BUT HOW MUCH DOES IT WEIGH?

Structural Weight Estimation of Aircraft Lifting Surfaces

The airframe structural weight is the most relevant component of the Operating Empty Weight (OEW) for structural designers. In fact minimizing structural weight is the main objective of aircraft structural design, taking into account constraints on structural integrity and cost. The importance of weight for aircraft performance makes weight control an essential part of the aircraft design process. A good weight control process cannot be performed without having proper weight estimation methods.

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WEIGHT ESTIMATION METHODS

Weight estimation methods used in the aircraft design process can be generally divided into four different classes. The lower the class, the more the method relies on (historical) statistics. Higher class weight estimation methods use less estimation and more calculation. Even when using advanced finite element analysis, it is not possible to calculate the total weight of an aircraft structure. For many components, estimation is still needed up until the moment when actual weight measurement can be applied. Each class of weight estimation methods is briefly discussed here.

Class I methods are mostly used at the very beginning of the aircraft conceptual design process to estimate the weights of the major weight groups. This is done by looking to the weight breakdown of a number of existing aircraft with the same mission as the aircraft under study. These methods, also known as *fraction* methods, represent the weight of each aircraft component as a fraction of maximum take off weight (MTOW), or any other reference weight like design gross weight, and they assume that within each aircraft category these fractions are constant.

Class II weight estimation methods are used when a simplified geometric definition of the aircraft configuration and the aircraft V-n diagram are available. These methods estimate the weight of each main aircraft component or group of components like the fuselage, wing and landing gear, using empirical equations that combine geometrical parameters and statistical based coefficients derived from weight breakdowns of existing aircraft.

In the 1950s, a new set of weight estimation methods was introduced based on elementary strength/stiffness analysis of the load carrying structure, augmented by experimental and statistical data. In these so-called *class II & ½* methods the amount of material required to resist the applied loads is calculated using analysis of a simplified model of the airframe structure. These methods not only provide better results than *class II* methods but they are also design-sensitive, hence they support the designer in assessing the impact of specific design decisions on the weight of various aircraft components.

Class III weight estimation methods use the Finite Element Method (FEM) to calculate the weight of the aircraft primary structure. In order to use these methods it is necessary to have a reliable load set, and a geometric model of the aircraft structure, including structural details such as cross-sectional shapes of spars, ribs and skins. As with the *class II & ½* method, a series of empirical equations (or coefficients) is still required to calculate the weight of the structural elements which are not modelled in FEM.

Statistical weight estimation methods are usually used in the early design stages when the designers knowledge of the new aircraft is limited, and the weight estimation process has to rely on previous experience. Once the design matures, there is an increasing understanding of the design and higher class weight estimation methods can be used.

Even from the initial design phase, where the aircraft layout is defined, the importance of an accurate weight prediction can hardly be overrated. Overestimating the maximum take-off weight will make the concept hard to sell. Communicating an underestimated aircraft weight to customers at the beginning of the design

Figure 1. Boeing 2707

Figure 2. Canadair Challenger

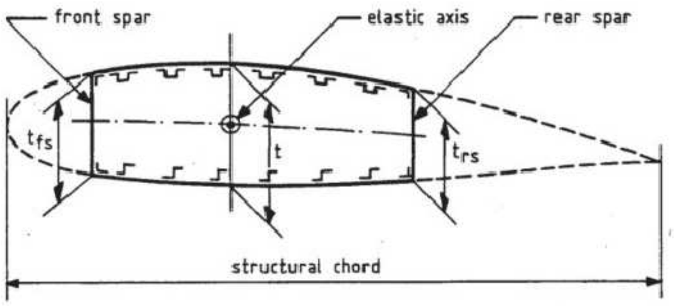

Figure 3. Wingbox structure

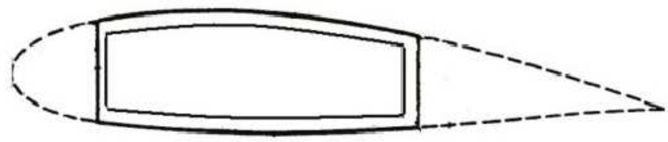

Figure 4. Equivalent panel representation

process can cause the company to incur financial penalties at the full scale development and production stage if it does not meet the weight that was stated. Some cases have been reported in which a design program has failed simply because of the wrong weight estimation in the initial phases. For example during the Boeing Supersonic Transport detail design phase it was discovered that the structural weight estimates had been too optimistic. The result was an airplane design that could meet its mission requirements only without payload: in other words, they did not have an airplane design. Boeing reported to the FAA and NASA that they had made a mistake and the government gave them a new contract to redesign the configuration, which resulted in the Boeing 2707 aircraft (figure 1). Another example is the Canadair Challenger (figure 2). The aircraft program was launched in 1976 with a MTOW of 33,000lb. During the flight tests the aircraft showed a disappointing range performance. To overcome this problem the designers changed the aircraft engine which increased the MTOW to 41,500lb. As a result of this change, the aircraft price had gone up from seven million dollars, to ten million dollars for the standard configuration.

REFINED PRELIMINARY WEIGHT ESTIMATION METHOD

Although several high class weight estimation methods are readily available, the lower class methods are still widely used in aircraft design, especially in Multidisciplinary Design Optimization (MDO) projects. In MDO, the fidelity of the solvers is often sacrificed for models with short computation times. *Class II & ½* methods are widely used in MDO projects. Their level of accuracy is higher than that of statistical methods while also being design sensitive. Additionally, the computational demands for such methods are much lower than for any *class III* method. Table 1 shows the results of some existing *class II & ½* wing weight estimation methods. From table 1, one can observe that some methods perform better for certain types of aircraft than others. This is mainly due to the reference aircraft data that are used to tune the semi-empirical coefficients in some of the weight component relations. However it should be noted that the level of accuracy of these methods is acceptable only for a point analysis of the aircraft mass. However for a multidisciplinary optimization process, a few percent error in weight estimation can shift the results too far from the real optimum point. For example, for a very large passenger aircraft (Airbus A380 class) with take off weight higher than 500 tons, a 3% error in wing weight estimation is equal to the weight of 30 passengers which has a significant effect on other disciplines such as cost analysis. So it was decided to develop a new *class II & ½* weight estimation method for aircraft lifting surfaces with higher accuracy and design sensitivity.

The origin of the errors can be found in the following three areas:

1. Geometric model: a large majority of the current methods use an oversimplified geometry model of the wing and tail.
2. Loads: due to the lack of an adequate geometric model, the aerodynamic loads are calculated using empirical equations or by assuming an elliptical lift distribution. In addition, not all of the load relief factors are taken into account.
3. Empirical coefficients: since these empirical coefficients are determined using statistical data, they are not sufficiently

Table 1. Results of some class II & ½ wing weight estimation methods

Aircraft	Error of wing weight estimation (%)				
	AdAstra	Torenbeek	Van Dijk	WP15	Macci
A300-600R	4.7	-17.9	4.6	-0.2	11.97
A310-300	-7.2	-24.6	-4.0	-0.3	-
A320-100	-7.0	-27.5	-9.1	-8.3	-4.55
A330-300	0.1	-26.6	-12.9	-12.7	-
A340-300	-1.4	-20.4	-2.4	-5.9	-2.83
A380-800	22.6	-9.9	8.5	0.4	-
B747-200	29.4	-1.0	15.6	22.0	-1.79
B747-400	55.5	13.1	38.9	42.4	-
B777-200	16.2	-7.1	10.8	16.1	-

Table 2. Results of aileron weight estimation			
Aircraft	**Material used in aileron**	**Error of Torenbeek method (%)**	**Error of modified method (%)**
A300-600	Metal	-7.8	-1.2
A310-300	Metal	-10.9	-9.8
A320-200	Composite	5.0	2.6
A321-200	Composite	4.5	2.5
A330-300	Composite	-18.4	-6.2
A340-300	Composite	-17.1	-4.7
A340-600	Composite	-14.6	-1.8

Table 3. Results of new developed class II & ½ wing weight estimation method

AIRCRAFT	MTOW (KG)	ERROR (%)
FOKKER 50	20820	-0.72
BOEING 737-200	52390	0.15
BOEING 727-200	95028	-2.71
A300-600R	170500	1.86
A330-300	217000	-2.18
BOEING 777-200	242670	2.66

generic.

Based on these listed problems, the new method should have an accurate geometry generator, a better load calculation and it should avoid tuning coefficients. In the proposed method, the use of semi empirical equations is limited to wing and tail secondary weights. An advanced analytical method is used to predict the weight of the torque boxes, based on the actual geometry of the aerodynamic surface and the computed lift force distribution.

An advanced parametric multi-model generator is used to model both the outer aerodynamic shape and the inner structural configuration of the lifting surfaces. Aerodynamic loads are calculated using a commercial Vortex Lattice Method (VLM) tool, based on specific load cases described in the airworthiness regulations. The weight relief effect due to fuel, wing engine installation and wing mass are also taken into account in the proposed weight prediction method.

A simplified structural model is used for structural analysis. Figure 3 shows the real internal structure of a wing, including skin, spar caps, spar webs and stringers. This structure can be simplified using equivalent panels. In this way the upper and lower skin, stringers and spar caps are modelled with an equivalent upper or lower panel, while the spar webs are modelled separately with vertical panels (see figure 4).

A set of mathematical equations has been derived to relate the required structural properties of the torque-box to the airfoil shape of the wing or tail. These equations can model the curved equivalent panels as two flat equivalent panels, and then calculate their "effective distance". This distance is actually the factor that allows accounting for the effect of the airfoil shape on the stress distribution in the panels, hence the weight of the panels.

The weight of the primary structure is calculated by stationary sizing of the wing-box structure. Eventually, the total weight of the given lifting surface is computed as the sum of the analytically calculated torque-box weight, the non-optimum torque-box weight (e.g. joints in skin-stringer panels and large cutouts) and the secondary weight (e.g. movables). The last two contributions are estimated on the basis of semi-empirical calculations, in this case those of Torenbeek (1992). They are used to estimate the weight of each part of the secondary structure separately. Some of those equations are modified to have better accuracy for advanced composite structures. Table 2 shows the validation results of basic and modified equations for aileron weight estimation.

Another advantage of this method is the capability to perform a weight estimation of composite structures. Existing statistical weight estimation methods (*class II* methods) have serious problems estimating the weight of aircraft with composite structures because their initial databases mostly include metal aircraft. In the newly developed weight estimation method, different combinations of material can be analysed for structural weight estimation including composite stiffened panel and composite sandwich structures.

The method is validated with a number of airplanes of different size and category. Table 3 shows the validation results for some existing aircraft. A regression method is used to derive the relationship between the analytically calculated wingbox weight (optimum weight) and the actual wing total weight. The result of this regression is shown in figure 5. This figure illustrates a perfectly fitted curve for different aircraft with a wide range of take-off weight.

The method described above has been implemented into a software application. The computational time is dramatically lower (in the order of 10 seconds from reading the inputs to creating the outputs) than any finite element analysis, while the level of accuracy (average error less than 2%) and design sensitivity is the same or even higher. This software is going to be integrated with other disciplines (e.g. aerodynamic and performance) within a Design Engineering Engine (DEE) which is under development at the Flight Performance and Propulsion group at the Aerospace Engineering faculty to support multidisciplinary design optimization of aircraft. Additionally, a simplified version of the tool has been developed as "student version" to be used by the students in their MDO projects.

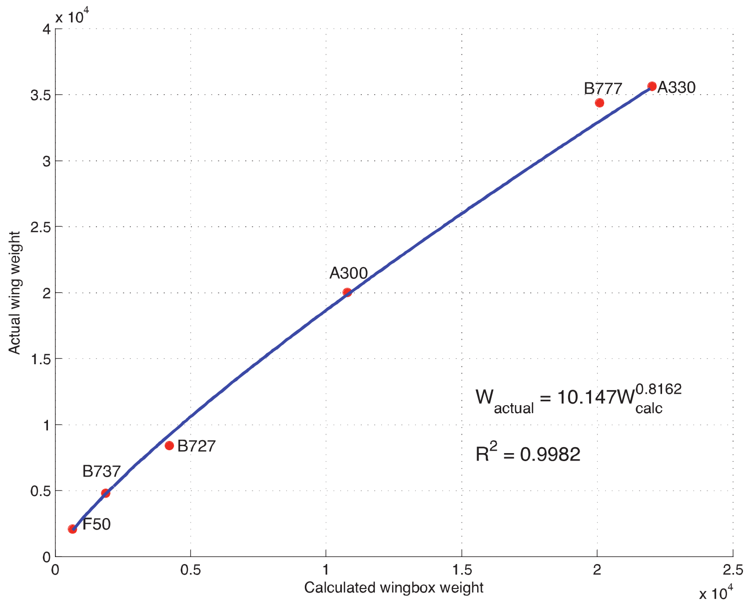

Figure 5. Power regression results

References

Torenbeek E., "Development and Application of a Comprehensive, Design-sensitive Weight Prediction Model for Wing Structures of Transport Category Aircraft", Report LR-693, Delft University of Technology, September 1992.