parameters provides the range $R \approx 1.1 \times 10^4$ (Km).

If the price of Jet A-1 fuel is 1.5 dollars per gallon, which was a typical value before 2005, then $P_{\text{fuel}} \approx 0.5$ (dollars/Kgw), and if $P_{\text{Al}} = 400$ (dollars/Kgw), then $F \approx 0.9$ is given by Equation (16) assuming that $N = 20,000$, which is a typical lifetime flight number.

(b) One future target for CFRP application is the volume-zone middle-range jetliner of the single-aisle, twin-engine, 170–230 passenger seats class such as Airbus A321neo and the successor to Boeing 757, which are the so-called “middle-of-the-market” (MOM) airliners (Jens, 2015). The parameters for these are as follows, providing $F \approx 0.4$ by Equation (16).

![Diagram of Cost-benefit increment of new materials.](image-url)
\[
\begin{aligned}
E_{\text{SFC}} &= 1.5 \times 10^{-5} \text{(Kgw/s/N, Cruise)} \\
C_l/C_D &= 18.5 \\
V_{\text{TAS}} &= 850 \text{(Km/h)} \\
W_{\text{structure}} &= 2.6 \times 10^4 \text{(Kgw)} \\
W_{\text{propulsion}} &= 2.0 \times 10^3 \text{(Kgw, Single Engine)} \\
W_{\text{payload}} + W_{\text{system}} &= 2.0 \times 10^4 \text{(Kgw)}
\end{aligned}
\] (19)

The Breguet range Equation (9) provides the range \( R \approx 6.0 \times 10^3 \text{(Km)} \) with \( W_{\text{fuel}} = 2.5 \times 10^4 \text{(Kgw)} \); thus, \( W_{\text{TOGW}} = 7.5 \times 10^4 \text{(Kgw)} \), and the growth factor is given by Equation (5) as G.F. \( \approx 3.8 \).

(c) For a typical regional jetliner, \( F \approx 0.2 \) and \( R \approx 3.5 \times 10^3 \text{(Km)} \). The parameters are given as follows.

\[
\begin{aligned}
E_{\text{SFC}} &= 1.8 \times 10^{-5} \text{(Kgw/s/N, Cruise)} \\
C_l/C_D &= 18.0 \\
V_{\text{TAS}} &= 850 \text{(Km/h)} \\
W_{\text{structure}} &= 1.5 \times 10^4 \text{(Kgw)} \\
W_{\text{propulsion}} &= 1.5 \times 10^3 \text{(Kgw, Single Engine)} \\
W_{\text{payload}} + W_{\text{system}} &= 1.4 \times 10^4 \text{(Kgw)}
\end{aligned}
\] (20)

The strength superiority of a typical CFRP is \( S_{\text{CFRP}}/S_{\text{Al}} = 1.2 - 1.3 \), and the cost premium has been reported as \( P_{\text{CFRP}}/P_{\text{Al}} \approx 1.8 \) (Takeda et al., 2005). However, Equation (16) reveals that the cost premium must remain at the level of \( P_{\text{CFRP}}/P_{\text{Al}} < 1.4 - 1.6 \) for the long-range case, \( P_{\text{CFRP}}/P_{\text{Al}} < 1.3 - 1.4 \) for the middle-range case, and \( P_{\text{CFRP}}/P_{\text{Al}} < 1.2 - 1.4 \) for the regional jet case. Therefore, CFRP is concluded as being of questionable merit as a reasonable material under the Jet A-1 fuel price of lower than 1.5 dollars per gallon. A circumstantial evidence for the conclusion may be the slow sales of new CFRP jet liners around 2015 as a direct result of low fuel price, while the sales of lower-priced, older, and less efficient legacy aluminum liners have been steady (Aussick, 2016a, 2016b; Reed, 2015; Scott, 2016).

This conclusion for the trade-off between CFRPs and legacy aluminum alloys can, however, drastically change under the conditions of (1) higher fuel price, (2) new production methods for lower-cost CFRPs, and (3) strength improvement owing to CFRP itself or by a modified definition of “strength.”

(1) Fuel prices spiked in 2008 to 3.866 dollars per gallon or \( P_{\text{fuel}} \approx 1.3 \) (dollar/Kgw) leading to \( F \approx 2.3 \) for long-range jet liners; thus, \( P_{\text{CFRP}}/P_{\text{Al}} < 1.7 - 2.0 \). These values imply that the cost advantage of legacy aluminum alloys is inferior to present CFRPs of \( S_{\text{CFRP}}/S_{\text{Al}} = 1.3 \) and \( P_{\text{CFRP}}/P_{\text{Al}} \approx 1.8 \) as schematically depicted in Figure 4, which is given as Equation (15) = 0 with fixed \( P_{\text{fuel}}/P_{\text{Al}} \) variable \( P_{\text{CFRP}}/P_{\text{Al}} \) for (a) to (c), and interpolations of the quadratic functions.

For the middle-range case, \( F \approx 1.0 \). Thus, \( P_{\text{CFRP}}/P_{\text{Al}} < 1.4 - 1.6 \). These values imply that the cost advantage of legacy aluminum alloys over CFRPs is close to a negligible level. Therefore, in the near future, with higher fuel price, CFRPs can once again have cost superiority over legacy aluminum alloys.

For regional jet liners, however, \( F \approx 0.6 \). Thus, \( P_{\text{CFRP}}/P_{\text{Al}} < 1.3 - 1.5 \) are given by Equation (16). These values imply that legacy aluminum alloys are reasonable over the CFRPs of \( P_{\text{CFRP}}/P_{\text{Al}} \approx 1.8 \).

(2) Figure 4 implies that a CFRP of \( P_{\text{CFRP}}/P_{\text{Al}} < 1.5 \) holds full-range cost advantage over legacy Al alloys for the case of \( S_{\text{CFRP}}/S_{\text{Al}} = 1.3 \), \( P_{\text{CFRP}}/P_{\text{Al}} < 1.3 \) for the case of \( S_{\text{CFRP}}/S_{\text{Al}} = 1.2 \), and \( P_{\text{CFRP}}/P_{\text{Al}} < 1.2 \) for the case of \( S_{\text{CFRP}}/S_{\text{Al}} = 1.1 \). Figure 5 is a modification of Figure 4 for Equation (15) = 0 for variable fuel price and fixed \( S_{\text{CFRP}}/S_{\text{Al}} \) showing that a CFRP of \( P_{\text{CFRP}}/P_{\text{Al}} < 1.4 \) and \( S_{\text{CFRP}}/S_{\text{Al}} = 1.3 \) effectively holds full-range cost advantage over legacy aluminum alloys.
Mitsubishi Aircraft Corporation has already selected an A−VaRTM CFRP, which is produced using the vacuum-assisted resin transfer molding (VaRTM) method for tailplane components in the MRJ project. A−VaRTM has been reported to have superiority in both strength and cost as follows (Takeda et al., 2005):

\[ \begin{align*}
S_{\text{CFRP}} / S_{\text{Al}} & \approx 1.2 - 1.3, \\
P_{\text{CFRP}} / P_{\text{Al}} & \approx 1.2 + \alpha.
\end{align*} \]  \tag{21}

Equation (21) implies that the A−VaRTM CFRP has already been competitive over legacy aluminum alloys in region II as shown in Figure 2 if the excellence in cost is maintained in mass production, keeping the level of high quality for aerospace components. New manufacturing technologies relating to AM are also positive factors for selecting CFRPs instead of aluminum alloys due to the potential of drastic reduction in the cost through on-demand production for CFRP-made large components.
(3) The strength of $S_{\text{CFRP}} / S_{\text{Al}} = 1.4 - 1.6$, which is attainable if matrix cracks are acceptable in structural material according to the strength definition in the aircraft-type certification (TC), expands the cost performance of CFRPs. Figure 6 schematically shows the present TC condition of matrix crack onset at $A$, the ultimate strength at $C$, and the upper limit of elongation-strength repetition at $B$, which may be accepted as the renewed TC condition. Thus, CFRP can expand the application for regional jetliners.

Therefore, we conclude that rising fuel price and new production methods at lower cost, in addition to provable modification in the TC, will drastically change the materials of commercial jetliners from legacy aluminum alloys to CFRPs.

4. Conclusions
A simple new trade-off method of cost and weight has been proposed for the selection of airframe materials. The method clarifies the benefit of using new materials, the use of which is a result of specific strength, cost, fuel price, and aircraft range. The model analysis indicates that rising fuel price, new CFRPs of lower unit-weight cost, and applications of lower LCC technologies relating to AM can bring about a drastic change in aircraft materials from legacy aluminum alloys to CFRPs.

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