Dynamic crushing of spacecraft landing gear with crash legs

G A Scheglov\(^1\) and R O Lukovkin\(^1,2\)

\(^1\) Department of Aerospace Systems, Bauman Moscow State Technical University, 2nd Baumanskaya St. 5, Moscow, 105005, Russian Federation

\(^2\) E-mail: LukovkinRO@ya.ru

Abstract. The paper describes spacecraft landing on a landing gear consisting of four crash legs supported by beam struts. The first part is dedicated to verification of low dimension shell finite element model parameters in the MSC Nastran SOL700 software. An elastoplastic crushing test problem of square aluminum specimens with various thickness is simulated. The comparison of simulation results with experimental data shows that the proposed mathematical model provides the error of less than 10% for the specimens with a width-to-thickness ratio \(C/s > 30\). The second part of the paper discusses landing gear legs crushing during vertical landing on a rigid soil. An analysis of the results showed that it is possible to reduce the crash legs mass by 35% and the landing gear will provide safe landing conditions with a limited level of peak loads acting on the spacecraft. The characteristic features of the crash leg dynamic deformation process open possibilities for further reduction the landing gear weight and design optimization. The paper opens up a new avenue in design of high energy absorption lightweight gear components for the spacecraft landing process.

1. Introduction

Landing gear (LG) is the most important system for the successful landing of the spacecraft on a planet’s surface. So success and completeness of the flight program depend on LG.

Different types of LG were designed and successfully used in USSR and USA for their space programs. LG was used on missions for soil research on Moon, Venus and Mars and, of course, for manned flights to the Moon. LG with traditional construction is the most common. It consists of several lever rod legs. Cellular elements are located in piston-type shock absorbers and are used for energy absorption [1–4]. Large number of structural elements (such as rods, pillars, and frames) is the main disadvantage of LG with traditional construction because these structural elements are useless for spacecraft’s kinetic energy reduction. Besides, they increase support stiffness and overall weight. Part of the load flow bypasses energy absorption devices and goes straight to support attachment points in the process of landing. This fact can lead to high overload and damage to local body parts. All these disadvantages are especially critical for the LG designed for perspective reusable spacecrafts such as new Russian spaceship called «Federation» spaceship because LG’s excess weight reduces the efficiency of the transport operation. And significant loads to the main body of the spacecraft lead to the need for additional complicated and expensive control systems used for landing.

The disadvantages of the LG with lever-rod legs can be confronted by increasing the number of disposable items capable of plastic deformation.

Thin-walled tubular and box-shaped metal structures are widely used as energy-absorbing elements [5]. They have significant efficiency due to progressive elastic-plastic folding in the process of energy dissipating under impact loads. Similar designs are used in various branches of engineering [6–8].
advantages of thin-walled energy absorbers are most clearly shown in the automotive industry, where they are used both as elements of power spars [9] and as independent disposable plastic-wrinkled thin-walled crash boxes [10]. These thin-walled crash boxes are box-shaped shells of variable cross-section, ensuring the process of programmed and controlled deformation of the vehicle's passive safety system.

The possible advantages of using crash boxes in the supporting structure of the LG of a modern reusable spacecraft are shown in [11,12]. The modification of this LG (figure 6) is considered in the present work and consists of the introduction of supporting elastoplastic beam struts into the design of crash legs (figure 7). These beam struts are designed to increase the stability of the landing process for spacecraft with horizontal and vertical initial speeds.

The purpose of the work is to evaluate the performance of a new design of plastically deformed LG [6] with the most dangerous initial conditions for regular landing on hard ground, suggesting the presence of initial transverse velocity. The objective of the work is to determine the dynamic characteristics of the transitional landing regime and to identify the characteristic features of the process of crash-support deformation. To achieve this goal, a mathematical simulation of the landing process of the spacecraft on the LG was carried out in the MSC Nastran SOL700 [13] software package, which implements an explicit time integration scheme.

2. Verification of model parameters

To identify and verify calculation model parameters in MSC Nastran SOL700 software the model problem of axial crushing aluminum square tubes is studied in this paper. Tubes are made from aluminum alloy AA6061 T6 with the wall thickness $s = 0.8...2.0$ mm and side size $C = 36$ mm (figure 1 (a)). Experimental research of the axial crushing test experiment is given in [14].

![Figure 1](image_url). Square tubes with various wall thickness configurations (a) and (b) finite element model.

Schematic diagram and finite element model for tubes are given in figure 1 (b).

An absolutely rigid wall is moving along $OZ$ axis with constant speed $V = 1$ m/s and crushes the top end face of square tube part with $L = 126$ mm length, which is fixed along the lower edge.

The desired energy absorption main features: force-displacement of specimen $P(d)$, peak $P_{\text{max}}$ and mean crushing force $P_m$, effective crushing distance $\delta$ and absorbed energy level $E_a$ [14] are determined in an elastoplastic fold formation after the interaction.
The model was meshed according to recommendations given in [15,16]. The specimen is meshed by equilateral shell QUAD4-elements in such a way that its side contains 16 elements. The shell elements are defined as fully-integrated (parameter DYSHELLFORM = 16) with the additional option to control the hourglassing-effect (parameter DYHRGIHQ = 8). The number of integration points for 2D elements is DYSHNP = 5.

Initial imperfections have been introduced by moving the nodes of two opposite sides to a distance of 0.2 mm at a distance λ from the upper edge of the specimen to induce the initial fold of the model according to experiment and improve the correctness of the results obtained by numerical simulation [17].

The mechanical properties of the AA6061 O material are: Young’s modulus $E=68.9$ GPa, Poisson's ratio $\nu=0.33$, material density $\rho=2730$ kg/m$^3$, yield stress $\sigma_y=62.8$ MPa, and the ultimate stress $\sigma_u=115.0$MPa. Figure 2 presents the tensile engineering stress-strain curve. This material is specified by the elastoplastic model MATD024 and the parameter DYLDKND = 0 in the MSC Nastran SOL700 software package.

The rigid wall is modeled using the simplified material model of an undeformable solid body MATD020. A friction coefficient of 0.3 was used for the contact interaction between the wall and the specimen, as well as for the self-contact of the specimen surfaces [14]. Besides, a slight global system damping DAMPGBL is set to 0.01 to increase the calculation stability and to smooth the possible high-frequency peaks of the resulting solution.

The deformation modes of the specimens simulated by numerical analyses compared with experimental data are shown in figure 3.

The force-displacement curves of square tubes with thickness $s = 0.8..2.0$ mm are plotted in figure 4.

![Figure 2. Engineering stress-strain curve of AA6061 O](image)

![Figure 3. The deformation modes of the specimens: (a) – experiment; (b) – simulation](image)
Figure 4. Force-displacement curves of square tubes with thickness variation: (a) – \( s = 0.8 \) mm, (b) – \( s = 1.2 \) mm, (c) – \( s = 1.6 \) mm, (d) – \( s = 2.0 \) mm; 1 – experiment, 2 – simulation.
It can be observed that the simulated deformation modes, peak frequency, and amplitude are in good agreement with the experimental results. The divergence between numerical simulation and experiment occurs at the final step of deformation when the wall displacement $d > \delta$ and the construction density is significant, where the shell model does not provide an adequate description of the specimens deformed geometry.

The specimen’s main energy absorption characteristics are listed in table 1. It should be noted that the errors in determining the peak force $\Delta P_{\text{max}}$ and the mean crushing force $\Delta P_{\text{m}}$ decreased with increasing $C/s$ (ratio of specimen width to thickness) and for $C/s > 30$ error does not exceed 10%.

| $s$, mm | $\lambda$, mm | $\delta$, mm | $P_{\text{max}}$, kN | $P_{\text{m}}$, kN | $E_a$, J | $\Delta P_{\text{max}}$, % | $\Delta P_{\text{m}}$, % |
|--------|------------|-------------|-----------------|----------------|--------|------------------|----------------|
| 0.8    | 51         | 89.3/90.9   | 7.32/7.10       | 2.54/2.41      | 226.8/219.1 | -3.0             | -5.1            |
| 1.2    | 87         | 90.2/94.1   | 13.35/12.97     | 5.44/4.97      | 490.7/467.7 | -2.8             | -8.6            |
| 1.6    | 108        | 88.0/92.3   | 21.18/20.08     | 9.32/8.16      | 820.2/753.2 | -5.2             | -12.4           |
| 2.0    | 27         | 85.3/87.7   | 30.26/26.22     | 15.24/12.5     | 1300.0/1096.3 | -13.4          | -18.0           |

The proposed simplified shell finite element model provides quite reliable results in highly nonlinear problems of thin-walled constructions elastoplastic crushing. Such approach can be used for LG modeling.

3. Simulation of spacecraft landing on hard soil

3.1. Problem statement.

The gravity vector $g = 9.81 \text{ m/s}^2$ is directed along $OZ$ axis in a fixed coordinate system $OXYZ$ (figure 5). An absolute rigid surface is situated in the plane $OXY$ and simulates a hard soil. At starting point of time $t = 0$ spacecraft with mass $M = 6000 \text{ kg}$ and moments of inertia about the three coordinate axes $I_{xx} = I_{yy} = I_{zz} = 10,000 \text{ kg} \cdot \text{m}^2$ is moving with constant velocity vector components $v_{x0}$ and $v_{z0}$, which are directed along $OX$ and $OZ$ axes, respectively. The body of a spacecraft is replaced by a point mass, located in a mass center point $M$ of the spacecraft, to simplify the model definition. A moving coordinate system $O_1X_1Y_1Z_1$ is attached to the spacecraft so $O_1Z_1$ axis would be aligned with spacecraft vertical axis and point $M$ is placed on $O_1X_1$.

![Figure 5. Model definition](image-url)
The landing gear is attached to point $M$ by absolutely rigid weightless links. This gear consists of 4 crash legs I-IV, which are arranged symmetrically relative to axis $O_1Z_1$. Principal dimensions of the model are: $O_1C = 1.8\, \text{m}$, $AB = 1.4\, \text{m}$, $CB = 2.2\, \text{m}$, angle between $AB$ and axis $O_1Z_1$ is $20^\circ$. Distance from point $M$ to axis $O_1M$ is $0.25\, \text{m}$.

At the starting point of time $t = 0$ system is in free fall. The first contact with the surface occurs at time $t_1$. Structural and viscous friction in elements of crash legs assumed to be 0, the friction coefficient between the soil surface and crash legs assumed to be 0.5.

Various scenarios of starting orientations of the spacecraft regarding landing surface are considered. According to empirical recommendations and statistical data of landing systems’ working conditions, following spacecraft orientations assumed for next cases: landing scheme 4–0 ($\theta = 0^\circ$, pitch angle $\gamma = 0^\circ$, yaw angle $\psi = 0^\circ$), landing scheme 1–2–1 ($\theta = 15^\circ$, $\gamma = 0^\circ$, $\psi = 0^\circ$), landing scheme 2–2 ($\theta = 15^\circ$, $\gamma = 45^\circ$, $\psi = 0^\circ$). Dynamic characteristics of the landing process, that correspond to standard landing conditions of a spacecraft prototype, with starting velocities $v_{X0} = v_{Z0} = 3\, \text{m/s}$ are considered in the study. This paper presents the results of landing simulation for the case defined by scheme 2-2, as the most critical and dangerous landing case for spacecraft [11].

The model of landing on an LG consisting of four crash legs is created using verified parameters of the model of a single energy absorber. The finite element model of the crash leg is shown in figure 7. The crash leg consists of vertical and inclined energy absorbers that are made of crash boxes (pos. 1) interconnected with by support rings and plates. The contact between the crash leg and underlying surface happens via big and small segmental-spherical plates (pos. 5 and 6). Absorbers are connected by folding passive elements-plates (pos. 4) forming a triangle at the top of which there is a bracket (pos. 3) for mounting to a spacecraft. A more detailed description of the support is reported in the patent [12]. In this paper, the design of the LG is done with beam struts of the annular cross-section to increase the bending stiffness of the LG and prevent reverse stroke of the crash legs.

![Figure 6. Crash leg](image1)

![Figure 7. Finite element model of the crash leg with struts](image2)

Crash boxes (pos. 1 in figure 7), small and large plates (pos. 6 and 5), the soil are modeled with fully integrated shell QUAD4-elements. Support rings (mandrels), plates (pos. 4) and the bracket (pos. 3) are modeled with HEX8-elements, struts (pos. 2) are modeled by BEAM-elements, the spacecraft is modeled by a point mass. Different types of finite elements are interconnected with rigid coupling elements RBE2.

Elastoplastic model MATD24 of aluminum alloy AMg6 was used for modeling the energy absorbers and struts, and elastic model MATD1 of titanium alloy VT6 was used for modeling the passive elements of crash legs (plates and support rings). The mechanical properties of materials are given in table 2.

| Table 2. Mechanical properties for materials |
| Material | Density $\rho$, kg/m$^3$ | Young’s modulus $E$, GPa | Poisson ratio $\mu$ | Yield stress $\sigma_y$, MPa | Ultimate stress $\sigma_u$, MPa | Elongation $\delta$, % |
|----------|--------------------------|--------------------------|------------------|--------------------------|--------------------------|------------------|
| AMg6     | 2.640                    | 69.6                     | 0.32             | 161.9                    | 358.1                    | 22               |
| VT6      | 4.430                    | 122.63                   | 0.3              | –                        | –                        | –                |

The thickness of the upper and lower belts of the crash boxes are 2.8 and 4 mm, respectively. The struts have a tubular cross-section with an average radius of 20 mm and a thickness of 10 mm. The design parameters of the crash legs were chosen so that the energy absorption problem for the considered combinations of initial landing conditions was solved by the predominant deformation of the upper crash-box belt, and the lower belt provided the required clearance and damping reserve in case of emergency situations at $v_{20} > 3$ m/s.

Simulation of the landing process was carried out by the finite element method in a non-stationary dynamic setting in the MSC Nastran/SOL700 software environment by using an explicit time integration scheme.

3.2. Numerical simulation results.

The basic results of numerical simulation are deformed shapes of LG for each phase of landing and graphs of vertical $v_z = \ddot{z}$ and horizontal $v_x = \dot{x}$ speeds, longitudinal $n_z = \ddot{z} / g$ and lateral $n_x = \dot{x} / g$ load factors versus time at the point $M$.

Simulation demonstrates that landing scheme 2-2 causes the most complex conditions of landing legs unsymmetrical bending, due to the initial contact with the surface only by two legs I and III (figure 8). The moment $t = 0.08$ s since the initial interaction of large leg plates with the landing surface is characterized by the biggest increase of longitudinal load factor (figure 9) reaching the value of 4g. Further follows the prevailing deformation of the leg I caused by non-uniform loading because the spacecraft center-of-mass is displaced closer to the leg I. The appearing bending moments cause the formation of plastic hinges in weakened sections either in the lower or the upper layer of energy absorbers. That causes a break and a collapse of crash boxes. The contact of large leg plates II and IV with the landing surface begins at the moment $t = 0.3$ s and is accompanied by the increase of longitudinal load factor to the value of 3g. At the end of the transient process of landing $t_k = 0.9$ s (figure 10) all four legs of LG are in contact with the landing surface, and a safe distance between the bottom of the spacecraft and the soil is assured.
Figure 8. LG deformation stages by the landing scheme 2-2: (a) — $t = 0$; (b) — $t = 0.08$ s; (c) — $t = 0.30$ s; (d) — $t = 1.00$ s

Figure 9. Graphs of point $M$ parameters versus time for landing scheme 2-2: (a) — vertical $v_z$ and horizontal $v_x$ speeds; (b) — longitudinal $n_z$ and lateral $n_x$ load factors

The ultimate deformed shape of the LG (figure 10) demonstrates the considerable bending of the leg I from the plane of symmetry. That causes the formation of a plastic hinge and the leg fall, without lesser leg plate touching the landing surface. Crushing of leg III crash boxes occurs almost uniformly by the whole length, and few lateral folds appear. The Leg II deformation is limited to the upper sections of energy absorbers’ upper belt. There is no crushing of the leg IV.
The modeling results of the landing scheme 2-2 demonstrate that this mode is the most dangerous for probable spacecraft failure caused by significant non-uniform deformations of LG legs. The complex approach for the improvement of LG work conditions is needed: bending moments reduction by landing legs length shortening, legs bending stiffness increase in basic planes by changing of energy absorbers, knees and support branches construction. Furthermore, the increase of legs initial stiffness is possible by guaranteeing simultaneous contact of large and little leg plates with the landing surface.

4. Conclusion

Introduction to the design of the crash leg of simple beam struts allows ensuring a safe landing of spacecraft on LG in the range of standard initial conditions of the landing of spacecraft prototype with horizontal and vertical speed components $v_{x0} = v_{z0} = 0...3 \text{ m/s}$.

The mass of the considered crash leg with beam struts is 62 kg, which is 35% less than a traditional construction leg.

For the landing scheme 2–2, the initial frontal impact conditions lead to the formation of plastic hinges in weakened sections of energy absorbers, which reduce the stability of the landing process as a whole with a low level of longitudinal overload $n_z$ (up to 4g) and significant ground clearance at the end of the transition process.

The considered design parameters of crash supports are satisfactory, but not optimal, which leads to underload and a slight collapse of the energy absorbers of supports II–IV, as well as an excessive margin of spacecraft clearance.

The obtained results make it possible to formulate an important requirement for the implementation of a sustainable landing process on LG with crash legs according to scheme 2–2 when there is a non-simultaneous contact of the ground with the plates. In order to exclude the total loss of stability of crash legs, which disrupt the normal functioning of LG in these cases, it is necessary to reduce the time intervals between the successive entry of the landing legs into contact with the surface. This requirement can be satisfied with the help of an integrated approach to reduce the load bending moments and increasing the stiffness of crash legs in the main planes.

The aim of the further work of the authors is defining the optimal design of LG, on the base of the recommendations pointed in this article.

References

[1] Kokushkin V V, Shchiblev Iu N, Ososov N S, Petrov N K, Borzykh S V and Voronin V V *Spacecraft landing gear* Patent no. 2546042 Russian Federation 2015 URL: https://patents.google.com/patent/RU2546042C2/en?oq=RU+2546042

[2] Blumrich J F *Landing pad assembly for aerospace vehicles* Patent no. 3175789 A USA 1965
[3] Turner R D *Deployable spacecraft lander leg system and method* Patent no. 6227494 B1 USA 2001

[4] Lawrence C, Solano P, Bartos K *Deployable Landing Leg Concept for Crew Exploration Vehicle* NASA Technical Report NASA/TM-2007-214705 E-15930 2007. URL: http://hdl.handle.net/2060/20070031904

[5] Abramowicz W Thin-walled structures as impact energy absorbers 2003 *Thin-Walled Struct.* 41 91–107

[6] Baroutaji A, Sajjia M, Olabi A G On the crashworthiness performance of thin-walled energy absorbers: Recent advances and future developments 2017 *Thin-Walled Struct.* 118 137–163

[7] Alghamdi A A A Collapsible impact energy absorbers: An overview 2001 *Thin-Walled Struct.* 39 189–213

[8] Airoldi A, Janszen G A design solution for a crashworthy landing gear with a new triggering mechanism for the plastic collapse of metallic tubes 2005 *Aerospace Science and Technology* 9 445–55

[9] Johnson W, Walton A C An experimental investigation of the energy dissipation of a number of car bumpers under quasi-static lateral loads 1983 *Int J Impact Engng* 1 301–308

[10] Chung Kim Yuen S, Nurick G N The energy-absorbing characteristics of tubular structures with geometric and material modifications: an overview *Applied Mechanics Review* 61 1–15

[11] Shcheglov G A, Lukovkin R O Analysis of the spacecraft vertical landing dynamics on the platform with crash legs 2017 *Russian Aeronautics* 60 382–390

[12] Lukovkin R O, Shcheglov G A *Landing gear with crush supports for spacecraft* Patent no. 2580601 Russian Federation 2016 https://patents.google.com/patent/RU2580601C1/en?q=RU+2580601

[13] Doelfs P, Neubauer I Using MSC. Nastran for Explicit FEM Simulations *LS-DYNA Anwenderforum* Bamberg 2004 URL: https://www.dynamore.de/en/downloads/papers/04-forum/using-msc.nastran-for-explicit-fem-simulations/at_download/file

[14] Zhang X, Zhang H Crush resistance of square tubes with various thickness configurations 2016 *Int. J. Mech. Sci.* 107 58–68

[15] Du Bois P A Crashworthiness Engineering: Course Notes 2004 *Livermore Software Technology Corporation*

[16] Bala S, Day J General guidelines for crash analysis in LS-DYNA 2006 *Livermore Software Technology Corporation*, URL: ftp.lstc.com/anonymous/outgoing/jday/faq/guidelines.pdf

[17] Otubushin A Detailed validation of a non-linear finite element code using dynamic axial crushing of a square tube 1998 *Int J Impact Engng*. 21 349–368.