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Design of Skid Landing Gears by Means of Multibody Optimization

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This paper discusses a numerical approach to the design of skid landing gears, based on an optimization procedure linked to a multibody explicit code. The modeling technique has been validated with the experimental results of a drop test considering the overall landing performances as well as the levels of bending strains developed along the cross members. According to the presented numerical-experimental correlations, the numerical analyses obtained appreciable results at a very low computational cost. The technique has been applied to generate a parameterized model of a skid landing-gear, suitable to be adopted in an automatic optimization procedure. To adequately formulate the optimization process, the basic aspects involved in the design of skid landing gears have been reviewed, and two optimization procedures have been developed. These formulations have been directed, respectively, to optimize the landing performances and to obtain an optimal plastic strain distribution along the cross members axes. The optimization search applied to different design tasks shows that the developed numerical tools can identify well-sized landing-gear configurations that satisfy all of the imposed constraints on the landing performances and are characterized by uniform strain distributions along the cross members, thus maximizing the strength and the durability of the landing system.

Nomenclature

C_f = skid-soil friction coefficient
c_{lim} = maximum allowable helicopter-soil clearance in the design landing conditions
d = distance of the outer fibers from the neutral axis of a beam section in bending
$f_{\Delta\varepsilon}$ = quadratic variation of the maximum bending strain along the cross members of the gear
J = moment of inertia of a beam section
L_{FWD} = total length of the forward cross member
L_{REAR} = total length of the rear cross member
MS = structural margin of safety of a cross member in the design landing condition
n_{LG} = landing-gear load factor
Q = static moment of the portion above the neutral axis of a beam section in bending
R_V = vertical component of the ground load applied to a cross member
$\Delta\delta_{\max}$ = maximum difference between the deflection of the cross members in the design landing condition
δ = generic deflection of a cross member
δ_{res} = permanent deflection of a cross member in the design landing condition
δ_U = deflection at failure of a cross member
δ_Y = deflection at yielding of a cross member
δ_0 = maximum deflection of a cross member in the design landing condition
$\varepsilon_{\mathrm{AVE}}$ = average value of the maximum bending strain along the cross members of the gear
$\varepsilon_{\max}$ = maximum strain in a beam section in bending
η = efficiency of a landing system
$\sigma_{\max}$ = maximum stress in a beam section in bending
σ_0 = characteristic strain of a fictitious stress distribution in a beam section in bending

I. Introduction

THE baseline configuration of a skid landing gear consists of two skids and two cross members that absorb the impact energy. This simple layout and the low cost of skid landing gears are the most appealing factors for their adoption within small and light helicopter models.

Despite their constructive plainness, the overall landing performances of these systems are not necessarily lower to those obtained by oleo-pneumatic landing gears. A key factor to obtain high efficiency levels and to dissipate the impact energy is the yielding of the cross members that is allowed by current civil aviation regulations even in limit landing conditions.[1,2]

Hence, a significant amount of energy can be absorbed by the plastic bending of the structural elements, containing the load factors with deflections that are comparable to the strokes of a wheel landing gear with oleopneumatic shock absorbers.

As it was pointed out since the early 1960s,[3] a reliable method to analyze the performance of a cross member should take into account either its large deflections as well as the yielding of the element, so that a structural problem including geometrical and material nonlinearity has to be solved. The approaches presented in Refs. 4 and 5 have been focused on the development of a landing-gear model considering the mutual interactions between elastic cross members. Accurate results should moreover consider the effects of the skid-soil contact interactions and the presence of additional damping devices, often introduced to prevent ground resonance.

Nowadays, the modern computational tools allow the development of dynamic and nonlinear models of a whole landing gear, which can be used for analyses in different conditions, including nonleveled landing attitudes. A fully detailed finite element model of the landing-gear structure can be developed for analysis purposes and solved with an explicit time-integration scheme in order to easily handle the material nonlinearities and the contact phenomena.[6] Such an approach does not seem adequate, however, to be adopted in the early design phases of the system, as it would involve excessive modeling efforts and computational costs.

Multibody dynamic models represent an alternative to the traditional design methods. These methods are characterized by a limited modeling effort and by low computational costs. Nevertheless, this approach can fully take into account the dynamic aspects of the

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gear working mechanism, the mutual interaction between the cross members, and the presence of additional damping devices.

This approach was proposed developing a multibody model of a skid landing gear,[7] implemented adopting Ve.Dy.ac.,[8] a nonlinear code, with an explicit time-integration scheme, already used for full-scale analyses of helicopter crashes.[9] This modeling technique obtained an appreciable correlation with the experimental results of a series of drop tests performed in different landing attitudes, with calculation times of the order of hundreds of seconds.[7,10]

A basic aspect of this technique consists in the characterization of the nonlinear spring elements, modeling the cross members with plastic bending curves determined applying the Cozzone's theory, a well-established and simplified method to predict the yield and ultimate strength of beams in bending.[11]

More recently, the same numerical methodology was applied to develop an optimization tool[12] using Musiac, an enhanced version of the Ve.Dy.aC code, exploiting the low computational costs required by each analysis. The optimization procedure aimed to minimize the load factor of skid landing gears, considering different helicopter masses, fulfilling a set of constructive and performance constraints.

Moving from the previous results, this paper proposes and discusses a new numerical approach to the design of a skid landing gear. The design problem has been formulated to take into consideration both the functional and the structural aspects of the landing system, and it has been solved using the multibody approach within an optimization procedure.

In the following, the multibody modeling technique and its validation are briefly reviewed. Thereafter the design problem is discussed, and a parameterized model of the skid landing gear is presented. Two different formulations of the design problem are then used to identify optimal configuration of skid landing gears.

II. Multibody Modeling Technique for Skid Landing Gears

The modeling technique adopted within this work is a multibody approach using beam elements to model the slender members that constitute the gear. The resulting dynamic and nonlinear model of the whole system was solved adopting Musiac, a multibody code with an explicit time-integration scheme developed at Politecnico di Milano.[8] In the following section the approach will be discussed and validated by correlating the numerical results with the experimental data obtained in a drop test of a skid landing-gear prototype.

A. Test Case for the Validation of the Approach

The considered prototype was designed for a 2700-kg mass helicopter and was manufactured with Al 7075–T6 circular tubes. The cross members were chemically milled according to a well-defined tapering law so to tune their elastic-plastic bending response. The layout of the landing system is schematized in Fig. 1. The forward member was constrained at two points with the fuselage. The rear one was constrained with the fuselage at the middle, where a riveted reinforcement was applied to the tube, and by two damping devices, with a viscous response characterized by a cutoff load at about 6000 N. Thought these dampers were installed to prevent ground resonance, their effects on the landing performances were expected to be not negligible.

The drop tests of the prototype were performed on a threaded steel plate at 2-m/s sink speed, with an equivalent mass evaluated by assuming a rotor lift of $\frac{2}{3}$ the design weight. The data-acquisition system consisted of more than 20 measuring devices, including linear variable differential transformer transducers, load cells, and couples of strain gauges located along the axes of the cross members to measure the bending strains, as shown in Fig. 1.

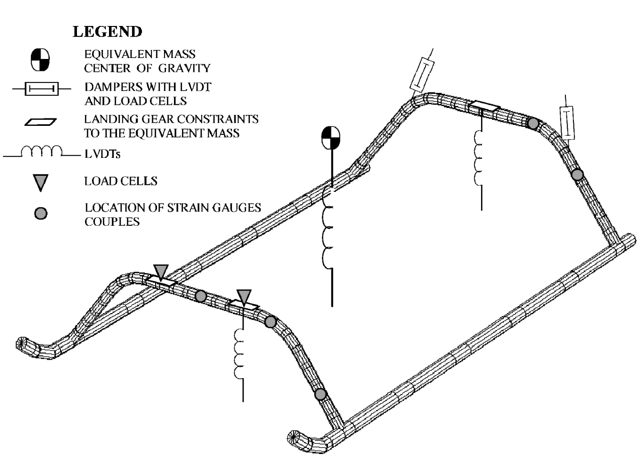

Fig. 1 Layout of the skid landing-gear prototype and location of the measurement devices used in the drop tests.

B. Multibody Model

Following the proposed approach, the slender elements were modeled by means of a limited number of lumped masses, mutually connected by mass-less beam elements with a nonlinear generalized constitutive law.

The equivalent drop mass used in the experiments was modeled using a single rigid body, connected to the mass elements by constraint elements. Finally, the dampers were introduced in the model using rods having a nonlinear viscous behavior, calibrated according to the experimental response of the adopted devices. The resulting model is shown in Fig. 2 and consists of about 60 lumped masses and 60 generalized beam elements.

The elastic-plastic bending responses of the cross members and of the skids play a fundamental role to obtain a reliable numerical evaluation of the landing system performances. These responses were described in detail by means of moment vs unit rotation curves. The Cozzone's procedure[11] was applied to calibrate the response of each beam element in the model, considering the geometrical characteristics of the local cross section.

The procedure, well assessed in the aircraft field for the evaluation of the yield and ultimate strength of a beam in bending, considers a beam having a rectangular section with moment of inertia J and outer fibers at distance d from the neutral axis. A fictitious trapezoidal stress distribution, characterized by a stress σ_0, is then assumed according to the one shown in Fig. 3. For a given load condition, with maximum strain level $\varepsilon_{\max}$, the fictitious distribution has to satisfy 1) the equivalence of the maximum stress in the section $\sigma_{\max}$ and 2) the equivalence of the moment according to Eq. (1):

$$\int_0^{\varepsilon_{\max}} \sigma_{\text{true}} \varepsilon \, \mathrm{d}A = \int_0^{\varepsilon_{\max}} \sigma_{\text{trapezoidal}} \varepsilon \, \mathrm{d}A \tag{1}$$

Equation (1) allows the determination of a $\sigma_0(\varepsilon_{\max})$ curve that depends only on the considered material.

The resultant moment M from the assumed trapezoidal stress distribution can be evaluated according to Eq. (2):

$$MD/J = \sigma_{\max} + (2Qd/J - 1)\sigma_0(\varepsilon_{\max}) \tag{2}$$

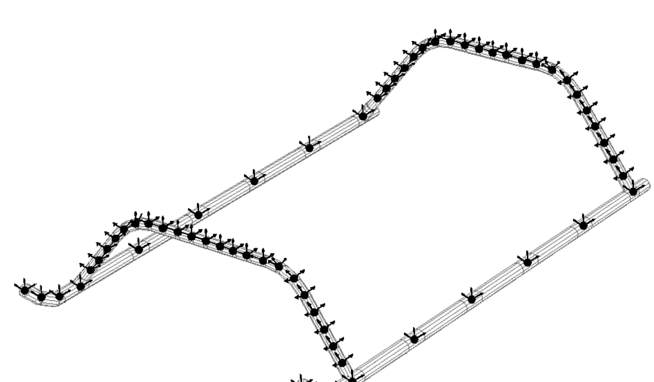

Fig. 2 Musiac multibody model of the skid landing gear.

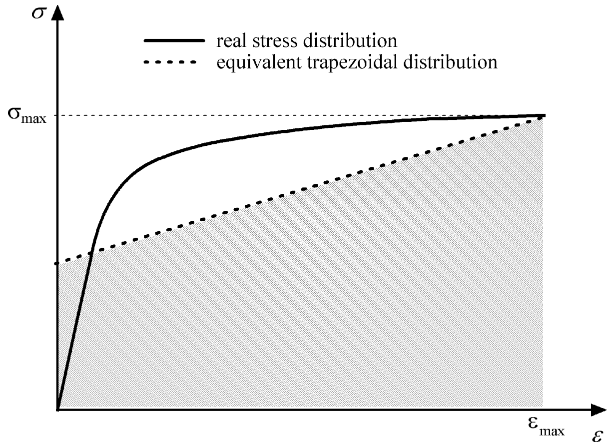

Fig. 3 Cozzone's equivalent stress distribution in plastic bending.

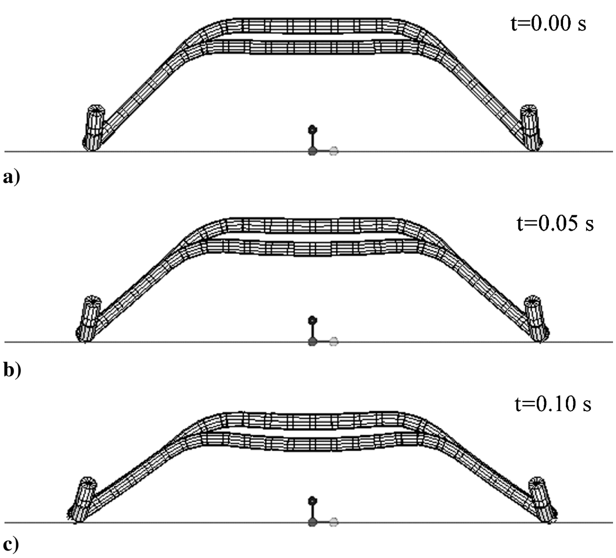

Fig. 4 Numerical simulation of the drop test.

where Q is the static moment from the section area above the neutral axis. According to the original formulation, Eq. (2) gives the section yield and ultimate bending moments by setting $\sigma_{\max}$ to the yield and ultimate stress of the material, respectively.

When a double symmetric section is considered, Eq. (2) evaluates the yield and the ultimate bending strength with a reported accuracy of 5% with respect to the actual values.[11] In this work the procedure was applied incrementally varying $\varepsilon_{\max}$ to determine the entire moment vs unit rotation response, assuming the validity of the Kirchoff–Love hypothesis.

Another major issue in the modeling of the drop test is a correct representation of the skid-soil interactions. Exploiting the features of the solver code, the skid-soil contact was modeled by using body-to-body penalty algorithms. In particular, cylindrical surfaces were used to model the surfaces of the skids, interacting with a plane surface representing the soil. The skid-soil friction coefficient C_f was set to 0.35, and only a very limited numerical interpenetration was allowed between the contact elements (1 mm $\div$ 2 mm).

C. Numerical and Experimental Correlation

Solving the model with the Musiac code, the analysis of the drop test performed in level landing condition took about 100-s CPU time on a Pentium IV 2.54-GHz personal computer.

Figure 4a presents the initial instant of the analyzed drop test, while Figs. 4b and 4c show the deformed shapes of the skid landing gear at 0.05 and 0.1 s after the contact with the soil, respectively. Figure 5 presents the numerical-experimental correlation of the load transmitted through the fuselage constraints. In particular,

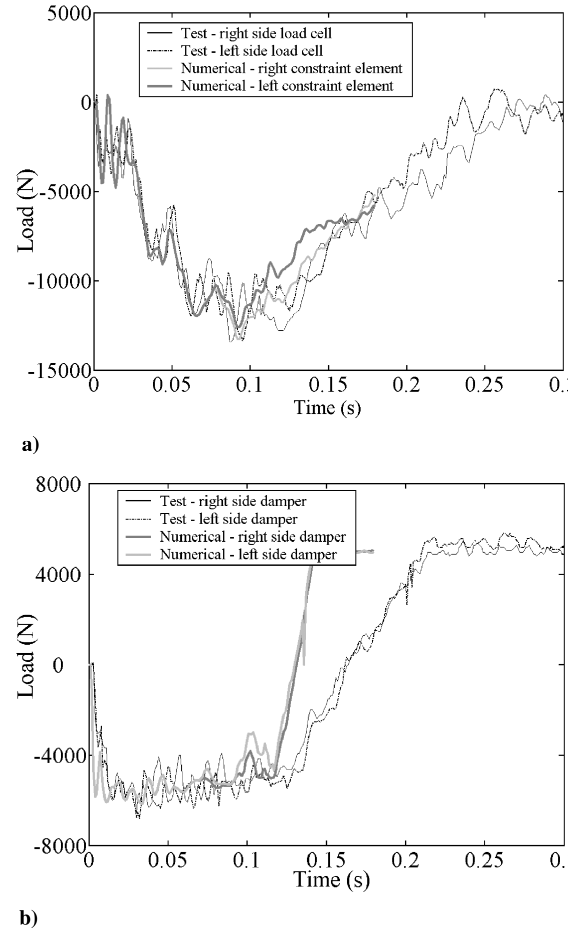

Fig. 5 Numerical and experimental correlation in terms of the loads transmitted a) by the forward cross member and b) by the dampers.

Fig. 5a reports the load levels relevant to the load cells located in the forward cross member, whereas Fig. 5b reports the axial load level experienced by the rear damping devices. The maximum load levels, the time duration, and the characteristic frequencies have been accurately reproduced. Figure 6 reports the time histories of the deflections measured at different locations of the landing system. These results show that, as far as the overall landing performances are concerned, an appreciable correlation has been obtained.

The model validation was also focused on the capability to evaluate the distribution of the bending strains along the slender elements of the landing gear. Within the applied multibody approach, the evaluation of the equivalent bending strains was performed developing a postprocessing technique that uses the moment vs unit rotation curve characterizing the beam behavior, after that the beam displacements had been computed.

The obtained strains were compared to those recorded during the drop tests of the skid landing-gear prototype. Figure 7 presents the numerical distribution of the bending strains along the left half of the two tapered cross members, compared with the experimental data measured by the strain gauges. The correlation is presented considering three different time instants and the overall maximum values. The obtained results proved the reliability of the proposed approach not only with respect to the global indices such as the cross members deflections and the loads transmitted to the fuselage, but also in terms of local aspects such as the bending strain distributions.

III. Formulation of the Design and Optimization Problem

The reliability of the obtained results and the limited computational cost of the multibody approach suggested using it for design

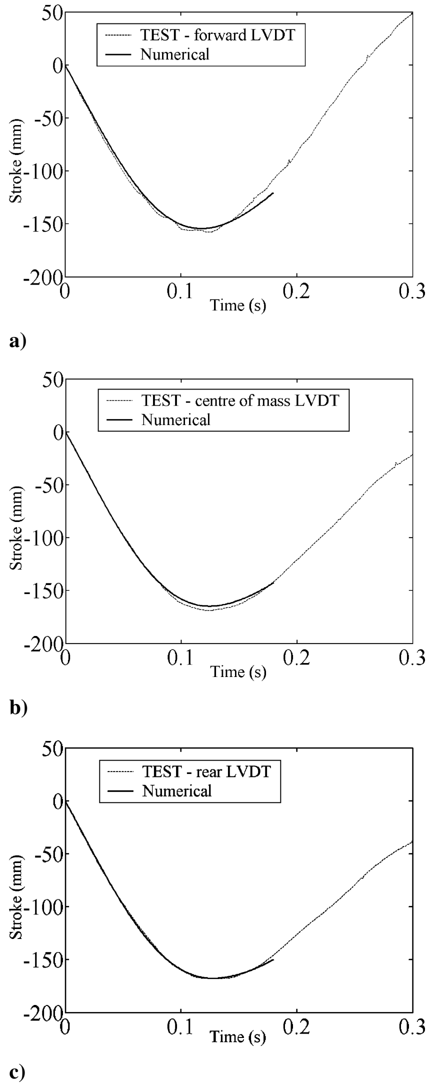

Fig. 6 Numerical and experimental deflections a) at the constraint point of the forward member, b) at the center of mass, and c) at the constraint point of the rear member.

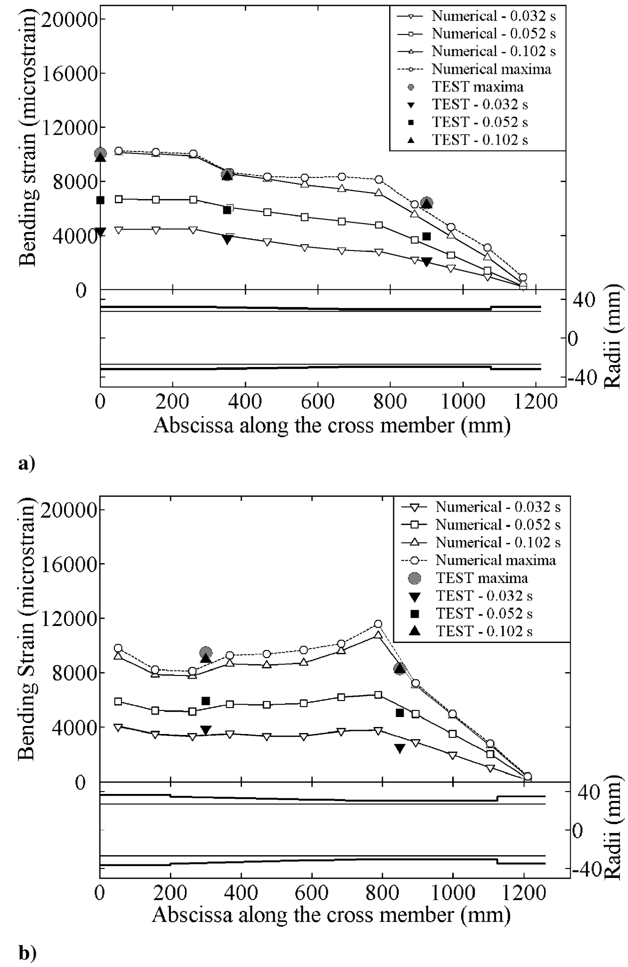

Fig. 7 Numerical and experimental bending strains along the left half of a) the forward and b) the rear cross member.

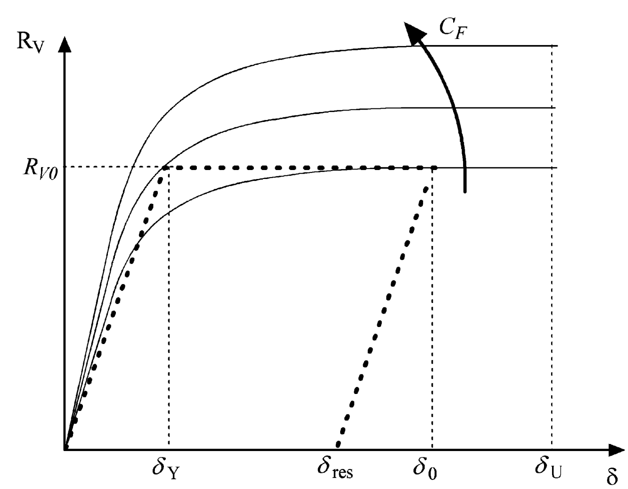

Fig. 8 Typical vertical ground reaction vs deflection curve for a cross member.

and optimization purposes. Particularly, once the design problem had been clearly defined, an optimization procedure was developed based on the already described multibody approach. The engineering problem is hereby discussed with the aim to point out the aspects relevant to the performances and the strength of a generic skid landing gear.

A. Basic Aspect in the Design of Skid Landing Gears

The landing system has to fulfil functional and structural requirements, respecting a set of constructive constraints that depend on the characteristic of the helicopter adopting the gear, such as the position of the constraint between the gear and the fuselage.

Once these constraints have been set, the design of the cross members plays a primary role to meet the performance requirements. Each cross member can be separately studied and characterized by a curve that correlates the vertical component of the ground reaction force R_V to the cross member deflection δ, measured at the constraint point with the fuselage. The typical responses, as the ones reported in Fig. 8, are characterized by an initial part of the load vs deflection curve, slightly nonlinear because of purely geometrical effects, followed by a significantly nonlinear second part, beginning after the yielding of the cross member. These curves are sensibly influenced by the horizontal reactions determined by the skid-soil friction.

For a given helicopter mass, design landing conditions, and soil characteristics, the cross members must be designed to contain the load factor and the helicopter-soil clearance within imposed limits. Clearly, the characteristics of the cross members significantly influence not only the landing performances but also the strength of the whole landing system.

A simplified bilinear response (dashed line in Fig. 8) can be assumed to formalize how the cross member performances and their strength cannot be separately considered. To draw the simplified curve, a deflection at yielding δ_Y and a deflection at the failure δ_U can be identified, and a maximum deflection in the design landing condition δ_0 can be assumed, as shown in Fig. 8. Moreover, an unloading path and a final permanent deflection δ_{res} can be defined. Accordingly, the efficiency of the cross member η can be expressed as a function of δ_0, as proved in Eq. (3):

$$\eta = \frac{\frac{1}{2}R_{V0}\delta_Y + R_{V0}(\delta_0 - \delta_Y)}{R_{V0}\delta_0} = \frac{1}{2}\left(1 + \frac{\delta_0 - \delta_Y}{\delta_0}\right) = \frac{1}{2}\left(1 + \frac{\delta_{res}}{\delta_0}\right) \tag{3}$$

Although the strength of the cross members should be verified in different load conditions,[1,2] a significant strength index can be obtained evaluating the margin of safety in the design landing condition. This margin can be expressed in terms of the cross-member deflections and, using Eq. (3), as a function of the landing-gear efficiency as shown in Eq. (4):

$$MS = 1 + \delta_U/\delta_0 = 1 + (\delta_U/\delta_Y)2(1 - \eta) \tag{4}$$

Equations (3) and (4) indicate that when the efficiency in a given landing condition is increased the structural margin of safety is reduced, and the residual deflections are increased. It is worth noting that also the margin of safety in subsequent landings and the overall durability of the system are reduced. In fact, if the permanent deflection exceeds a given level, there will be no more available stroke to absorb the impact energy.

Equation (4) shows also that, for a given efficiency η, the margin of safety can be increased by raising the ratio of ultimate to yield deflection. This objective can be accomplished by moderate levels of plastic strains over a large portion of the cross members paying particular attention to avoid localized plastic hinges and failures. Accordingly, because the bending moment along the cross member increases towards the constraints to the fuselage, the cross members can be conveniently tapered, with the aim to distribute as uniformly as possible the plastic strains.

This discussion points out that optimal solutions should be identified not only designing the cross members for the best landing performances, but also controlling the local levels and the distribution of the bending strains. The shape and the tapering laws of the cross members appear hence as the most important parameters in the design problem. Moving from the previous considerations, the formalization of the optimization procedure was carried out, as described in the next sections.

B. Formulation of the Optimization Process

The development of an optimization procedure for the design of a skid landing gear required a rigorous formulation of the problem, namely, the choice of the design variables, of the constraints and of the objective function to be minimized or maximized.

As far as this research was concerned, different formulations could have been adopted to take into account all of the aspects of the design problem. Unfortunately, there were no certainties that an a priori adopted formulation would have led to a feasible solution because there were no ways to predict the path followed by the optimization process within the domain of interest. Furthermore, other aspects should have been considered in order to obtain realistic design hypotheses, such as the overall dimensions of the landing system and the manufacture of the cross members.

A solution to identify a correct formulation of the problem was found developing a flexible parametric model and adequate postprocessing tools. This approach allowed the selection of the design variables among all of the parameters that defined the model and the choice of objective functions and constraints among all of the outputs of the postprocessing tool. The parametric model, the postprocessing tool as well as the optimization program, have been implemented within MATLAB®.[13] Accordingly, the developed software consists of three major parts: 1) a preprocessing tool that defines the parametric model of the skid landing gear and generates a corresponding model for each configuration analysed during the optimization process; 2) a postprocessing tool that reads and computes the desired results from each multibody analysis carried out with Musiac; and 3) a main optimization tool that controls the data flow driving the multibody runs in such a way to lead at the optimal solution.

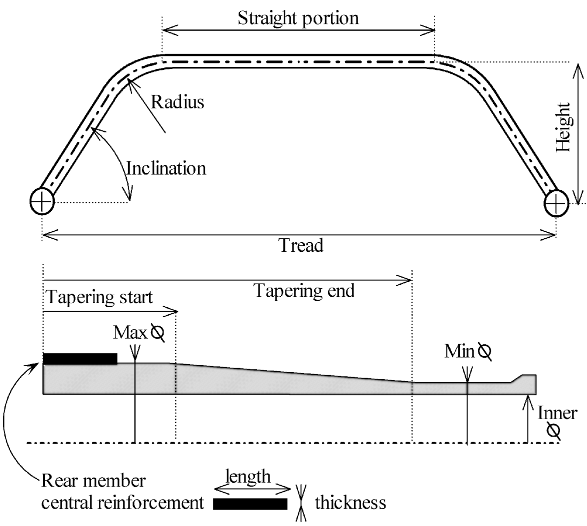

Fig. 9 Design variables of the optimization problem.

1. *Parameterized Model of a Skid Landing Gear*

The parameterized model of the skid landing gear was developed to freely change the inertial properties of the helicopter, the kind of the constraints to the fuselage, and the position and the characteristics of the damping devices.

The configuration of the gear was then described by a set of parameters In particular, the tread and the height of the gear were used to define the overall dimension of the system. The geometrical configuration of the cross members was described by six parameters defining the shape of the tube axes of the forward and rear cross members, separately considered. The relative position and the vertical orientation of the cross members were also parameterized. In this way, the general configuration of the whole landing system could have been adapted to a generic helicopter fuselage.

Finally, it was decided to maintain a complete separation between the shape of the tube axes and the tapering of the cross members. A piecewise linear law was chosen to describe the outer diameters, so that tapering was completely defined by four parameters. When the rear member was considered, two further parameters were introduced to describe a reinforcement applied to the central straight portion of the tube. Another parameter defined the inner diameter of the tubes.

As shown in Fig. 9, these parameters allowed to adequately control the shape and the cross section of the cross members.

2. *Definition of the Optimization Procedures*

In the presented optimization procedures, the helicopter mass, the kind and the relative position of the constraints to the fuselage, as well as the position and the characteristics of the dampers were considered as design constraint, defining a specific problem to be solved by the optimization. The vertical orientation of the cross members was as well assigned.

A total number of 18 parameters were selected as design variables to control the geometric configuration and the tapering laws of the cross members. The domain of interest was set in order to obtain cross members and tapering laws that could have been actually manufactured.

Nonlinear inequality constraints were introduced to meet the performance and strength requirements. A limit was set on the minimum fuselage-soil clearance, denoted as c_{lim}, and on the maximum difference between the deflections of the two cross members in limit conditions $\Delta\delta_{max}$, aiming to control the rotational acceleration of the helicopter. The maximum value of the bending strains in the cross members, denoted as $\varepsilon_{\max}$, was constrained during all of the optimization searches.

The tread and the height have a primary influence on the gear performance. Accordingly they were considered as design variables in all of the optimization procedures. However, their values should have been constrained to obtain well-sized design hypothesis. An additional constraint was thus introduced on the overall dimensions, defining an equivalent area computed as the product of the tread times the height of the landing gear.

Two different problem formulations were developed as design methodologies for skid landing gears. In the first one, in the following referred as $n_{\min}$, the load factor was chosen as objective function to be minimized. Thus, the optimization was primarily oriented to improve the landing performance, whereas the strength requirements were considered only constraining $\varepsilon_{\max}$.

The second one, in the following referred as $\Delta\varepsilon_{\min}$, was formulated in order to distribute as most uniformly as possible the bending strain ε_b along the cross members axes. To accomplish this objective, an average strain was computed on both the cross members according to Eq. (5):

$$\varepsilon_{\mathrm{AVE}} = \frac{1}{L_{\mathrm{FWD}}}\int_{\mathrm{FWD}} \varepsilon_b \,\mathrm{d}l + \frac{1}{L_{\mathrm{REAR}}}\int_{\mathrm{REAR}} \varepsilon_b \,\mathrm{d}l \tag{5}$$

where L_{FWD} and L_{REAR} are the lengths of the forward and the rear member, respectively.

The objective function $f_{\Delta\varepsilon}$ to be minimized was then defined as the quadratic variation of the distribution of ε_b along the axes, according to Eq. (6):

$$f_{\Delta\varepsilon} = \frac{\sqrt{\int_{\mathrm{FWD}} (\varepsilon_b - \varepsilon_{\mathrm{AVE}})^2 \,\mathrm{d}l + \int_{\mathrm{REAR}} (\varepsilon_b - \varepsilon_{\mathrm{AVE}})^2 \,\mathrm{d}l}}{L_{\mathrm{FWD}} + L_{\mathrm{REAR}}} \tag{6}$$

Adopting this second objective function, the optimization was directed to improve the cross-member strength, avoiding local weak points in the structure. A further constraint was introduced on the load factor, in order to fully consider the performance requirements.

The strategy used to solve both these nonlinear constrained optimizations exploited a sequential-quadratic-programming (SQP) algorithm,[14,15] transforming the original problem into several easier subproblems that can be solved using an iterative process.

IV. Optimization Results

The developed procedures were applied to the design of two skid landing gears. The first one was expressively designed considering an helicopter mass 25% lower than the mass considered for the landing-gear prototype used to validate the numerical approach, assumed as reference. Similarly, the second configuration was designed considering an helicopter mass 25% higher than the reference one. In all of the optimization runs, the fuselage constraints, the position, and the characteristics of the dampers as well as the vertical orientation of the cross members were fixed according to the prototype configuration.

The product of the tread times the height of the gear was limited to be lower than 1.00 m^2. Other constraints were imposed on the soil clearance, by fixing c_{lim} at 370 mm and on the maximum difference between the cross member deflections, by setting $\Delta\delta_{\max}$ at 25 mm. Furthermore, the value of the maximum allowable bending strain $\varepsilon_{\max}$ was fixed at 22,000 $\mu\varepsilon$.

For both the proposed cases, the prototype configuration was chosen as the initial guess solution.

A. Optimization with 75% of the Reference Mass

When a helicopter mass 25% lower than the reference one was considered, namely, a mass of 2025 kg, the initial configuration presented a stiffness of cross members excessively high. The optimization was thus required to reduce the load factor without excessively weakening the cross members.

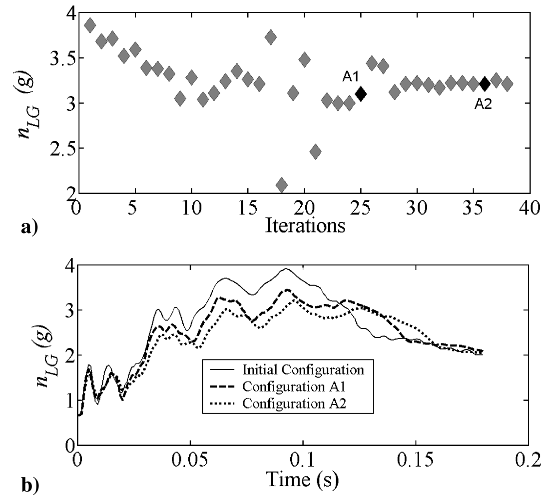

Fig. 10 Optimization results: a) objective function evolution and b) numerical load factors in selected configurations obtained minimizing the load factor for a 2025-kg helicopter mass.

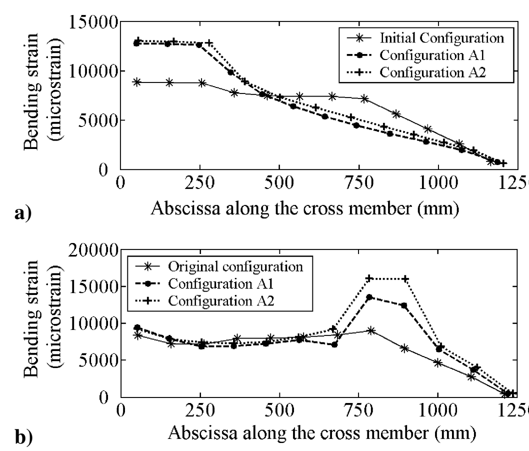

Fig. 11 Numerical strains a) in the forward and b) in the rear cross members for two selected configurations obtained minimizing the load factor for a 2025-kg helicopter mass.

The optimization procedure $n_{\min}$ acted to directly minimize the load factor n_{LG} achieving a significant reduction of the load factor in few iterations, as shown in Fig. 10a. Thereafter, it prosecuted slowly because of the increasing difficulty of meeting the imposed constraints. Figure 10b reports the time histories of the load factor in the initial and in the two configurations selected among those analyzed by the optimization process (A1 and A2 in Fig. 10a). Both the selected configurations satisfied the imposed constraints and achieved a load factor of 3.44 and 3.21, respectively. The required performances were however obtained without a uniform strain distribution along the cross members, with peaks of strain up to 15,000 $\mu\varepsilon$ in few limited portions of the forward and rear cross members, as shown in Fig. 11.

The optimization procedure $\Delta\varepsilon_{\min}$ was then applied with an additional constraint to limit the load factor at 3.5 g. Among the configurations analyzed during the optimization search, two configurations, denoted as B1 and B2 in Fig. 12a, have been selected for further investigations. Both the configurations satisfy all of the imposed constraints, but the first one exhibits a maximum load factor of 3.39 g, while the second one exhibits an higher maximum load factor of 3.5 g.

These configurations were derived from the original landing gear by introducing significant variations of the diameters, of the tapering laws of the cross members and of the axis shapes, as reported in Fig. 13.

The resulting bending strain distributions, shown in Fig. 14, are appreciably uniform. Configuration B1, with the lower load factor, presents the higher strains, with a peak of about 12,000 $\mu\varepsilon$ in the

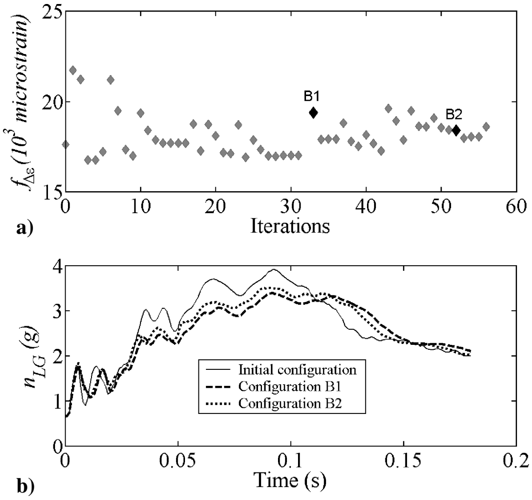

Fig. 12 Optimization results: a) objective function evolution and b) numerical load factors in selected configurations optimizing the strain distribution for a 2025-kg helicopter mass.

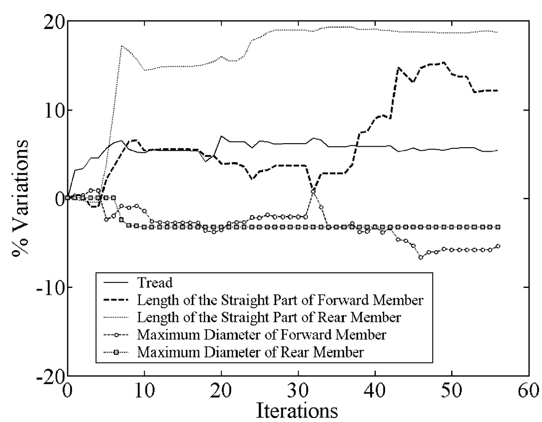

Fig. 13 Evolution of the most significant design variables in the procedure optimizing the strain distribution for a 2025-kg helicopter mass.

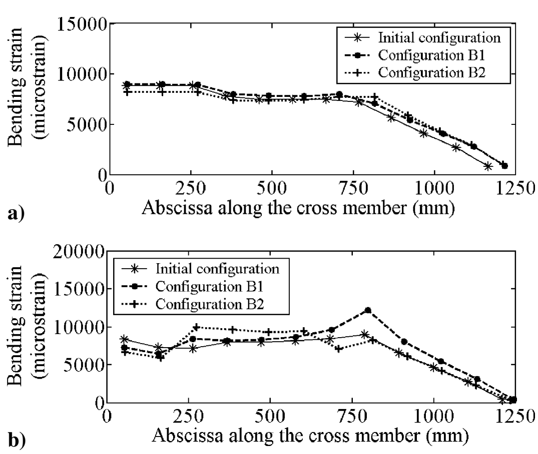

Fig. 14 Numerical strains a) in the forward and b) in the rear cross members for two selected configurations obtained optimizing the strain distribution for a 2025-kg helicopter mass.

rear member. For the configuration B2, a load factor substantially equal to the imposed constraint has been obtained, but the bending strain does not exceed 10,000 $\mu\varepsilon$, presenting a very good strain distribution on both of the cross members.

B. Optimization with 125% of the Reference Mass

When an helicopter having a mass of 3375 kg, 25% higher than the reference one, was considered, the reference skid landing-gear configuration resulted excessively soft. The constraint imposed on the minimum clearance from soil played a critical role in the optimization search.

Because the initial configuration was unfeasible as a result of the soil clearance, the optimization procedure $n_{\min}$ worked initially to meet the imposed constraints. Accordingly, the objective function was increased in the first two iterations. Once a feasible solution was identified, the optimization proceeded progressively, minimizing the load factor up to 3.21 g. Figure 15b shows the deflections of the cross members of the initial configuration and of the optimal configuration denoted as A3 in Fig. 15a, respectively. The cross-member deflections were significantly reduced with respect to the initial configuration against an increasing load factor.

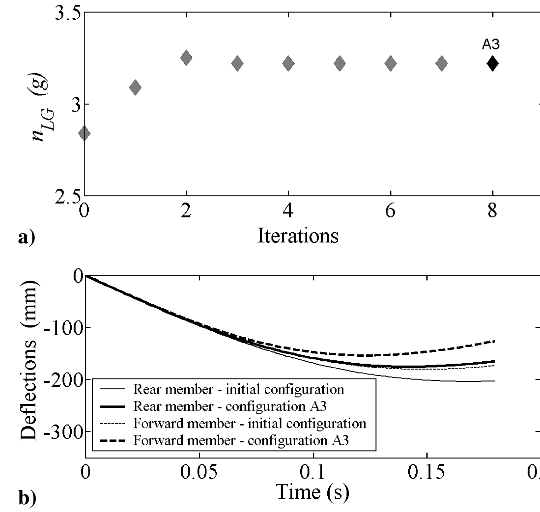

Fig. 15 Optimization results: a) objective function evolution and b) numerical deflections of the gear in selected configurations obtained minimizing the load factor for a 3375-kg helicopter mass.

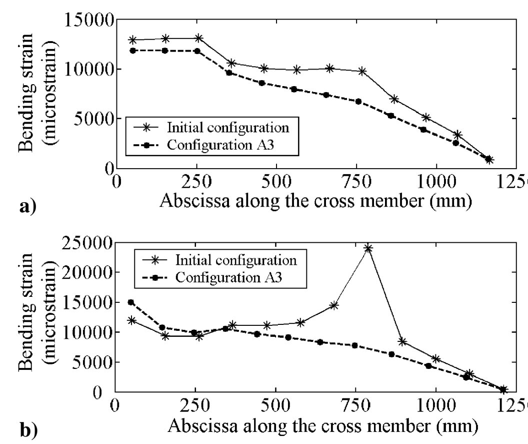

Fig. 16 Numerical strains a) in the forward and b) in the rear cross members for a selected configurations obtained minimizing the load factor for a 3375-kg helicopter mass.

Figure 16 compares the numerical strain distributions of the identified optimal configuration A3 with the initial one. The optimization was able to eliminate the plastic hinge that developed immediately after the damper attachments on the rear cross member of the initial configuration.

However, the final bending strain distribution is not completely uniform because of the presence of a strain peak up to 15,000 $\mu\varepsilon$ in middle of the rear cross member.

To obtain a better strain distribution and to improve the structural strength of the skid landing gear, the optimization procedure $\Delta\varepsilon_{\min}$ was applied limiting the load factor to 3.5 g. Unfortunately, in this case the optimization was not able to identify feasible solutions starting from the prototype configuration.

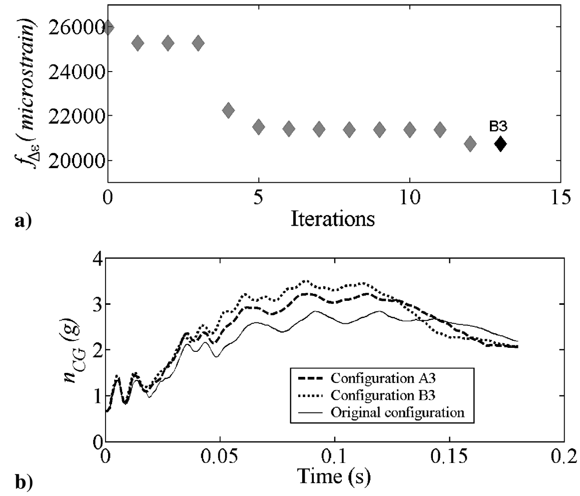

Fig. 17 Optimization results: a) objective function evolution and b) numerical load factors and in two selected configurations obtained applying both the optimization procedures for a 3375-kg helicopter mass.

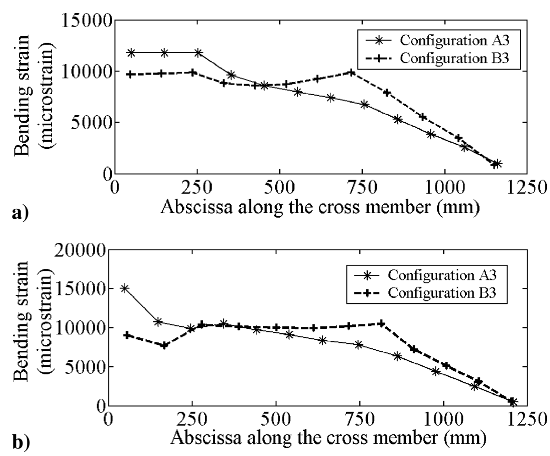

Fig. 18 Numerical strains a) in the forward and b) in the rear cross members for two selected configurations applying different optimization procedures for 3375-kg helicopter mass.

To escape from this infeasible region, the same optimization search was started from a different initial guess point. The configuration already obtained by minimizing the load factor, namely, A3, was chosen as the new starting point of the optimization procedure $\Delta\varepsilon_{\min}$ because it satisfied a priori all of the imposed constraints.

Figure 17a shows the objective function $f_{\Delta\varepsilon}$ vs the iterations of the optimization algorithm. The quadratic variation of the bending strain along the cross members was progressively minimized. The load factor time history of the optimized configuration, marked as B3 in Fig. 17a, is reported in Fig. 17b together with the one of the reference configuration and the one previously obtained by minimizing the load factor, namely, A3.

The strain distributions of the configurations A3 and B3 are finally compared in Fig. 18. The results achieved by optimizing the strain distribution are particularly appreciable. In fact, the cross members do not present any evident weak point, and a uniform bending strain, at about 10,000 $\mu\varepsilon$, is obtained along a large part of the cross members.

V. Conclusions

In this work, a multibody approach was developed to predict the behavior of a skid landing gear in the most general conditions, adopting an explicit time-integration algorithm particularly suitable to model complex contact interactions, geometrical and material nonlinearity.

Explicit multibody analyses succeeded in evaluating the landing-gear performances and the distribution of the bending strains along the structural elements with adequate accuracy and low computational costs. The presented numerical-experimental correlations, relevant to a drop test of a gear prototype in limit landing conditions, show that the loads transmitted to the fuselage, the gear deflections, as well as the local strains along the cross member of a skid landing gear, were accurately predicted requiring a couple of minutes on a common personal computer.

The numerical approach was then considered particularly appealing for design and optimization purposes. The development of a numerical tool to accomplish such objectives was pursued by defining a parameterized model of a generic skid landing gear, allowing the changing of the shape of the cross member axes and their tapering law.

Two optimization procedures have been proposed to take into account both the functional and the structural role of the cross members. These procedures were applied to design the skid landing-gears of two helicopters with significantly different masses. In the first formulation, the skid landing-gear configurations were obtained by minimizing the load factor, leading to the best landing performances, even if a uniform strain distribution was not achieved and weak points were introduced in the gear structure.

The second formulation was implemented adopting a specific objective function, aimed to optimize directly the strain distributions. This formulation came out directly from the traditional engineering feeling but led to more irregular optimization paths, because of the difficulty of satisfying all of the imposed constraints. To escape these difficulties, the optimization directed to minimize the load factor was used to identify preliminary design hypotheses satisfying the imposed constraints. According to the presented results, the final identified configurations fulfilled all of the design requirements with substantially optimal strain distributions, improving noticeably the gear strength with respect to the solution identified by minimizing only the load factor.

The developed optimization procedures, jointly used, were thus able to design skid landing-gear configurations obtaining the required performances and optimizing the strength of the gear. The modeling technique allowed the accomplishment of the design task in a very limited computational time, not exceeding the 36 h on a personal computer, making moreover available a numerical model for further verifications in landing conditions characterized by different soil characteristics, attitudes, and sink speeds, including crash landing conditions.

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