Journal of KONES Powertrain and Transport, Vol. 19, No. 2 2012

ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1137924

MODIFIED HAGG & SANKEY METHOD TO ESTIMATE THE BALLISTIC BEHAVIOUR OF LIGHTWEIGHT METAL/COMPOSITE/CERAMIC ARMOUR AND A FUSELAGE SKIN OF AN AIRCRAFT

Sławomir Klimaszewski, Marta Woch

Air Force Institute of Technology
Division for Reliability & Safety of Aeronautical Systems
Księcia Bolesława Street 6, 01-494 Warsaw, Poland
tel.: +48 22 685 10 31, +48 22 685 10 67, fax: +48 22 836 44 71
e-mail: slawomir.klimaszewski@itwl.pl, marta.woch@itwl.pl

Abstract

Hagg & Sankey method assesses the functionality of containment rings, which prevent perforation of an aircraft's elements from turbine engine disc fragments after disc burst. However, the method assumption was based on studies of mechanism of destruction of ballistic shields made of among others ceramics, by small arms bullets. The hard ceramic facing of the ballistic shield blunts the projectile and breaks up the projectile's hard core used for armour piercing. As an impact result, a conoid of finely pulverized ceramic dust is formed, absorbing energy in the formation process. The dust, containing the remnants of the projectile's energy hits the backing, but is now spread over a larger area. With backings made of fibre, energy is absorbed in stretching, breaking and delamination. With backings made of ductile metal, energy is absorbed in elastic deformation. Modification of the method consisted of taking into account the stratification of the ceramic-metal composite and the occurrence of an aircraft stiffened skin, in order to better assess the effectiveness of ballistic shields. The concept of estimating the resistance was based on the described destruction mechanism, where the object of analysis is a metal containment ring with an additional ceramic protective ballistic shield. A comparison of two scenarios- with and without an additional 2 mm aluminum alloy skin was taken into account. For this particular scenario, results were sufficient for both of the two analyzed endurance criteria.

Keywords: *reliability, ballistic shield, bullets perforation*

1. Introduction

The aim of this study was to modify the method of Hagg and Sankey (H & S hereafter) in order to estimate the ballistic behaviour of the composite/ceramic or metal-ceramic lightweight ballistic armour and an aluminum stiffened fuselage skin of an aircraft.

The modified method to estimate the ballistic behaviour of lightweight metal/composite/ ceramic armour and a fuselage skin of an aircraft is based on the Presley study [1] in particular. The method presented in that report assesses the functionality of containment rings, which prevent perforation of an aircraft's *elements from turbine engine disc fragments after disc burst*. However, the assumptions of the method were based on studies [2] of ballistic shields destruction mechanisms by small arms bullets.

Detention rushing turbine disc fragments inside the containment ring prevents further damage of the aircraft elements and systems. A containment ring can be made of high-strength metal alloys or composite materials. The additional inner layer is made of ceramic panels, bonded to the outer ring with epoxy adhesive, which improve the capture of fragments of the disintegrating engine characteristic. The use of ceramics for that purpose allows cover weight reduction due to extremely high strength properties.

The containment of a disk burst requires prevention of the containment ring perforation and also absorbs the substantial translational kinetic energy of the disk fragments. The energy absorption mechanism dependents on the characteristics of the fragments and of the containment system.

The destruction process of a metal containment by a disintegrating turbine disc was observed. Impact Energy of scattered turbine disc remains is dissipated during subsequent events. The first stage, shown on Fig. 1, is the initial inelastic impact of the fragment with the ring. As a result of the impact of the turbine disc fragment on the containment ring regions are deformed due to compression and shear appeared. Noncontainment in this stage results in the perforation of the ring in a local area (1st stage failure mode). Scattered remains pierce a hole in the containment ring and carry with them a shear plug. For the composite rings, rotating fragment cause tearing and cutting of fibbers in the local area of impact. The perforation is the result of insufficient protection.

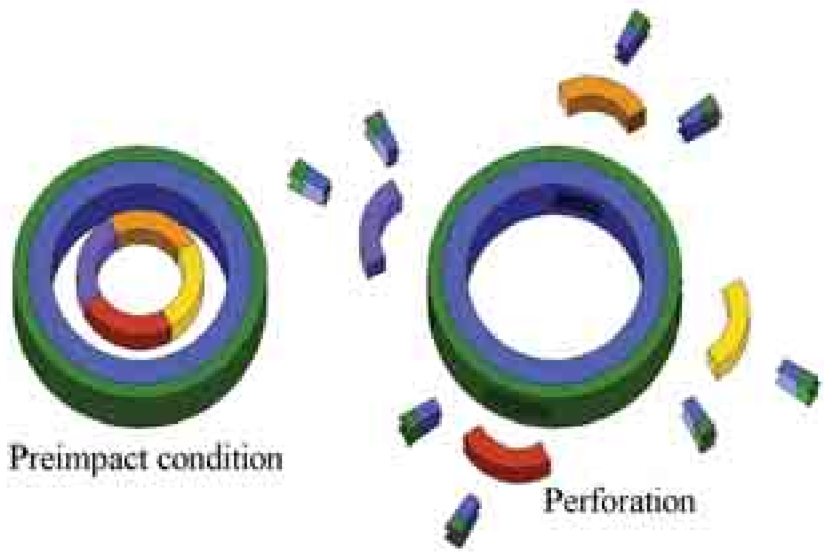

Fig. 1. First stage failure mode - perforation

In the case where the ring will not be perforated (first stage failure mode), the remaining energy causes the inelastic strain and ring's deformation. If the remaining energy of rushing turbine disc remains will not be squandered, tensile failure will occur. Tensile failure of the ring is also the result of inadequate protection.

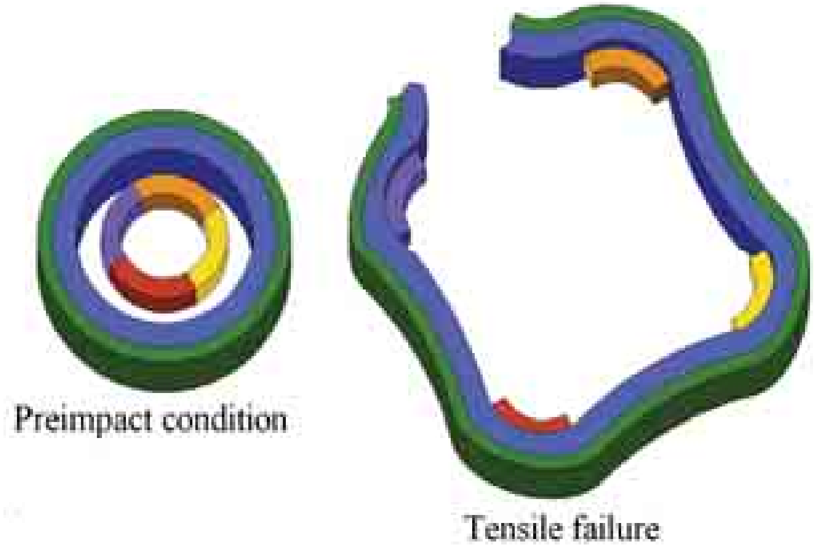

Fig. 2. Second stage failure mode – tensile failure

The failure mechanism of destruction of ballistic shields made of, among others, ceramics by small arms bullets, described in [2] by Florence, is shown in Fig. 3. The hard ceramic facing of the ballistic shield blunts the projectile and breaks up the projectile's hard core used for armour piercing. As an impact result, a conoid of finely pulverized ceramic layer is formed, absorbing energy in the formation process. The dust, containing the remnants of the projectile's energy hits the backing, but is now spread over a larger area. With backings made of fibre, energy is absorbed in stretching, breaking and delamination. With backings made of ductile metal, energy is absorbed in elastic deformation.

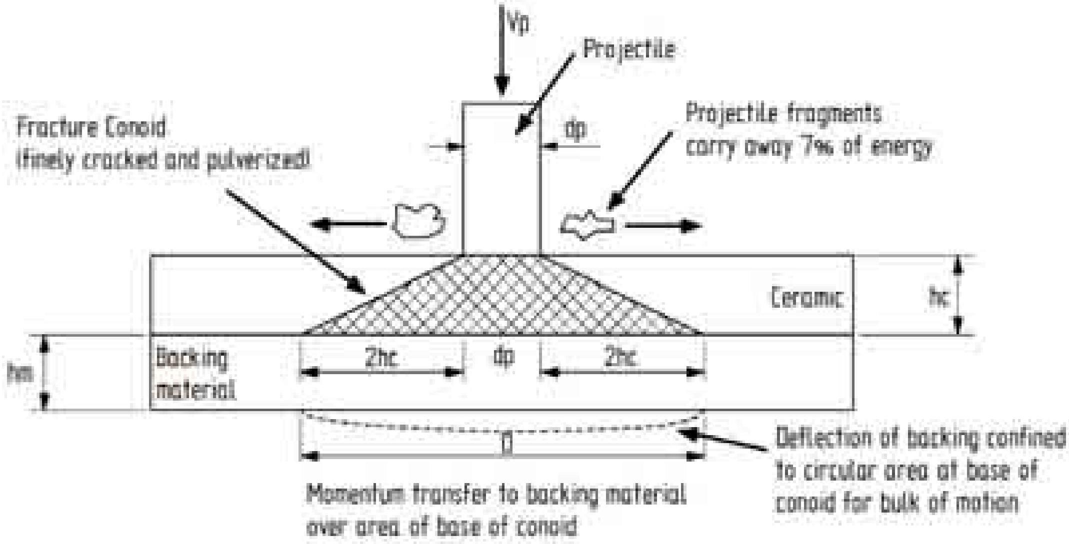

Fig. 3. Florence's observation on projectile – armour interaction

2. Description of the ballistic containment criteria - the method of H&S (Hagg & Sankey)

The concept of estimating the resistance was based on the above-described mechanism of destruction [1, 2], where the object of analysis is a metal ring with an additional protective ballistic shield made of ceramic materials. The following equations represent the energy criterion for assessing whether a ballistic shield is sufficiently resistant.

The dependence (1) represents the energy change for stage 1:

$$\Delta E_1 = \frac{1}{2} M_1 V_1^2 \left(1 - \frac{M_1}{M_1 + M_2} \right), \tag{1}$$

where:
ΔE_1 – 1^{st} stage energy,
M_1 – disc fragment mass,
V_1 – disc fragment translational velocity,
M_2 – target mass.

Containment criterion for the first stage is:

$$\Delta E_1 \le AT\varepsilon_c \sigma_d + K\tau_d PT^2 + V\varepsilon_\theta \sigma_f , \tag{2}$$

where:
A – contact area of disc fragment on ring,
T – ring thickness,
ε_c – shear plug compression strain,

σ_d – dynamic flow stress,
K – empirical coefficient,
τ_d – dynamic shear stress,
P – shear plug perimeter,
V – volume of ceramic fracture conoid,
ε_θ – equivalent ceramic strain,
σ_f – equivalent ceramic plastic flow stress.

Energy change for 2nd stage:

$$\Delta E_2 = \frac{1}{2} M_1 V_1^2 \frac{M_1}{M_1 + M_2}, \tag{3}$$

where:
ΔE_2 – 2nd stage energy.

Containment criterion for the second stage is:

$$\Delta E_2 \leq Q \sigma_d \varepsilon_t, \tag{4}$$

where:
Q – active volume subjected to tensile strain,
ε_t – average tensile strain in active volume subjected to tensile strain.

In order to describe the geometry some equations should be written:

$$A = L(h + 4t_c), \tag{5}$$

where:
L – disc fragment arc length contacting ring,
h – disc fragment rim width,
t_c – ceramic thickness,

$$P = 2(L + h + 4t_c), \tag{6}$$

$$K \cdot \tau_d = 0.27 \sigma_d, \tag{7}$$

$$V = L \cdot t_c (h + 2t_c), \tag{8}$$

$$Q = L \cdot T(h + 4t_c + 2a), \tag{9}$$

where:
Q – active volume subjected to tensile strain,
a – plastic hinge length,

$$M_2 = M_{21} + M_{22}, \tag{10}$$

$$M_{21} = V \cdot \rho_c + L(h + 4t_c)\rho_m, \tag{11}$$

where:
ρ_c – ceramic density,
ρ_m – metal ring density,

$$M_{22} = \frac{k^2}{a^2} L \cdot 2a \cdot T \cdot \rho_m, \tag{12}$$

where:
k – radius of gyration about plastic hinge.

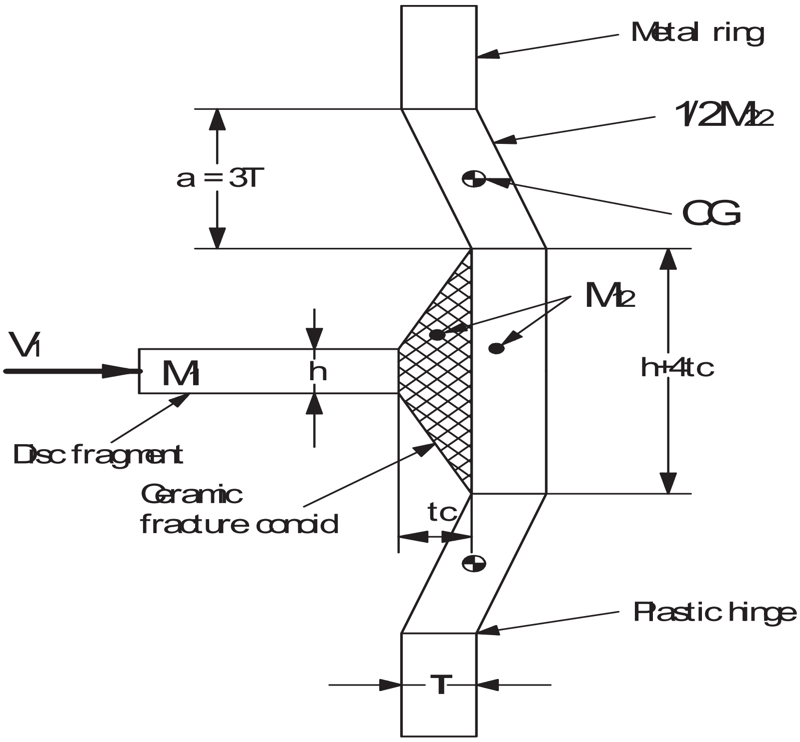

Fig. 4. Incorporation of effect of ceramic into method of H & S [1]

Verification of protective capacity of the first stage containment is based on a calculation of the energy dissipated in the initial impact compared to the energy required to perforate the ring. The inelastic compression of a shear plug and the energy to shear the plug out of the ring are involved in the perforation energy.

In the above works it was noted, that during ballistic shield perforation ceramic fracture a conoid is being formed. It is used as the projectile energy dissipating area, as well as transfers this energy to the guarded surface (protective ring, armour, etc.). Fig. 4 shows underlying assumptions.

Overall dimensions have been proposed for the hypothesis presented in literature [2]. Modifications have been made to the calculation method [1]. The effect of ceramic layer was included in these energy calculations. Mass of the target M_2 has been increased by the ceramic fracture conoid mass resulting in an energy increase ΔE_1 in equation (1). The second modification of the equations was to increase the size of the of the shear plug to equal the area at the base of the fracture conoid. The modification resulted in an increase of parameters A - contact area of disc fragment on ring, and P - shear plug perimeter in the formula (2) as well as the value of energy absorbed by the containment ring. The third modification was to account in the formulas for the energy required for the formation of the ceramic fracture conoid. This energy is similar to and additive to the compressive energy involved in inelastic compression of the shear plug.

3. Modification of the method H & S

Modification of the method takes into account:
- the stratification of the ceramic-metal composite,
- the occurrence of an aircraft stiffened skin,

in order to better assess the effectiveness of ballistic shields.

Figure 5 visually shows the modifications adopted.

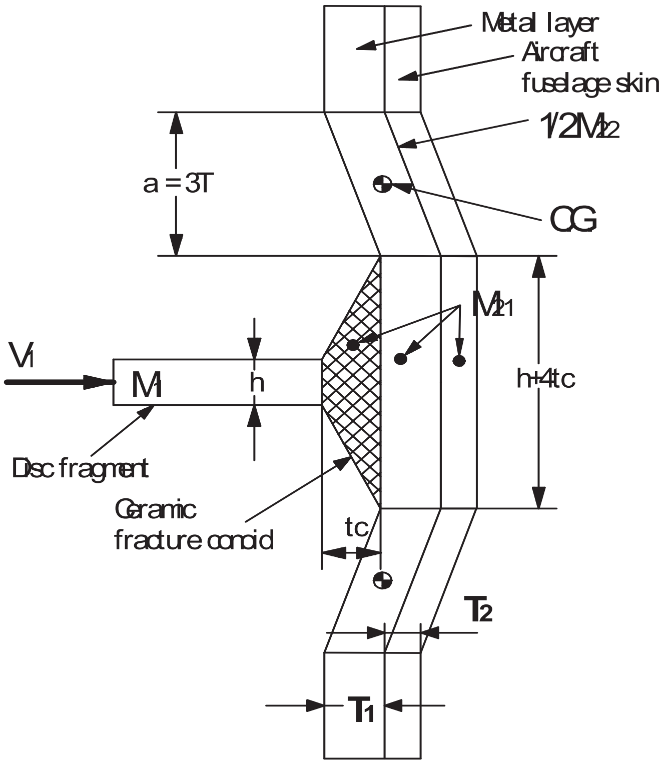

Fig. 5. Modified method H & S scheme

The concept of estimating the resistance was based on the described destruction mechanism [1, 2], where the object of analysis is a metal containment ring with an additional ceramic protective ballistic shield. Equations (1), (2), (3) and (4) represent the energy criterion for assessing whether a ballistic shield is sufficiently resistant.

Introducing stiffened fuselage skin of an aircraft modified the formulas for the M_{21} (13) and M_{22} (14). The equations also included variation of the cover thickness T (15):

$$M_{21} = V\rho_c + L(h+4t_c)(T_1\rho_{m1} + T_2\rho_{m2}), \tag{13}$$

$$M_{22} = \frac{k^2}{a^2} L \cdot 2a(T_1\rho_{m1} + T_2\rho_{m2}), \tag{14}$$

$$T = (T_1 + T_2), \tag{15}$$

where:
T_1 – aircraft fuselage skin thickness,
T_2 – ballistic shield thickness,
ρ_{m1} – aircraft fuselage skin density,
ρ_{m2} – ballistic shield density.

4. Results

Corresponding calculations have been carried out in order to compare the results. The input data for the calculations presented in Tab. 1 were adopted mainly from literature [1].

For a no ballistic shield case, following results were obtained:

Energy change for 1st stage: $\Delta E_1 = \frac{1}{2} M_1 V_1^2 \left(1 - \frac{M_1}{M_1 + M_2}\right) = 668.1\,[J]$.

Tab. 1. The input data for calculations

Parameter		Value	Unit
M_1	bullet mass	0.00791	kg
V_1	bullet translational velocity	700	m/sec
T	ring thickness	0.002	m
ε_c	shear bullet compression strain	17	%
ε_t	average tensile strain in active volume subjected to tensile strain	24	%
σ_d	dynamic flow stress	175 000 000	Pa
ε_θ	equivalent ceramic strain	15	%
σ_f	equivalent ceramic plastic flow stress	344 740 000	Pa
h	bullet diameter	0.00762	m
t_c	ceramic thickness	0.002	m
L	disc fragment arc length contacting ring	0.01562	m
k	radius of gyration about plastic hinge	0.006	m
ρ_c	ceramic density	5000	kg/m^3
ρ_m	metal ring density	2720	kg/m^3

Containment criterion for the first stage was $AT\varepsilon_c\sigma_d + K\tau_d PT^2 + V\varepsilon_\theta\sigma_f = 3340.7\,[\mathrm{J}]$.

Energy change for 2nd stage: $\Delta E_2 = \frac{1}{2}M_1V_1^2\frac{M_1}{M_1+M_2} = 1269.8\,[\mathrm{J}]$.

Containment criterion for the second stage was $Q\sigma_d\varepsilon_t = 3624.0\,[\mathrm{J}]$.

After taking into account the presence of 2 mm aluminum aircraft skin with a density of 2720 kg/m^3 calculations were as follows:

Energy change for 1st stage: $\Delta E_1 = \frac{1}{2}M_1V_1^2\left(1-\frac{M_1}{M_1+M_2}\right) = 793.9\,[\mathrm{J}]$.

Containment criterion for the first stage was $AT\varepsilon_c\sigma_d + K\tau_d PT^2 + V\varepsilon_\theta\sigma_f = 4827.8\,[\mathrm{J}]$.

Energy change for 2nd stage: $\Delta E_2 = \frac{1}{2}M_1V_1^2\frac{M_1}{M_1+M_2} = 1144.0\,[\mathrm{J}]$.

Containment criterion for the second stage was $Q\sigma_d\varepsilon_t = 10396.9\,[\mathrm{J}]$.

The results have shown that mutual contribution of both the armour and the stiffened aircraft skin influences the ballistic performance of the specific armour structure.

5. Conclusions

Based on a comparison of calculated results, the presence of a 2 mm aircraft fuselage skin significantly affects the obtained numerical results. The first containment criterion for assessing the strength increased by 44.5% (from 3340.7 J to 4827.8 J) with a slight increase of the energy needed to perforate the coverage (the value has changed by 18.8%, from 668.1 J to 793.9 J). There was a significant increase of strength in the second criterion (by 186.9%, from 3624.0 J to 10396.9 J) with decrease of the energy needed to break the coverage by 9.9% (from 1269.8 J to 1144.0 J).

References

[1] Presley, K. L., *Assessment of an Advanced Containment System,* DOT/FAA/AR-97/82. February 1999.
[2] Florence, A. L., *Interaction of Projectiles and Composite Armor*, Part II, AMMRC CR 69-15, NTIS AD 698543, August 1969.
[3] Hagg, A. C., Sankey, G. O. *The Containment of Disk Burst Fragments by Cylindrical Shells Journal of Engineering for Power*, Trans. ASME, Paper No. 73-WAPwr-2.
[4] Lundin, S. J., *Engine Debris Fuselage Penetration Testing Phase II*, DOT/FAA/AR-01/27,II. September 2002.