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Damage of Combat Aircraft Airframe by Projectiles of Calibre 7.62 and 12.7 mm

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Abstract:

This contribution solves the issues of primary damage of aircraft skin. The emphasis is laid on determination of mutual relationship between the extent of damage caused by small calibre projectiles and various factors, which influence the extent of such damage. Based on the experimental data, the theoretical conclusions are modified for the given type of material into a form, which can be used for automated estimation of aircraft vulnerability.

Keywords:

Airframe damage, vulnerability estimation, small calibre projectile

1. Introduction

The term primary damage is perceived as a mechanical erosion of the continuity of the aircraft part material caused by a projectile or a fragment. Such damage can be a cause of immediate loss of the part functionality. Eventually, a faster degradation of the construction element bearing strength can be expected.

During the analysis of the primary damage, the main attention is paid on two subjects.

The first subject is the extent of the damage. Such information can be immediately exploited for the evaluation of the residual static strength or for the evaluation of the safety level of the frame after the causation of damage.

The second subject is the evaluation of the nature of the damage. These findings are bound especially to the kind and thickness of the involved part material. Their importance should be seen especially in making it possible to estimate the further

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evolvement of the damage as well as the time interval, in which the erosion evolves into the phase of stable propagation.

Tab. 1 Used designations

Used designations:		
A_c	[J]	Overall quantity of work performed by the projectile during the penetration
A_p	[J]	Quantity of work necessary for cutting through the hole
A_r	[J]	Quantity of work necessary for ripping the edges of the hole
A_o	[J]	Quantity of work necessary for bending the edges of the hole
ΔE_k	[J]	Decrease of kinetic energy after penetration
F	[N]	Force necessary for penetrating the material
a	[m]	Extent (diameter) of primary damage
d	[m]	Diameter of the projectile tip
k	[m]	Length of the ripped part of the hole
l	[m]	Working length of projectile
m	[kg]	Mass of projectile
n	[1]	Number of bent elements after ripping the edges of the hole
t	[m]	Thickness of the damaged part
v_o	[m/s]	Projectile velocity before penetration
v_1	[m/s]	Projectile velocity after penetration
a	[°]	Vertex angle of a simplified projectile
s	[MPa]	Tension strength of the damaged part material
s_k	[MPa]	Yield limit of the damaged part material
t	[MPa]	Damaged part resistance to shearing

In this contribution, the attention is paid on determination of the extent of the primary damage in such a form that would be suitable for automated aircraft vulnerability assessment. These problems were partly covered in [1] and [2], where the basic entry conditions for the solution are defined:

- In the first phase of the assessment, damage by a 7.62 mm calibre projectile is considered.
- Only the extent and nature of the skin damage is monitored.
- The projectile impacts the centreline of the monitored area upright.
- The sample is considered perfectly flexuraly rigid and does not move at the moment of projectile impact.
- Two materials are evaluated – common dural D16 AT and pure dural D16Tč.
- With respect to the possibilities of velocity measurement in front of and behind the sample piece, the distance from the chase is several meters.

- Only one penetration per sample is made during the experiment.

2. Damage by 7.62 mm Calibre Projectile

During the penetration of the 7.62 mm projectile through the airplane or helicopter skin, a mechanical erosion is created. Extent and nature of the erosion depend on many factors [3], [4]. Though, the geometry and the momentary kinetic energy of the projectile as well as the geometry of the aircraft part and the nature of its material, have the decisive portion on it.

With respect to the amount of influences, which tell the extent of the damage, the theoretical solution is evolved basing on the following simplifying presumptions:

- The process of mechanical erosion consists of cutting through the hole, its ripping and bending of its edges.
- The friction between the projectile and the material is neglected.
- The projectile shape is simplified to a cone with vertex angle a and height l.
- The initial energy of the projectile is constant for each thickness of the material.
- The process of initiation of the mechanical erosion is considered identical for skin thicknesses between 0.6 and 2.5 mm.
- The solution is based on the equality of the quantity of work done by the projectile and the decrease of the kinetic energy, which occurs during the penetration of material.

The quantity of work is generally expressed by the expression $A = Fs/2$, where F represents the force necessary for penetrating the material and s is the trajectory on which the work of the projectile is performed. The overall quantity of work A_c necessary for penetrating the material is expressed by the sum of the quantity of work necessary for cutting through the hole A_p, the quantity of work for the entire ripping of the material A_r and the quantity of work necessary for bending the edges of the hole A_o, according to the simplifying presumptions [5]. In the first case, the trajectory on which the force F applies is the thickness of the material. In the second and third case, it is the length of ripping $k/2$ as shown in Fig. 1.

The top of the projectile is not an ideal tip. Instead, a small area of the diameter d is created on it. On the basis of this fact, the projectile is further considered as a cutting punch, which at first creates a hole in the material that is equal to the diameter of the small area. However, the mentioned approach is acceptable only for thin plates. The entire problem is schematically shown in Fig. 1.

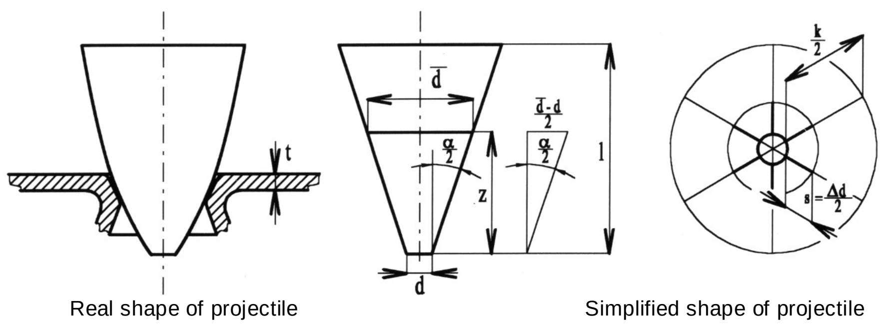

Fig. 1 Cutting through the hole

On the basis of this consideration, it is possible to define the quantity of work necessary for cutting through the hole of diameter ***d***:

$$A_p = \frac{1}{2} p\, d\, t\, t^2 \,. \tag{1}$$

After cutting through the hole, the second phase, which is characterized by gradual roguing of the material, comes. In order to describe this phase, a simplified shape of the projectile is considered, as shown in Fig. 1. For this phase of the process, it is necessary to put forth a quantity of work as it is expressed by formula (2).

$$A_r = \frac{1}{2} n\, t\, s\, \tan\frac{a}{2} l^2 \,. \tag{2}$$

During the gradual penetration of the projectile into the material, the diameter of the hole increases and the loose edges created by ripping the material are gradually bent. This can be characterized as the third phase of the primary damage creation. By introducing the influence of plastic deformation, it is possible to express the quantity of work necessary for bending the edges by an equation

$$A_o = \frac{1}{2} s_k t^2 l \cdot n \cdot \tan\frac{180}{n} \,. \tag{3}$$

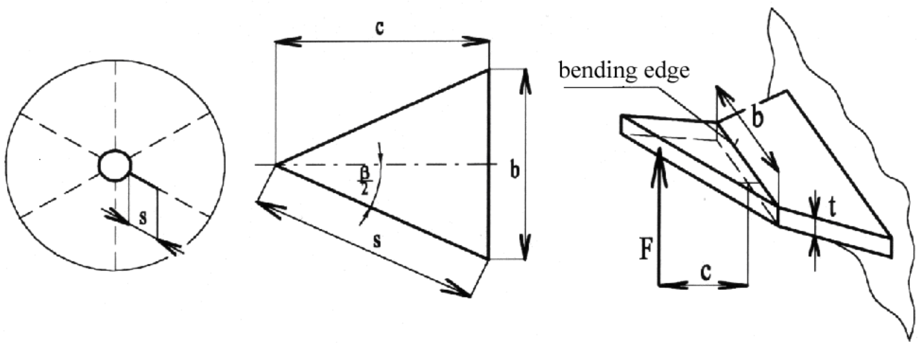

Fig. 2 Geometry of bending

The overall quantity of work done by the projectile during the penetration of material is expressed as a sum of the partial quantities of work:

$$A_c = \sum A_i = A_p + A_r + A_o \,. \tag{4}$$

By substituting the expressions (1), (2) and (3) into the equation (4), we get the formula for the overall quantity of work:

$$A_c = \frac{1}{2} t^2 n \left(\frac{p\, d\, t}{n} + \frac{s\, \tan\frac{a}{2} l^2}{t} + s_k\, l \tan\frac{180}{n} \right) \tag{5}$$

A further simplification can be achieved by using approximate formulas for elasticity and strength, which express the relationship between tension and shear strength and the yield limit of the material [6]:

$s_k = 0.6s$, $t = 0.36s$ where: s is the tension strength of the material

After substitution and subsequent modification, it is possible to express the overall quantity of work by formula

$$A_c = \frac{1}{2} s\, t^2\, n \left(\frac{0.36p\, d}{n} + \frac{\tan\frac{a}{2} l^2}{t} + 0.6 l \tan\frac{180}{n} \right). \tag{6}$$

The first expression in the bracket represents the quantity of work necessary for cutting through the hole. The second one stands for the quantity of work required for ripping, while the third one represents the edge bending.

The comparison of individual expressions is conducted with the use of a very simple but less precise method with the intention to exclude the least important elements. It is assumed, that individual symbols in the expressions for quantities of work occur most often in the following orders (see Tab. 2):

Tab. 2 Quantities order

Desig.	Title	Order		Desig.	Title	Order	
d	Diameter of projectile tip	Units	1	tan *a*	Projectile vertex angle	Tenths	0.1
n	Number of rippings	Tens	10	*p*	Ludolf's number	Units	1
l	Active length of projectile	Tens	10	0.36	Constant	Tenths	0.1
t	Thickness of plate	Units	1	0.6	Constant	Tenths	0.1

Cutting through the hole: $\frac{0.36p\, d}{n} = \frac{0.111}{10} = 0.01$

Ripping the edges: $\frac{\tan\frac{a}{2} l^2}{t} = \frac{0.1\times 10^2}{1} = 10$

Bending the edges: $0.6 l \tan\frac{180}{n} = 0.1\times 10\times 0.1 = 0.1$.

This first approximation as well as experimental data listed in [1] and [2] confirm that the quantity of work performed by the projectile during the initial cutting through the material does not exceed 1% in any monitored case and therefore it can be entirely neglected.

The ratio of the quantity of work done by the projectile during ripping the edges of the forming hole plays a dominant role in all the cases.

The quantity of work necessary for bending the ripped edges differs in dependence on the thickness of the plate. In the case of smaller thicknesses, its value is neglectable. However, at thicknesses around 5 mm, this ratio reaches 10 % and therefore is not neglectable. It is necessary to recall, that the principle of mechanical

erosion begins to change in the case of these materials. Hence, the proposed theory gradually runs out and does not suit for thicknesses over 5 mm at all.
While deducing the relationship between the extent of the primary damage ***a*** and other factors, it is crucial to go from the equality of the kinetic energy decrease ΔE_k of a projectile coming through an obstacle and the quantity of work, which is performed by such projectile $A_c = \Delta E_k$.

The kinetic energy decrease is expressed by equation:

$$\Delta E = E_{ko} - E_{k1} = \frac{1}{2} m v_o^2 - \frac{1}{2} m v_1^2 = \frac{1}{2} m \left(v_o^2 - v_1^2 \right) \tag{7}$$

Considering just the quantity of work necessary to rip the edges of the hole, the overall quantity of work done by the projectile during the penetration of material is expressed by equation:

$$A_c = A_r = \frac{1}{2} n t s \tan \frac{a}{2} l^2 . \tag{8}$$

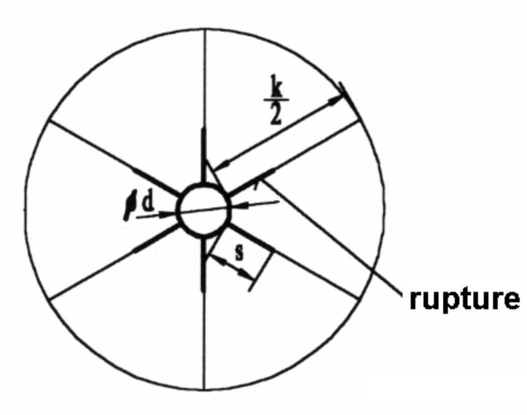

Fig. 3 The overall geometry of the hole

After the overall adjustment made in compliance with Fig 3, it is possible to express the general relation between the overall primary damage and the factors, on which this damage depends:

$$a = \sqrt{\frac{4m \tan \frac{a}{2} \left(v_0^2 - v_1^2 \right)}{n t s} + d} . \tag{9}$$

From the equation (9) we can conclude, that these factors (beside the projectile kinetic energy decrease) include most of all the projectile geometry and mass as well as the geometry of the sample and its material rigidity.

However, for practical use, the equation (9) is too complicated, since it demands quite a big amount of input data. In doing so, especially the information about the projectile velocity before and after the penetration are not available, much like the number of rippings *n*, which is dependent on the characteristic of the given material. Though, for the actual type of projectile, it is possible to convert this equation into a simpler form by introducing a linear relationship between the kinetic energy decrease and the thickness of the material together with an exponential relationship between the number of rippings and the thickness into (9) – see equations (13) and (14). A detailed procedure of the modification of equation (9) to a form (10) is mentioned in resource [1] and [7]. The equation will then get this form:

$$a = \sqrt{\frac{53.532 t^{0.19}}{s}\left(612 + \frac{1}{t}\right)} + d \ . \tag{10}$$

Here it is necessary to substitute the length proportions in meters and the tension s in pascals. This equation is usable for thin dural plates of a material strength between 300 and 450 MPa and a 7.62 mm projectile of a mass $m = 0.008$ kg and a mean vertex angle $\alpha = 33°$.

By introducing a particular material, e.g. dural of a rigidity of 440MPa, it is further possible to simplify it into a form

$$a = 3.48\ 10^{-4} \sqrt{t^{0.19}\left(612 + \frac{1}{t}\right)} + d \ , \tag{11}$$

which would be able to be exploited for automated aircraft vulnerability calculations. The equation (11) can also be expressed in a general way

$$a = x \sqrt{t^{y}\left(z + \frac{1}{t}\right)}, \tag{12}$$

where x, y, z are material characteristics gathered from an experiment, which also involve the projectile peak diameter d. With this modification, along with a relatively short range of laboratory work, it is possible to achieve a formula, which enables us to determine the actual extent of the primary damage of the aircraft skin with a sufficient accuracy. On the basis of an analysis made in [2], it is also possible to use it for calculation of a primary damage caused by projectiles of calibre 12.7 mm.

3. Experiment

The experimental work, which was carried out as a part of solution of this problem pursued two basic aims:

- Determine mutual relationships between some of the parameters, which influence the extent of primary damage and thus make it possible to determine final formulas that could be exploited in a practical way.
- Compare the experimental outcomes with the values of primary damage obtained from the calculation model.

Within the frame of experimental work, live firing of calibres 7.62 and 12.7 mm onto the samples of the proportions of 120 × 200 mm was conducted. The samples were made of dural D16AT and D16Tč of thicknesses 0.6, 1.2, 1.7, 2.5 and 5 mm. Each set consisted of three samples. The relatively small number of samples was limited by the number of allotted ammunition and by a relatively high price, which was necessary to pay for the conducted live fire experiment [8]. Though, in this case the accuracy of solution was not distinctively impaired by the limited number of samples.

During the experiment, the projectile velocity before and after penetration was registered by optoelectronic means. On each sample, the extent of primary damage was ascertained as well as the number of edge-rippings as a result of the projectile penetration. It was demonstrated, that from the observed parameters point of view, the differences between the tested materials D16AT and D16Tč are insignificant. Hence, a joint exponential relationship between the number of rippings and the thickness of material was assessed for both types of material and for the calibre 7.62 mm:

$$n = 2.55\, t^{-0.19}\,. \tag{13}$$

A linear relationship between the decrement of the square of velocities and the thickness of material was assessed subsequently:

$$\Delta\left(v^2\right) = 8.68\, 10^6\;\, t + 14182\,. \tag{14}$$

Both of these relationships express the relation between each of the parameters with minimum deviations.

Both of these formulas were used for the already mentioned modification of the equation (10). At the same time, a graphic relationship between the material thickness and the extent of the primary damage was assessed on the basis of achieved results. Such relationship demonstrates a good match between the experimental measurings and the values obtained from the derived formulas.

4. Conclusion

The contribution analyses a theory of determination of the extent of primary damage caused to aircraft skin by small calibre projectiles (i.e. 7.62 and 12.7 mm). On the basis of experimentally obtained data, the general formulas are concretized for the most common types of material, i.e. above all for D16 AT and D16 Tč durals.

The results of the solution are processed into a diagram that can be seen on the Fig. 4, from which it is evident, that despite some deviations, the match between experimental and calculated data is acceptable. In this regard, it is possible to use the derived equations for the automated calculations of primary damage in full. The increase in the extent of the damage towards small thicknesses of the material is logic, since the experiments imply, that the smaller the thickness of material, the larger number of edge-rippings and therefore the bigger extent of the primary damage. However, in praxis, it is not possible to count on the fact, that skin materials of thicknesses smaller than 1 mm would be used on a combat aircraft. For that reason, this area is useless for practical usage. The right side of the diagram can be accepted up to the thickness, which do not exceed t = 5 mm. Considering thicker materials, where the penetrating projectile causes a significant plastic deformation, also the elastic component of the deformation is tangible. In such case, both the theoretical solution and practical evaluation of the experimental data demands an entirely different approach. That is after the penetration of a thicker material, a situation where the created hole is smaller than the projectile diameter could occur. This fact is respected just partly by the proposed mathematical model. Therefore, it is not appropriate to use it for greater thicknesses without further experimental verification.

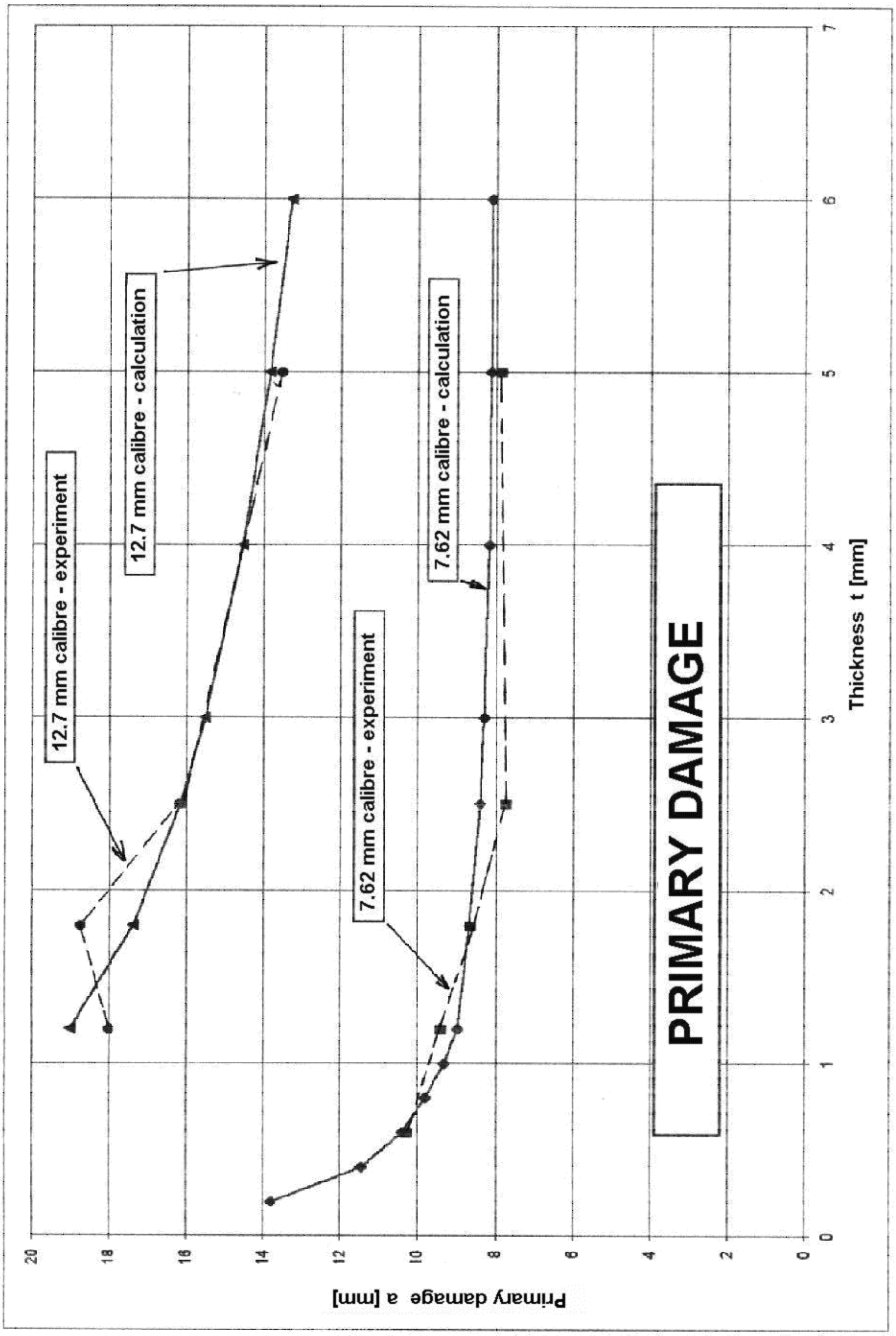

Fig. 4 Primary damage diagram

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