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Assessment of Dynamic Effects on Aircraft Design Loads: the Landing Impact Case

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Abstract
This paper addresses the potential benefits due to a fully dynamic approach to determine the design loads of a mid-size business jet. The study is conducted by considering the fuselage midsection of the DAEDALOS aircraft model with landing impact conditions. The comparison is presented in terms of stress levels between the novel dynamic approach and the standard design practice based on the use of equivalent static loads. The results illustrate that a slight reduction of the load levels can be achieved, but careful modelling of the damping level is needed. Guidelines for an improved load definition are discussed, and suggestions for future research activities are provided.

Keywords: *design loads, dynamic simulation, aircraft design, damping.*

1. Introduction

The DAEDALOS project aimed to develop new methods to reduce the uncertainty and the conservatism of today's design and certification procedures. Among the objectives of the project, an in-depth investigation was carried out to account for dynamic effects in the context of the design loads evaluation. The present effort focuses on dynamic landing, a loading condition usually relevant for the fuselage design.

Early studies on dynamic landing are found in the works of Biot and Bisplinghoff [1] and Williams and Jones [2]. They assume that the landing gear reactions are independent on the elastic properties of the structure. Once the reactions are computed, they are applied to the elastic aircraft, which is represented by means of simple analytical models. Pioneering work on effects due to coupling between landing gear and structure are due to McPherson et al. [3] and Cook and Milwitzky [4], where the structure is modeled with a two-degree of freedom model. More recently, extensive use of the finite elements has been used to model the response of an elastic aircraft. An example is found in Luber et al. [5], where dynamic loads due to landing impact on the main wheels are computed and then the attachment loads of the landing gear are used as input for the excitation of the aircraft structure. In Ref. [6], the simulation tool developed by EADS is briefly reviewed. In this case, the landing gear nonlinear behaviour is considered, together with its interaction with the flexible structure. The simulation is performed using MSC Adams and MSC Nastran. A similar strategy is proposed in [7] for aircraft tailless configurations. The effects on the landing impact due to the pitching motion and the response of the nose gear were accounted for by Chester [8].

Despite the improvements due to modern simulation techniques, common design practice still relies on the use of equivalent-static approach to establish the stress distribution in response to dynamic loading conditions, such as those due to a landing impact.

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The main advantage of the standard design practice can be found in its simplicity and time effectiveness. Indeed, the evaluation of the aircraft internal forces and the subsequent evaluation of the stress distribution can be performed by direct application of a predefined set of static loads on the finite element model of the structure. However, the procedure suffers from its inability to account for the propagation behaviour along the fuselage of the loading forces - mainly related to the frequency content of the input load and the characteristic frequencies of the fuselage structure - and damping, i.e. the capability of the structure itself to damp the loading waves amplitudes, starting from the zone close to the load introduction point and propagating away from it.

In particular, the underlying assumption is that the model does not absorb any energy by the stringer/frame/skin constructions and the "full" load acting at a certain location is "propagated" along the fuselage without attenuation arising from structural damping.

Up to date, very few studies have been directed towards the assessment of the potential reduction of the section forces propagating to the rest of the aircraft, accounting for the effects of energy dissipation near the load introduction location, and the transfer of energy from local impact locations to other parts of the fuselage.

It follows that the final design can be affected by the approximation due to this approach, with an impact on the final weight of the configuration.

Contrarily, an improved fully dynamic approach could be adopted if more refined finite element model is used since the early phases of the design phase. In this case, the transient dynamic analysis is performed directly using a shell model, with no need to transfer the relevant loads from the stick to the shell model in the form of static loads. In this context, the structural response, which can be performed in the time or in the frequency domain, is determined for different loading conditions by adopting numerical models with a larger number of degrees of freedom. Therefore, the stress distribution of the various portions of the structure can be directly monitored at the various timeframes of the load history. The increase of the overall analysis time is noticeable and, for this reason, classical design procedures have usually discarded a fully dynamic design procedure.

Nowadays, thanks to the improved computational resources available, the assessment of the benefits due to a fully dynamic approach is compatible with the time needed to complete the overall sizing process and a fully dynamic procedure can be adopted during the aircraft design phase.

The goal of the present work is to assess the possible advantages due to the adoption of a dynamic approach in the sizing process of a typical business jet. The benefits due to a dynamic design strategy are investigated in terms of weight. Part of the study is directed towards the evaluation of the effects due to the damping properties on the reduction of the design loads. The investigation culminates into a novel proposal to reduce the conservativeness of static design loads, providing guidelines for an improved sizing for the next generation of aircrafts.

2. Aircraft Model Description

The aircraft model here considered was developed within the DAEDALOS consortium on the basis of the experience of the industrial partners involved in the project. The aircraft configuration is considered as representative of a mid-size business jet, powered by two turbofan engines mounted in the aft fuselage. A sketch of the model and its relevant dimensions are provided in Figure 1. The wingspan is 15.38 m and the overall length is equal to 15.65 m; the wing reference area is 32.38 m^2. The structural configuration is characterized by a two-spar box structure for the wing, a fuselage with a multi-frame configuration, a sandwich horizontal tail and a vertical tail with a three-spar configuration.

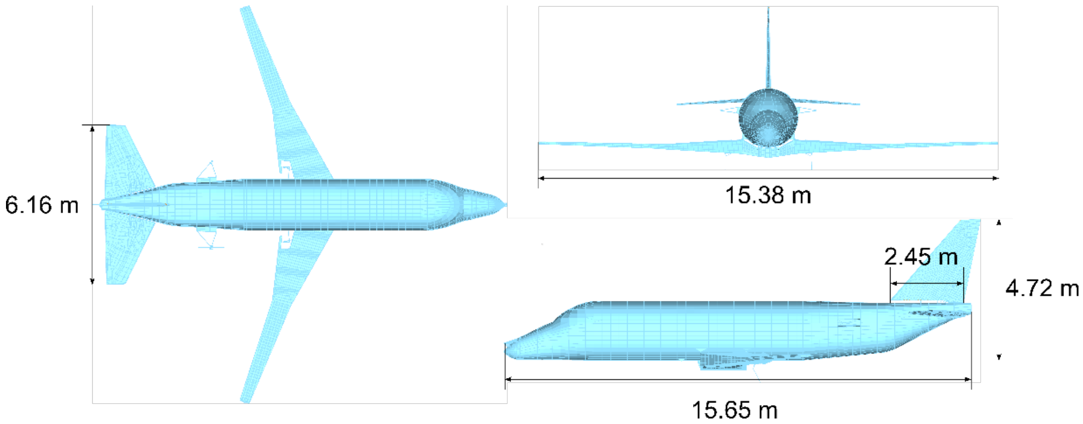


Figure 1. DAEDALOS aircraft model.

2.1 Structural Section

The assessment of the potential benefits due to an improved dynamic approach is conducted on the design of the mid fuselage section. This portion of structure is the one experiencing the highest load levels in response to the fuselage bending after an impact loading. A sketch of the portion of structure is highlighted in Figure 2. As observed, the model is reduced to half of the structure due to symmetry of the loading conditions resulting from the landing.

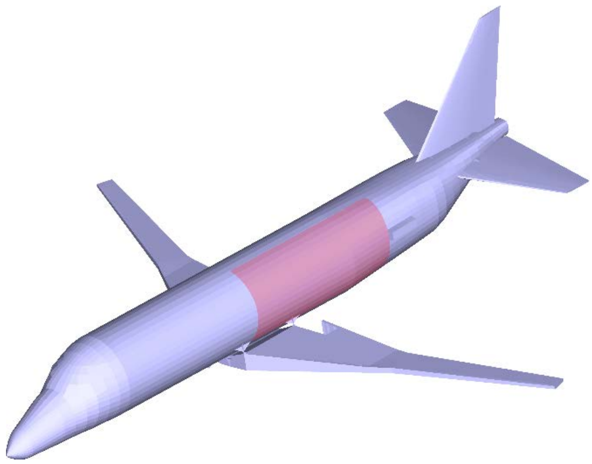


Figure 2. Fuselage section selected for the study.

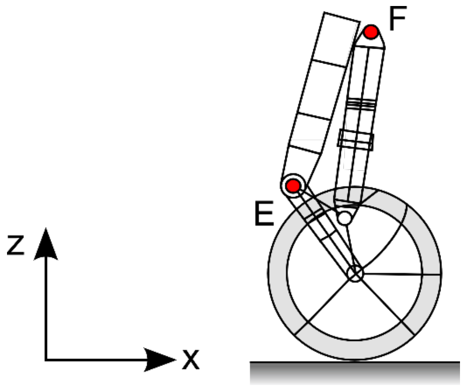
This section extends from a distance of 5582 mm from the fuselage nose, up to 9905 mm. The overall length of the barrel here considered is then 4323 mm.
The comparison between the standard procedure and the improved one is conducted by comparison of the stress levels in terms of components σ_y, where y denotes the direction along the fuselage axis. To this aim, the stress level is monitored for all the elements of the selected section.

2.2 Landing Gear

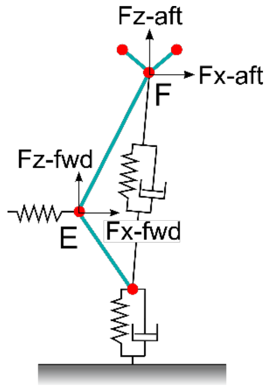
The stress distribution due to a landing impact is influenced by the load introduction in correspondence of the landing gear attachment. The DAEDALOS aircraft model is characterized by a trailing link landing gear, with the presence of an energy absorbing element (shock absorber) mounted between the rigid upper trunnion part and a moving element or trailing link. The main advantage of this configuration relies in the good balance between an adequate value of stroke and a compact gear design. A sketch of the landing gear is reported in Figure 3(a).

The shock absorber is assumed to be of the oleo-pneumatic type. This type of damper absorbs energy by pushing a chamber of oil against a chamber of gas and then compressing the gas and the oil. Energy is dissipated by the oil being forced through one or more orifices, and after the initial impact, the rebound is controlled by the air pressure forcing the oil to flow back into its chamber through one or more recoil orifices.

Regarding the mathematical model of the landing gear, the shock absorber is approximated as a spring to represent the isotropic curve of the compressed gas and a damping element to account for the damping effect of the oil. The tire is also represented by its stiffness and damping coefficient. The fore-aft stiffness of the landing gear is represented separately by a specific stiffness element. A sketch of the landing gear model is presented in Figure 3(b).



(a)



(b)

Figure 3. Main landing gear: (a) configuration, (b) mathematical representation.

3. Loading Conditions

Typical design conditions of the fuselage section are those corresponding to the landing impact of the aircraft. These conditions, usually referred to as “dynamic landing”, are analyzed referring to the requirements of FAR/CS 25.473, 25.479, 25.481, 25.483, 25.485 [9, 10].

More specifically, the aircraft is assumed to impact the ground with a vertical velocity equal to 10 fps at level and tail down attitudes with a maximum gross weight up to the Maximum Design Landing Weight (MLW).

In the present sizing process, two weight configurations are used for the analysis of the loads due to landing:

- Basic Operating Weight (BOW): 7200 kg
- Maximum Landing Weight (MLW): 10200 kg

Furthermore, each of the two configurations are analyzed by considering four distinct landing conditions:

- Tail Down with Sea level conditions (TD_VL1)
- Tail Down with Hot and high conditions (TD_VL2)
- Level Landing with Sea level conditions (LL_VL1)
- Level Landing with Hot and high conditions (LL_VL2)

Tail down landings are analyzed by assuming a maximum pitch angle of 13°, while level landings assume a 0° pitch angle. The different conditions are summarized in Table 1, together with the corresponding ground speeds.

Condition		Configuration	True airspeed [m/s]	Pitch angle
Level landing	Sea level	BOW	44.27	0°
Level landing		MLW	52.18	
Level landing	Hot and high	BOW	71.56	0°
Level landing		MLW	84.33	
Tail down	Sea level	BOW	44.27	13°
Tail down		MLW	52.18	
Tail down	Hot and high	BOW	57.27	13°
Tail down		MLW	67.50	

Table 1. Landing conditions.

For the eight loading conditions of Table 1, the internal loads are evaluated at different fuselage sections. The critical condition is identified as the Tail Down with hot and high conditions (TD_VL2) for the MLW configuration.

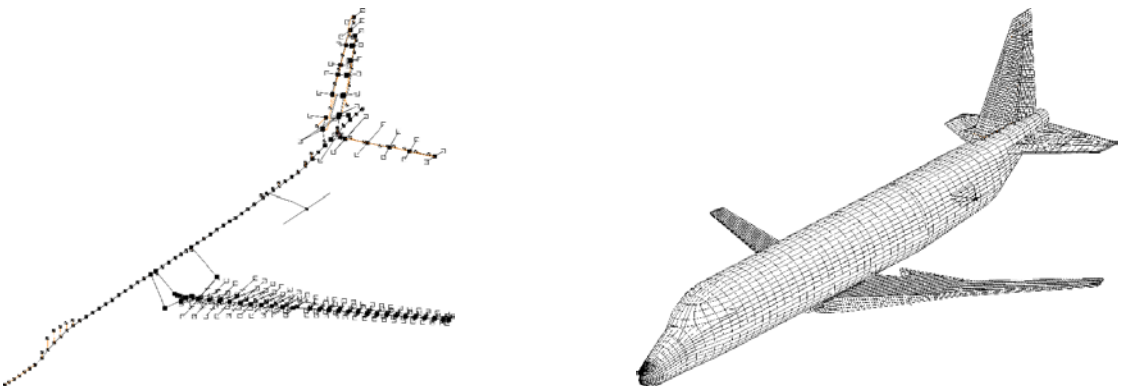
Both for the static and the dynamic approach, the net loads on the airframe due to the landing impact on the main landing gear are determined by the superposition of the 1g static loads acting on the aircraft just before touchdown, landing gear reactions, and dynamic loads of the aircraft structure.

Regarding the landing gear reactions, they are determined by adopting the mathematical model described in Section 2. To obtain more realistic values, the landing gear model is connected to the structure, so that the aircraft flexibility can be accounted for. The model is implemented in an in-house code developed by IAI and combined with MSC NASTRAN [11]. As discussed in the next section, in the standard design approach the landing gear is connected to the stick model, while in the dynamic approach it is connected to the full shell model.

4. Overview of the Methodologies

The static and the dynamic approaches have been applied to simulate the sizing process of a specific section of the fuselage and to establish, by comparison, any potential weight reduction. In the present investigation the stresses directed along the fuselage axial direction are taken as design parameters.

The analyses are performed with the commercial code MSC NASTRAN, and two kinds of finite element models, denoted hereinafter the stick and the 3D shell model, are adopted. An illustration is reported in Figure 4.



(a) (b)

Figure 4. Finite element models: (a) stick model (b) 3D shell model.

Due to the symmetry of the loading conditions, the models are reduced to half of the overall structure by imposing symmetry constraints at the intersection between the structure and the symmetry plane. The stick model, presented in Figure 4(a), is composed of 107 bar and 20 beam elements, respectively. Rigid elements and concentrated masses are introduced to achieve a good description of the dynamic properties of the aircraft.
The shell finite element model is reported in Figure 4(b). It is characterized by a relatively coarse mesh, with a number of 29965 shell elements, 17420 rods and 995 bars.
An overview of the static and the dynamic procedure is provided in Figure 5.

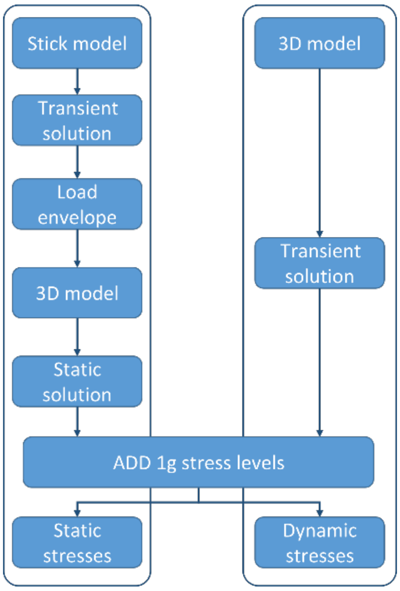


Figure 5. Overview of the standard approach and of the fully dynamic approach.

The static approach is summarized in the left part of the chart. In this case, the main landing gear reactions are applied to the stick model and a dynamic analysis is performed. Then, the design conditions are identified at each fuselage section on the basis of the internal force distribution as obtained from the stick model. Finally, the force distributions derived from the stick model are transferred to the 3D shell model in the form of equivalent static loads. A linear static analysis is then performed and the stress distribution for the structural sizing are established.
The workflow of the dynamic approach is illustrated in the right part of Figure 5. In this case, the landing gear reactions are applied directly on the 3D shell model, which is analyzed by performing a direct transient analysis. As result, time histories are available for each element of the model, and the sizing stresses are taken as the maximum values during the timeframe considered. For the fully dynamic approach, the damping effect is here investigated by means of a parametric study to quantify its impact on the final design. In particular, the results are compared by plotting the ratio between the stress levels obtained with the dynamic and the static approaches to establish the change in sizing loads.

5. Standard Approach Based on Equivalent Static Loads

The static loading approach relies on the adoption of a simplified finite element model of the aircraft, the stick model, which is used to determine the dynamic characteristics of the aircraft.

Standard design procedures based on static loadings make use of stick models derived from a full, detailed, FE model adopted for stress analyses. Furthermore, these models are generally updated and tuned on the basis of the results, if available, from ground vibration testing.
A set of load cases is then assembled based on the number of critical time points obtained from the dynamic analysis and by combining the 1g static loads with the incremental dynamic loads due to the landing impact. Maximum and minimum integral loads are obtained for each fuselage section and the corresponding load cases are selected as critical.
Each of the selected critical load cases is representative of a single time point taken from the whole time response, and is then expressed as a balanced static force distribution over the grids of the loads model. The load distribution is transferred, as a set of equivalent static forces, on the grids of the full FE model. The transfer of the set of forces describing a specific load case from the Loads Model to the full FEM, is done using a spline method, as illustrated in Figure 6.

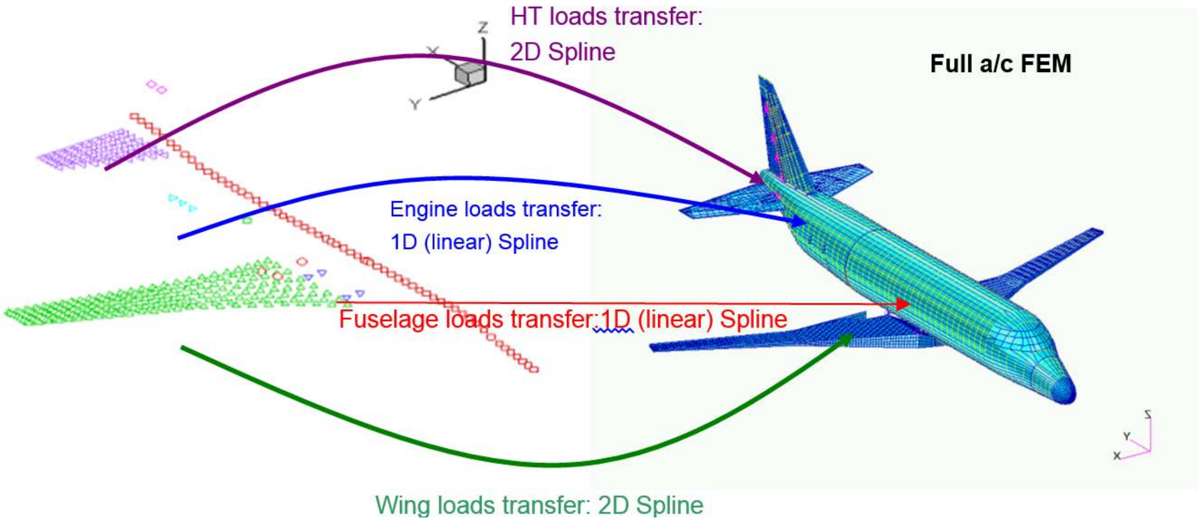
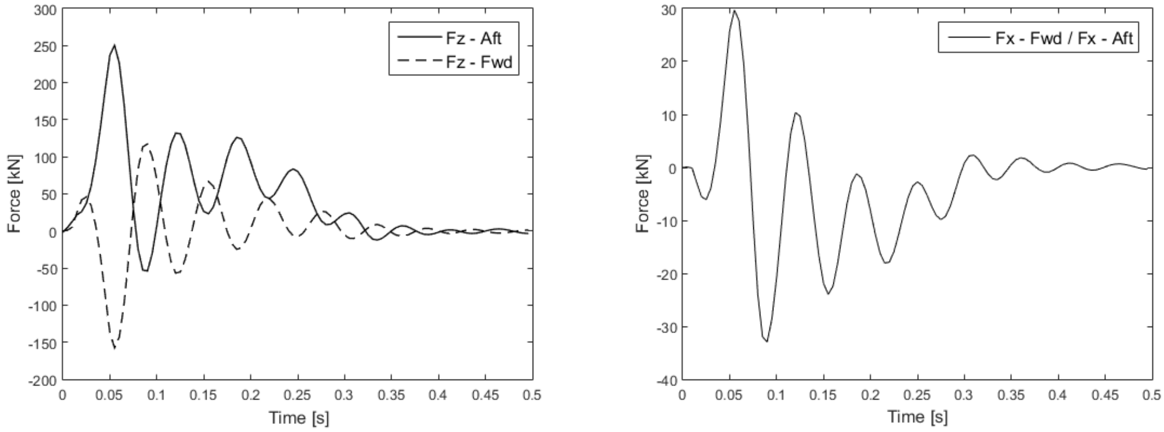


Figure 6. Transfer of loads from Loads Model to full FEM.

Once the load set is transferred to the full model, a linear static load is performed and the internal stress distribution is derived.
According to the load cases enumerated in Table 1, eight landing simulations were performed. For each simulation, landing gear reactions were obtained at the corresponding attachment points and, subsequently, they were used as forcing functions for the evaluation of the fuselage loads. As part of the landing impact simulations, time histories of local accelerations were computed at different aircraft locations.
To illustrate a typical results, the time history of the landing gear reactions are reported in Figure 7 for the landing condition TD_VL2 with MLW weight configuration, where the sign convention is based on the reference systems of Figure 3(a).



(a) (b)

Figure 7. Time history of the main landing gear reactions:
(a) vertical component Z, (b) horizontal component X.

5.1 Fuselage Load Envelopes

The fuselage design is performed by monitoring five sections at different stations. The sections are illustrated in Figure 8, were the acronym FS stands for "fuselage section", and the successive number identifies the coordinate along the fuselage axis measured from the fuselage nose.

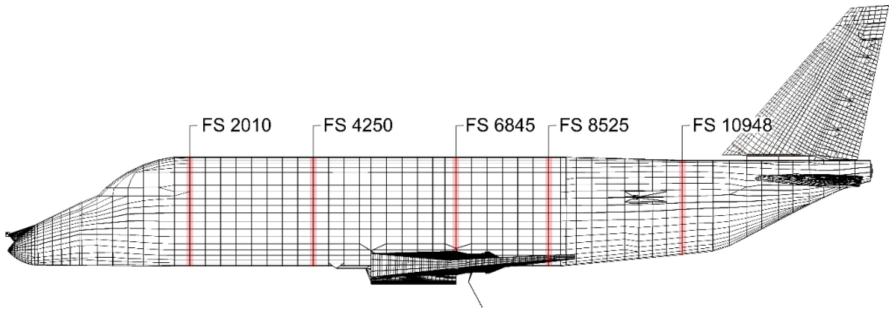


Figure 8. Fuselage sections.

As far as each of the eight landing conditions analyzed is composed of 100 time points, an overall number of 800 loading conditions was considered. A summary of the critical load cases defining the envelope at the monitoring stations is presented in Table 2, where the configuration, the landing condition and the time frame corresponding to the relevant loading condition is reported.

Configuration	Landing condition	Time frame [s]
BOW	Tail down	0.045
BOW	Tail down	0.300
MLW	Level landing	0.100
MLW	Tail down	0.055
MLW	Tail down	0.060
MLW	Tail down	0.150
MLW	Tail down	0.215
MLW	Tail down	0.220

Table 2. Fuselage critical landing cases.

Among the various conditions of Table 2, the one corresponding to the maximum design landing weight (MLW), tail down, and hot and high condition is identified as the critical one. It is here noted that the same landing condition will be used for comparison purposes in the section devoted to the analysis of the fully dynamic design procedure.
In the context of the static approach, the time frame corresponding to critical loading conditions is 0.055 s after the impact. The loads are then reported to the 3D shell model in the form of static counterparts, and a linear static analysis is performed with the NASTRAN SOL 101 solver. The results of the analysis are summarized in Figures 9 and 10. In particular, the stress distribution is reported in Figure 9 in terms of components y of the stress tensor. On the other hand, the deformed shape of the complete aircraft is presented in Figure 10. The magnitude of the deformed pattern is amplified to illustrate the fuselage bending, which is responsible for compressive stresses on the lower area and tension stress on the upper part.

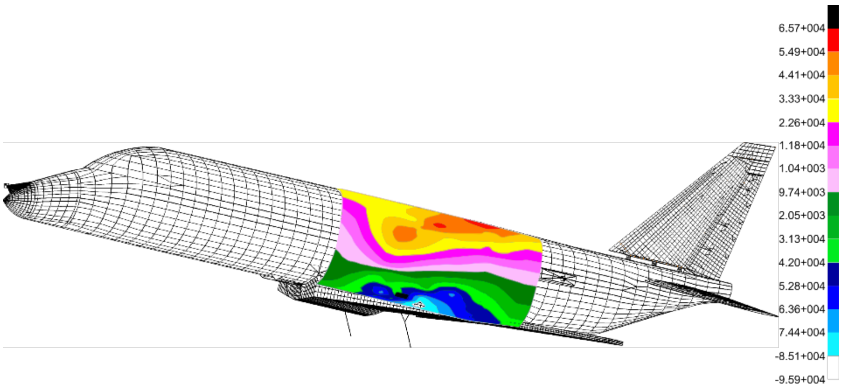


Figure 9. σ_y stress values for static baseline condition.

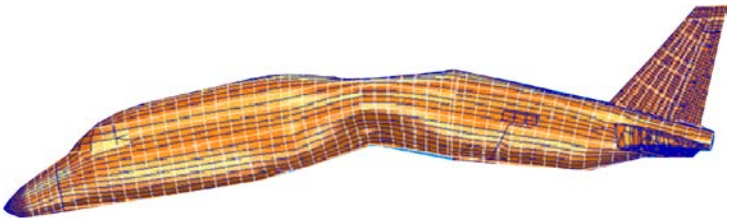


Figure 10. Deformed shape of the model for the static baseline condition.

6. Novel Procedure Based on Dynamic Loads

A novel approach based on a fully dynamic approach is then developed. Goal of the investigation is to check whether a weight reduction is possible in comparison to the current design methodology based on simplified models and equivalent static loads.
The dynamic response analysis is based on the 3D shell model, whose picture is presented in Figure 4(a), specifically developed within the DAEDALOS project.
As summarized in Figure 5, the approach is based on a direct transient analysis of the 3D shell model, which is performed using the MSC NASTRAN SOL 109 solution. The forcing function are represented by the reactions at the main landing gear attachments obtained by means of a specific landing simulation code.
As far as the analysis is conducted on the 3D shell model, the stress distribution in the fuselage elements is directly available from the analysis results in the form of time history. The critical time

frame is selected as the one corresponding to the peak stress values, which are then compared with those obtained using the static method.

6.1 Forcing Functions

As for the standard approach, the forcing functions are the time histories of the reactions at the main landing gear attachment. In the context of the approach outlined in Section 4, the reactions are obtained from the landing simulation results, making use of the stick model of the aircraft attached to the non-linear landing gear model.
To provide a more refined description of the effects due to aircraft flexibility, the reactions are now recomputed using the characteristics of the 3D shell model instead of the stick one.
In particular, the reactions are computed at two representative points, as illustrated in Figure 11.

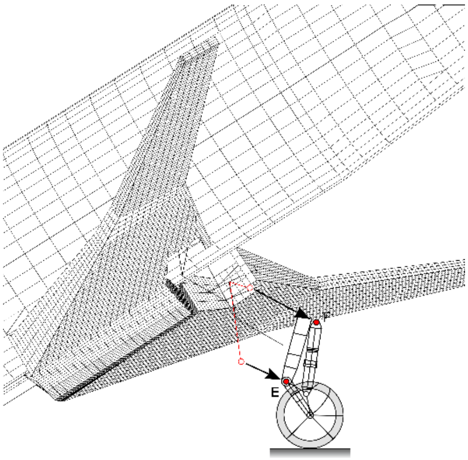


Figure 11. MLG reactions – application points of the forces.

As seen in the figure, the two points are defined in the 3D shell model and are connected to the bar element representative of the landing gear trunnion.
This second analysis allowed to determine a new set of reactions for each of the landing conditions previously outlined. As compared to the results obtained with the stick model, slightly lower values are registered during the time history. This small difference is attributed to the more refined description of the local stiffness characteristics at the MLG attachment.

6.2 Damping Modeling

As part of the fully dynamic approach, the effects due to energy dissipation are assessed to determine the impact of damping on the final design. In this context, two types of damping are usually introduced to model the response of linearly-elastic material: the viscous and structural damping. In particular, the viscous force is proportional to the velocity, and its expression is given by:

$$f_v = b\dot{u} \tag{1}$$

where f_v denotes the viscous force, b is the damping coefficient and $\dot{u}$ is the velocity.
On the other hand, the structural damping force is proportional to the displacement and is given by:

$$f_s = i\ G\ k\ u \tag{2}$$

where G is the structural damping stiffness coefficient, k is the stiffness, u is the displacement and i is the imaginary unit.

From the expression of Eqs. (1) and (2), it is observed that, for a sinusoidal displacement response of constant amplitude, the structural damping force is constant. On the other hand, the viscous damping force is proportional to the forcing frequency. It follows that one single frequency exists, hereinafter denoted as ω_3, associated to the identical damping forces f_v and f_s. A graphical representation of the viscous and structural damping forces is presented in Figure 12.

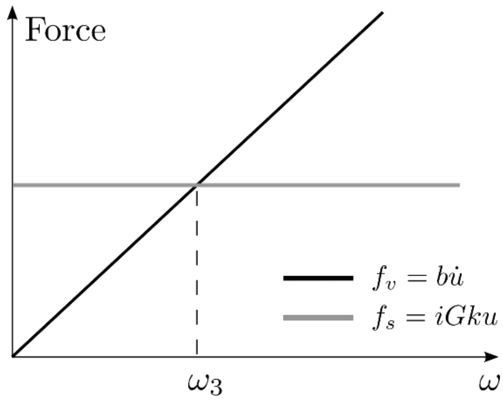


Figure 12. Structural damping versus viscous damping.

While a frequency-independent damping can be sought as a good approximation of the dissipative phenomena involved in the aircraft response, the present dynamic analysis is performed in the time domain. It follows that the structural damping, which is defined in the frequency domain, should be converted into an equivalent viscous counterpart.

In NASTRAN, the parameters G and ω_3 are defined using the cards PARAM G and PARAM W3, so that the equivalence between viscous and structural damping is guaranteed at the frequency level corresponding to ω_3. Below this frequency value, the system is underdamped, and beyond the system is overdamped.

The choice of the most appropriate frequency value ω_3 cannot be easily established a priori. In fact, the response of the DAEDALOS aircraft to the impact loading involves a relatively large number of modes. To face this uncertainty, a number of analysis has been performed by considering different values of ω_3, so that the sensitivity of the response to this parameter could be assessed. Furthermore, three different values are considered for the damping coefficient *G*, chosen on the basis of the industrial experience of the partners. The values adopted for the parametric study are summarized in Table 3.

G	ω_3 [Hz]
0.03	3, 6, 9, 12, 15, 18, 21
0.04	3, 6, 9, 12, 15, 18, 21
0.05	3, 6, 9, 12, 15, 18, 21

Table 3. Damping parameters used in the parametric study.

7. Results and Comparison with Static-Based Approaches

Direct transient analyses are performed for the critical landing condition considering each of the damping values reported in Table 3. A total number of 21 analyses is then performed, and the stress distribution is monitored for the elements composing the fuselage section under investigation. A typical result is reported in Figure 13, where the distribution of the stress component σ_y is reported at the most critical time frame for damping values G=0.05 and frequency ω_3=21 Hz. Analogously, stress distributions are derived for the other conditions here considered.

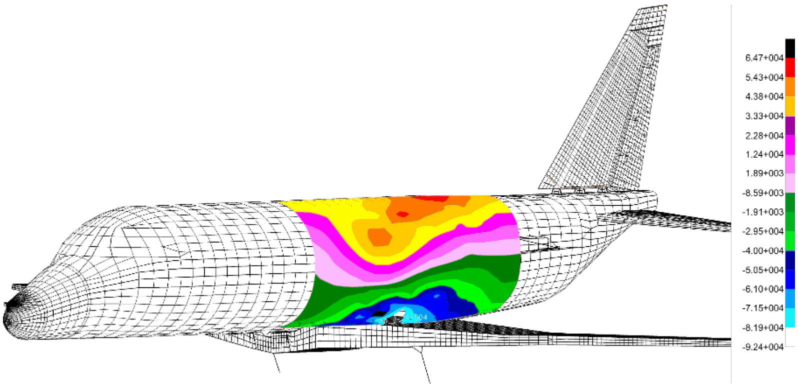


Figure 13. σ_y stress values for dynamic solution with G=0.05 and ω_3=21 Hz.

It is observed that all the peak stresses are registered simultaneously, at the time frame t=0.055 s. Therefore, all the design stresses are relative to the corresponding single time frame.

To check the differences between the dynamic and the standard approaches, the peak stresses are compared with the results from the baseline static analysis. As a metric to assess the potential improvements due to the fully dynamic approach, the stress ratio r_1 is introduced as:

$$r_1 = \frac{\sigma_y^{\mathrm{dyn}}}{\sigma_y^{\mathrm{ref}}} \tag{3}$$

where σ_y^{ref} denotes the stress obtained using the standard procedure, while σ_y^{dyn} denotes peak stress determined with the dynamic approach. The nondimensional parameter r_1 is computed for all the elements composing the 3D shell model. A typical plot is presented in Figure 14, where r_1 is reported versus the peak stress value. Due to a large scatter of the ratio r_1 in correspondence of small stress magnitudes, the results relative to elements undergoing stress values in the range from -20 MPa to 20 MPa are removed from the plot.

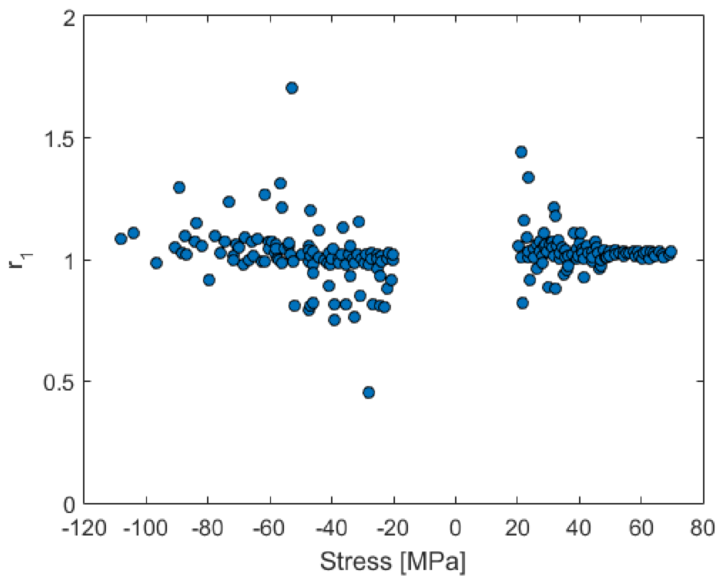


Figure 14. Dynamic to static stress ratio r_1 for G=0.05 and ω_3=21 Hz.

Plots in the form of Figure 14 are obtained for all the conditions summarized in Table 3, corresponding to the different combinations of damping values G and frequency values ω_3.
To derive useful design guidelines, a linear approximation is adopted to describe the behavior of r_1 versus the peak value, both for the elements in tension and those in compression. Interpolated data are then used to determine the mean value of r_1 for each of the 21 conditions. A plot summarizing the results is reported in Figure 15, where the mean value of r_1 is reported versus the frequency ω_3. Each curve corresponds to a different value of the structural damping stiffness coefficient G.

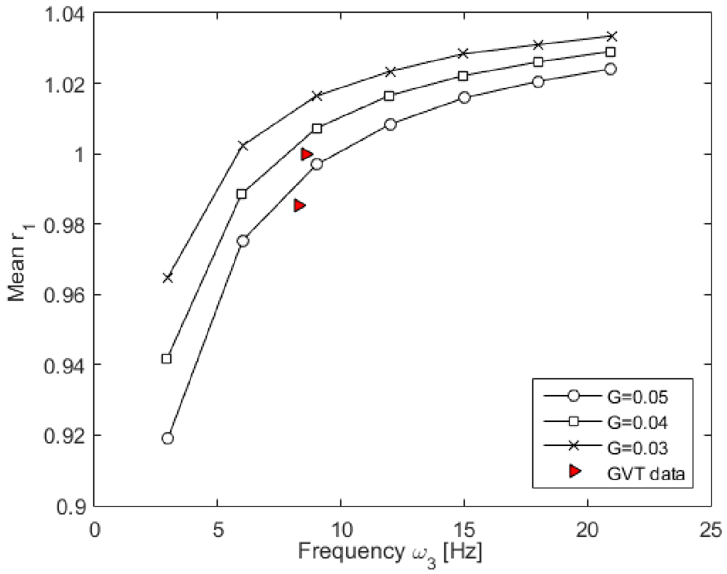


Figure 15. Mean values of the dynamic-to-static stress ratio for different values of damping.

From the results of Figure 15 it is observed that the ratio r_1 increases monotonically with the frequency parameter ω_3. It is worth highlighting that, for small values of ω_3, the parameter r_1 is smaller than 1. In this case, the stress peaks obtained with the dynamic approach are smaller than those available from the baseline procedure and, therefore, represent conditions where weight reduction could be achieved. As expected, the three curves of Figure 15 demonstrate the beneficial effects due to an increased damping level. Indeed, higher values of damping ratio *G* lead to smaller values of r_1, corresponding to an increased stress reduction due to the dynamic approach.
The dependence of the results of Figure 15 on the values of ω_3 demonstrates that considerations regarding any potential weight reduction are strongly dependent on the choice of ω_3. In principle, the most adequate value should be determined, for a given configuration, on the basis of the frequency content analysis of the structural time response.
In the present investigation, the critical elements for the design display a similar time response, characterized by a peak stress value at the time frame 0.055 s. These responses can be associated to a frequency of approximately 7-8 Hz. From Figure 15, it can be observed that, in this frequency range, the stress ratio r_1 is smaller than 1, thus suggesting the possibility of achieving a slight weight reduction.
For sake of completeness, typical damping values obtained from the ground vibration test of a medium business jet are reported in Figure 15. The two points are representative of the damping coefficients measured for two fuselage modes of a similar aircraft. In this case, the two values are slightly smaller than the unity, confirming the potentialities for a slight load reduction.

8. Discussion of the Results and Proposal for a Novel Load Definition

Based on the results of the previous section, an improved procedure is here presented to determine the aircraft design loads. The procedure aims to account for the dynamics effects commonly neglected when the equivalent static load approach is used. The proposal provides practical information that are thought to improve the current practice adopted by aeronautical industry.

The analysis of the stress ratio r_1 allowed to conclude that a slight reduction of the sizing loads - and consequently the structural weight - can be achieved if the stresses of the relevant fuselage sections are computed by means of a fully dynamic approach. As observed, this result is strongly dependent on the choice of the damping parameters, meaning that different conclusions can be drawn according to the assumed damping values. Furthermore, the results presented in this paper are restricted to a specific structural region of a given aircraft type, and different conclusions are likely to be obtained for different airplane types or structural areas. For this reason, the outcome of the present study is presented in the form of a methodology for a modified load definition, so that it can be applied in the future for a wider class of aircrafts and structural regions.
Starting from the description of the finite elements for the sizing process, the use of two distinct models is suggested. Their characteristics and the corresponding guidelines are briefly summarized here below:

- 3D Shell model:
  Usually built in the industries by people working in the stress group, the model accounts for the relevant airplane mass distributions by means of point mass elements connected to the structural elements through kinematic couplings or rigid elements.
  It is recommended to adjust this model since the early design stages, in order to adapt it for dynamic analyses. The adjustment procedure involves checking that local modes due to inadequate representation of certain structural elements do not compromise the results in the relevant frequency range. Furthermore, a careful check is recommended to verify that the masses are properly connected to the structure.
- Reduced model (Stick model):
  The model is usually developed by the Loads and Dynamics Group using the detailed stress finite element model as a starting point. In the context of the load proposal here discussed, the dynamic characteristics of the two models should be equivalent. To this aim, the tuning of the stick model properties should be performed in order to match the natural frequencies of the detailed model.

Despite the potential gains due to the adoption of the 3D model since the preliminary phases, the large amount of load cases to determine the critical design conditions makes this approach still too time-consuming. This problem is exacerbated by the need to continuously updating the model as the structural details of the plane are modified during the design iterations. For this reason, it is suggested to use a stick model and factorize the results to recover the aircraft dynamics. The five steps composing the modified load proposal are summarized here below:

1. Firstly, the different structural areas affected by specific load conditions associated with dynamic characteristics should be identified. This process can be conducted on the basis of the past experience on similar aircraft types. For instance, landing conditions are usually relevant for the design of mid fuselage sections, while manoeuvres or gust define the sizing of wing and empennage sections.
2. As a second step, the main frequency governing the response to the specific load condition of each structural region – the mid fuselage, the empennage, etc. – should be defined. To this aim, the use of the detailed FE model is suggested, using a preliminary representation of the forcing functions

to perform a sample run. The typical frequency can then be recovered from the analysis of the response.

3. The third step regards the definition of an adequate value of the damping coefficient G. In absence of specific values, it is suggested to use, as a first estimate, a value derived from the ground vibration testing of similar structures. As a rough estimate, a value of G=0.03 can be used in case of lack of relevant data from other sources. As observed in the previous sections, the higher the value of G, the higher the potential reduction in the design loads. However, an excessively large value of G not supported by experience or test data could lead to unconservative design loads.
4. The fourth step of procedure consists in the evaluation of the "reduction factor", which is derived by calculating the relevant loads or stresses using the baseline static method and comparing them to the dynamic analysis values at the appropriate W3 and G parameters. To perform the reduction, a mean value should be taken into account, due to the scatter that can be found in the results involving a relative large number of elements. In the present work, a linear interpolation was adopted, but other strategies are possible.
5. The final, fifth, step consists in the factorization of the static loads. To this aim, the reduction parameter can be used to factorize the static loads so that the dynamic results are matched.

9. Conclusions

The results of the present investigation illustrate that a certain, although limited, amount of load reduction can be achieved if a dynamic response analysis of the full aircraft is adopted.

For the aircraft model used in DAEDALOS, a relatively limited amount of load reduction can be achieved but, in general, the reduction could be more relevant for larger and more flexible aircrafts with lower natural frequencies.

The damping characteristics of the 3D shell model have been identified as the main factor contributing to a potential load reduction. For this reason, a refined numerical and experimental description of the damping is key to obtain valid and practical conclusions regarding the possibility of reducing the design loads. Based on the studies conducted during the DAEDALOS project, guidelines were derived for a methodology for loads redistribution.

The present study represents a first step into the definition of a novel design procedure based on dynamic analyses since the early phases. This topic covers different aspects, ranging from numerical to experimental procedures. Some of these issues have been partially covered during the DAEDALOS project, but further research activity is still needed. In particular, a deeper investigation is suggested with regard to damping effects, both in term of its experimental evaluation as well as its numerical modelling. Nonlinearities and buckling effects could be part of future analyses, despite the complicating effects due to the need of even complex finite element models.

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