DYNAMICAL ANALYSIS OF LANDING GEAR FOR CRITICAL WORK CONDITIONS

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Abstract. The research on the most effective methods of aircrafts’ landing gears design as well as the evaluation of the gear’s condition during utilization period and possibilities of extending its durability are the subject of numerous studies, including the ones by leading worldwide aviation companies and national scientific centers. It is indicated in these studies that numerical analysis of the strength of the construction elements of the examined aircraft’s part (beside experimental research) is a necessary stage of proper methodology of aviation research, in particular in programming and reliability evaluation and development of methods of increasing durability in case of solutions already used in practice. Majority of the fatigue numerical analysis and prediction of the landing gear’s lifetime is limited to the linear analysis and the local phenomena appearing around a failure. Such approach was developed at the first stage of the work. The influence of a failure on the complete landing gear system is subject of our consideration. Chosen experimental tests were performed at the drop stand. Appearing forces in the landing gear parts, accelerations and displacements were recorded during stand tests. Service fracture in the top leg of landing gear was appeared in the fatigue tests and is the main aim of this study. This fracture was caused by technological factors (disturbances). In the numerical part of these investigations various 3D models of the complex landing gear with different cracks lengths were developed and computed for the dynamic FE analysis using explicit integration scheme. Achieved experimental and numerical results of transport airplane’s landing gear with existing cracks are discussed in this paper.

Keywords: landing gear, crack, experimental and numerical studies

1. INTRODUCTION

The experimental testing of failures/damages to landing gear components and investigation into effects thereof on the whole structure is very expensive and not always feasible. Hence, what seems absolutely indispensable nowadays is taking account of failures and damages in computational models (more and more commonly applied) of such significant systems as, e.g. the aircraft landing gear. Failures/damages in question affect different functional components of the main and nose undercarriage. Different causes of failures/damages to landing-gear subsystems are given consideration: wear and tear, fatigue cracking, failures to sub-assemblies due to material and manufacturing defects (Airoldi, 2005, Hong-Chul, 2003, Lee, 2003 and Kaplan, 2002). The search for causes of failures and damages to systems of aircraft landing gear has become both very expensive and labour-consuming. This is what has made designers to switch over from the analysing of an actual model to analyses of a virtual one, as well as to generate mathematical models to describe phenomena that occur in the course of landing. A virtual model developed in the CAD environment has enabled reduction of cost resulting from the search for causes of damages. Numerical analyses are successfully carried out owing to the application of 2D and 3D software (Khapane, 2003). Most of the analyses regarding fracture mechanics and service-life predictions are only restricted to linear issues and local phenomena that occur around the crack. Obviously, fatigue life predictions refer to the whole structure and the assessment of correct operation thereof within some specific operational time. However, the present-day methods of estimating service life of a product resolve themselves to the assessment of predicted life of the product, or to ensure failure-free operation of the system with some probability assumed.

In this study the Finite Element analysis has been applied to dynamically simulate operation of a nominal (failure-free) system and a system with an intentionally introduced failure (i.e. a crack in some specific sub-assembly) of a complete undercarriage structure. What has been discussed in the paper is the drop testing work performed with a complete main landing gear of a transport aircraft engaged, and findings of fractographic examination used to generate numerical models with failures. More precise knowledge of non-linear patterns of stresses and concentrations thereof in the structure with failures needs more detailed FE models. In the first phase of numerical analyses of the landing gear with failures, a multi-stage global-local analysis was applied. The effect of the landing gear failure upon the effort of subassemblies of the system was modelled using the quasi-static analysis (Kajka, 2005). Various local models of the main-undercarriage lever were generated with account taken of different phases of failure growth within the welded joint between the upper and lower levers of the undercarriage leg. Global models of the landing gear were applied, the boundary conditions of which were applied for local analyses of the failure. Results of multi-stage analyses with the global-local method were then compared with those gained with dynamic simulations conducted with a fully-deformable 3D model of the landing gear. Results of experimental tests applied to dynamic simulations were used to verify numerical models of a complete landing gear.
2. EXPERIMENTAL TESTING

An aircraft landing gear is the structure exposed during operational use to many and various loads. The representing of these loads under laboratory conditions requires several different test stands to perform static and dynamic tests. Tests of the main landing gear were divided into three basic groups and covered: touch-down induced loads – tests carried out dynamically, loads that occur during the take-off run, the landing run, and the taxiing – tests performed dynamically and braking induced loads and side loads encountered during ground manoeuvres – tests carried out in a quasi-static way.

Numerically simulated were some landing gear touch-down tests. The touch-down induced loads were represented by means of free drops of the landing gear with a wheel remaining still or set turning. The test was carried out dynamically on a drop-weight type impact testing machine (Fig. 1a). The loads were found using, among other sources, the MIL-A-8866C standard, FAR-23 standard and flight test results.

With results gained during testing the landing gear on different test stands, loads were found with the FE method (FEM). Such approach enabled more accurate numerical representation of the landing gear behaviour during the tests.

Fatigue tests of the landing gear were also carried out under the bench testing work. The best way to perform fatigue testing would be representing the loads sequentially, as they occur during the operational use of the landing gear. In the course of drop testing the landing gear was damaged during the test representing the taxiing. Fig. 1b shows a picture of a fracture in the upper section of a damaged lever. Inside the upper section of the lever there was an alignment weld sleeve to align components of the lever prior to welding. The alignment weld sleeve was initially coupled with section 1 by means of tack welds located where two components were to be joined together with a circumferential weld; the arrangement of the tack welds was accidental. Some of these welds were damaged due to some material being torn out of the alignment weld sleeve.

3. DYNAMIC ANALYSIS IN THE 3D MODEL OF FAILED MAIN LANDING GEAR

Dynamic analysis were also performed under the study. Simulated was the landing gear touch-down under conditions corresponding to those of performing the landing at the maximum vertical rate of descent \( V_z = 3.05 \text{ m/s} \), which had been used in bench tests together with the horizontal velocity \( V_x = 38 \text{ m/s} \). To do this, two models found their applications: a nominal 3D model of a complete landing gear (a fault-free model described in detail in paper (Krason, 2008 and Malachowski, 2006), and a model for dynamic analyses of the complete landing gear with a failure taken into account. The 3D model of a complete landing gear with a failure, intended for dynamic analyses (Fig. 2a and b), included also an alignment weld sleeve and the coupling that joined the sleeve and the upper lever of the landing gear by means of seven (Kajka, 2005) tack welds. Such welds were also modelled: These welds were modelled by the pointwise linking of respective nodes of the sleeve and the lever. They only occur in the material continuity region, exactly as it is in an actual structure tested experimentally and analysed with a multi-stage method in local models.

Two crack faces (describing initial crack opening displacement) with openings of 0.01 mm (Fig. 3) were modelled between surfaces that represented failures in the welds of the lever. Crack faces upon the cross-section of the undercarriage lever were modelled as flat and smooth. In that case, the adjacent crack faces built up a contact pair. The ‘slave-master’ contact based on the penalty function between these surfaces representing the failure was adopted. The penalty function can be applied to normal displacements in the displacement-based approach; to normal velocities defined in the velocity-based approach; and to normal displacements in the velocity-based approach, the latter being the most often form of application. In the penalty function method the normal contact force is expressed with the following equation:

![Figure 1. The main landing gear on a drop test bench to represent touch-down a) and the upper part of the damaged landing gear b) (Kajka, 2005)]
\[
F_{\text{ij}} = \zeta \mathbf{u}_{\text{ij}} H(-\mathbf{u}_{\text{ij}})
\]

where: \(H(\cdot)\) is Heaviside step function and \(\zeta = 1/\kappa\), \(\kappa\) – coefficient of the penalty function.

Conditions of contact are checked on the grounds of \(B \mathbf{u} \geq \gamma\), where \(B\) is matrix that describes boundary conditions kinematics and \(\gamma\) is the vector of initial gap (in analysed case refers to the initial crack opening displacement, COD). In the course of numerical application of this method an imaginary energetic term is added in the form of the penalty function (Hallquist, 2005): \(\pi = \frac{1}{2} \mathbf{u}^T \mathbf{K} \mathbf{u} - \mathbf{u}^T \mathbf{f} + \kappa \left[ (B \mathbf{u} - \gamma) \left( (B \mathbf{u} - \gamma) \right)^T \right]\). In terms of physical interpretation of the penalty function parameter, operation thereof should be interpreted as an imaginary elastic element that appears between two nodes in contact. Value of this parameter is found on the basis of accuracy of a computing machine, number of unknowns, and the least stiffness of elements in contact at the moment.

Figure 2. The 3D model of a complete landing gear for dynamic analyses thereof, with a failure taken into account a) and the view of the 3D model of the landing gear during touchdown phase b)

Crack faces were modelled in effect of identification of appropriate walls of elements contiguous to the failure, and then by imparting suitable characteristics thereto. The in this way defined areas of contact on the crack faces allowed for their mating effected by their pressing at each other in the case compressive stress was transferred (crack gap closure), and for the crack opening in the case of tensile stress occurring in the region of the failure during dynamic tests.

Figure 3. Two crack gaps considered in the 3D model of the landing gear:
in the stretched (i.e. subjected to tensile stress) area of the welded joint between the upper and lower levers of the undercarriage leg a) and in the compressed (i.e. subjected to compressive stress) area of the welded joint between the upper and lower levers of the undercarriage leg b)

A model of a drop plate was also taken into account in these models (Fig. 2b). It was assumed that in both the cases, i.e. the touch-down simulation in the fault-free model and that with a failure introduced, the aircraft landed at the angle of attack \(\alpha = 13^\circ\) while flaring out for the landing, prior to the touch-down. This corresponded to the so-called tail-first landing, with only two wheels of the main landing gear touching down in the first phase of the manoeuvre.

Finally, the 3D model of a complete landing gear was arrived at, with a failure represented in the form as if just before a complete fracture of the cross-section of the lever of the landing gear subjected to tests. The model of a complete landing gear consisted of 130429 solid elements of the hexagonal and tetragonal type. A complete model of the landing gear with a wheel, with a failure introduced, incorporated more than 2760 2D elements (of the QUAD4 type) and 120 MPC elements. Statistics of this 3D model of a complete landing gear with a failure, applied in dynamic
analyses, was as follows: the total number of elements in the model of an landing gear was 133269, the total number of nodes in the model was 140889, the number of deformable elements in the model was 127749, the number of stiff elements in the model of a drop plate was 5520 and 22 material characteristics. Detailed descriptions of the 3D model structure, together with the theory of conducted numerical studies, have been already presented in the paper (Krason, 2008).

In the nominal model and that with a failure, applied in the \( C_{\text{nom}} \) and \( C_{\text{fail}} \) cases of the dynamic analysis - respectively, conditions of the main landing gear touch-down at two points (‘two-point’ touch-down) were represented, with account taken of the wheel set turning up to the angular velocity \( \omega = 127.52 \text{ rad/s} \) (Fig. 2b). In this way, the forward speed at the aircraft’s touch-down was simulated: \( V_x = 38 \text{ m/s} \). In the applied models, both nodes of fixing the main landing gear to the fuselage were represented; also, modelled were constraints that made the model of the drop-plate segment fixed (the plate in question was used to perform the touch-down of the landing gear subjected to tests). Loads affecting the landing gear were defined in the form of suitably arranged reduced masses that simulated the effect(s) of fuselage-imposed loads during the touch-down. Simulations of the landing gear’s touch-down (both the variants) were performed under gravity forces affecting the system, with pre-set initial and boundary conditions. All computations were performed using the so-called direct-integration procedure, colloquially called the “explicit integration” (Hallquist, 2005).

4. COMPARATIVE ANALYSIS OF RESULTS GAINED FROM ANALYSIS OF DYNAMIC AND QUASI-STATIC MODELS OF THE MAIN LANDING GEAR, WITH ACCOUNT TAKEN OF A PROPAGATING FAILURE

Results of dynamic simulations in the 3D model of the landing gear with a failure introduced, corresponding to the touch-down at vertical velocity \( V_z = 3.05 \text{ m/s} \), were used for the comparative analysis. This velocity corresponds to the maximum vertical speed of landing gear drops, applied during experimental tests on the drop-weight test stand. In all variants of numerical analysis given consideration, the undercarriage wheel was set turning up to the angular velocity \( \omega = 127.52 \text{ rad/s} \). In this way, the translational motion of the landing gear was simulated, identical to that during an actual aircraft landing with horizontal velocity \( V_x = 38 \text{ m/s} \). Different variants of numerical simulation of the landing gear touch-down were accomplished. Modelled were extreme conditions of operating the system during the aircraft’s landing upon two wheels of the main landing gear. It was assumed that the aircraft landed at the angle of attack \( \alpha = 13^\circ \) while flaring out for the landing, prior to the touch-down. This corresponded to the so-called tail-first landing, with only two wheels of the main landing gear touching down in the first phase of the manoeuvre. Another assumption was that during the touch-down simulation the undercarriage leg was only affected with a half-weight of the aircraft, since no lift was taken into account. Under actual aircraft-landing conditions, lift exerted upon lifting surfaces (wing, control surfaces, fuselage) compensated for some of mass loads upon the landing gear transferred via undercarriage-to-fuselage attachments. Hence, loads affecting the landing gear at touch-down were reduced. Therefore, at this stage of computations extreme variants of loading the landing gear at touch-down were applied. A fully deformable discrete 3D model of the landing gear of nominal parameters and a 3D model of a complete landing gear were used in numerical simulations, the latter one with a failure introduced in the form as if just before a complete fracture of the lever.

Simulations with the two above-discussed variants of the 3D model of a complete landing gear, i.e the nominal one and one with a failure, were applied to numerical simulation of the touch-down, under conditions identical to those of the selected bench test of the landing gear. Some selected parameters were recorded during the simulations, ones that described the landing gear operation at touch-down. The following items were used in comparative analysis of results from numerical models: maximum reduced stress in the region of a failure, i.e. the weld that joined the upper and the lower levers of the undercarriage leg, forces of vertical responses measured on the plate for the landing gear touch-down, relative displacement of the shock-absorber’s shank at the instant of touch-down and changes in components of the undercarriage system’s energy at the instant of touch-down (Krason, 2008).

Furthermore, in analyses carried out in the 3D model of the landing gear with a failure, the change in the distance between the crack-gap surfaces against time of analysis was also recorded.

The above-mentioned parameters describe operation of the landing gear and efforts of landing gear sub-systems under identical conditions defined in numerical tests. Results of dynamic numerical tests conducted for both the variants were compared to respective results of quasi-static analyses. Such comparison, as well as the reference to results of some selected bench tests would allow for the verification whether the applied methodologies of numerical analyses and models were correct. It would also enable formulation of some generalizations on capabilities arising from and prospects of applying dynamic analyses to examine/test aircraft landing gears.

Maximum values of parameters that described operation of the landing gear and were recorded while simulating the touch-down served as the basis for comparative assessment of results of dynamic analyses. Table 1 gives a statement of values recorded in particular cases of the simulation. Compared were: the maximum equivalent stress, \( \sigma_{\text{eqv}} \), which appears in the area of the welded sleeve that couples the upper and the lower levers of the undercarriage leg and maximum values of the crack opening displacement \( U_{\text{COD max}} \) (Fig. 4).
Table 1 presents also some selected results found in the quasi-static multi-stage method (Kajka, 2005) with local models applied for the undercarriage leg’s segment in the region of welded joint between the upper and lower levers of the landing gear subjected to tests. It was found that the region with cracks modelled in the analysed case C fail showed the greatest effort in the leg material. The maximum equivalent stress recorded in this case reached value of 2300 MPa, which meant that the ultimate tensile strength was considerably exceeded (for the steel 30HGSNA, R m = 1570 MPa). This value is four times as large as the maximum stress found in the fault-free nominal model, with initial and boundary conditions of the simulation assumed identical. The nature of the reduced stress found in the dynamic analysis, within the lever-subassemblies-joining weld section with failures, is very similar to the stress distribution determined with the multi-stage method in the quasi-static analysis. Stress concentrations occur in the undamaged tack welds between the alignment weld sleeve and the inner wall of the lever. Stresses of predominating values occur, which is obvious, immediately at the cracks, at crack fronts, i.e. at the tips of the modelled crack gaps/failures. Equivalent stresses found in the quasi-static analysis reach their maximum values of 2086 MPa where tack welds exist and 1905 MPa in the region with cracks (Kajka, 2005). Having compared these results to those gained in the C fail case, it becomes clear that values of these stresses are nearly 10% lower than the maximum stresses recorded in the dynamic analysis within the region of a failure, between the upper and the lower levers of the landing gear. High values of the equivalent stresses were found with both the applied methods in the immediate vicinity of regions with failures. It proves that the modelled configuration of failures is hazardous to correct functioning of the landing gear. In the considered region with failures, complex stress states occur. The discussed stress concentrations arise locally in the areas of undamaged tack welds, i.e. at the tips of the modelled crack gaps/failures. Therefore, they cannot prove decisive to the immediate and total destruction of the lever in the cross-section under examination, but can considerably affect the initiated crack propagation.

In the dynamic analyses of the touch-down, for various vertical velocities, maximum values of the distance measured between surfaces of the crack gap (called COD) were also found. In the analysed case C fail the value of this parameter did not exceed 1.3 mm (Fig. 4). Values of this parameter found in dynamic analyses with 3D models of a complete landing gear are evidently lower than those found in the quasi-static analysis in local models of a segment of the lever. Making generalizations about this observation, one could say that local analyses in such complicated cases could lead to overestimated results, which is greatly desirable for aeronautical structures from the standpoint of the increase in safety margin. At the same time, it may impede the desired optimisation of the structure and then result in some unjustified, from the aspect of the structure’s strength, redundancy in shaping the technical and operational parameters.

![Figure 4. The change of the COD recorded based on the numerical calculations](image)

Table 1. Comparison of results gained from the dynamic cases of the landing gear with those of quasi-static analyses C qst (Kajka, 2005)

<table>
<thead>
<tr>
<th>Case</th>
<th>$\sigma_{eqv}$ (MPa)</th>
<th>$U_{COD \ max}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{nom}$</td>
<td>590</td>
<td>–</td>
</tr>
<tr>
<td>$C_{fail}$</td>
<td>2300</td>
<td>1.28 (Fig. 4)</td>
</tr>
<tr>
<td>$C_{qst}$</td>
<td>2086</td>
<td>1.8</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

The applied methodology of multi-stage quasi-static analyses in global-local models (Kajka, 2005), and the method of dynamic simulation in models of a complete landing gear enable detailed numerical examination of the effort of the aircraft landing gear, both in nominal configurations and in those with operation-induced failures, subjected to effects that correspond to critical conditions of the touch-down.

The presented numerical simulations enable us to answer a question about the effect of the assumed (on the basis of laboratory tests) failure of an actual size in the phase just before an ultimate fracture upon the effort and correct operation of the whole system of the main landing gear under extreme service conditions, and hazardous conditions as well. Results gained from the model with a failure attract attention with evidently unstable and fast-changing nature of the recorded courses. It refers to courses of recorded reduced stress, force of response on the plate, and the value that describes the crack opening size. This kind of operation of the landing gear system, different from those observed in nominal models, can be determined by collisions between surfaces that model a crack gap in the course of loading while simulating the touch-down.

A matter of great significance in the case of aircraft landing gears is safe operation thereof as well as probable failures and their effect upon the system’s operation. Aeronautical rules and regulations impose a safe-life approach to the operational use of the landing gear. It means a period of safe work, in the course of which no failure to any of the landing gear’s components is permitted. Besides, periodical inspections of the landing gear are performed, in the course of which different damages, e.g. cracks or failures possibly hazardous to the safety of operation are searched for with standard non-destructive testing (NDT) methods usually used in workshops.

With results of fatigue tests and fractographic examination of an landing gear failed due to the multiple cracking, an effort has been made in the present study to analyse the 3D crack propagation and effects thereof upon the landing gear life. The crack propagation law has been gained from the landing gear tests. The test spectrum has been applied; hence, loads as well as the rate and direction of propagation have been defined on the basis of metallographic and fractographic examinations, and observations taken on the test stand. Determined are safe sizes of failures, i.e. ones that provide system’s operation with the assumed factor of safety. Application of available methods of numerical analysis will most certainly contribute to the knowledge of safe operation of the structure of aircraft landing gear. Dynamic and quasi-static analyses of a fault-free landing gear and one with a failure have been employed. Account has been taken of a local failure in the global model of a complete landing gear; also, of effects of dynamic phenomena upon the failed system’s operation.

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7. REFERENCES


8. RESPONSIBILITY NOTICE

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