Explosive technologies for testing composite constructions of aircraft for strength to heat-power non-stationary loading

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Abstract. Sets of explosive and heating devices for experimental study of strength of composite constructions of aircraft against complex thermal and mechanical action of radiation and particles fluxes of different physical nature are considered. Two new explosive devices for generating low-pulse loads of microsecond duration are proposed. Devices based on thermoelectric heating elements, conductive plates and pyrotechnic compositions applied to the surface of the tested structure have been developed to simulate thermal action of radiation and particles fluxes. A universal test bench using these sets of devices has been developed. This test bench allows testing the strength of composite constructions to the joint action of thermal and mechanical loads having given space-time distributions.

1 Introduction

The intensive development of sources of radiations and particles having various physical nature requires the design of flight vehicle (FV) operating under the conditions of high energy density fluxes. Constructive means of protection of FV based on heterogeneous porous materials and new generation of protecting coatings are developed no less intensively. The use of modern protective heterogeneous packages for FV constructions requires experimental confirmation of their effectiveness.

An experimental study of the aftereffects of the thermal and mechanical actions of radiation and particle flows (RPF) on constructive FV elements by direct irradiation of them is not possible because there are no powerful laboratory sources of this flows capable of generating the necessary energy densities on surfaces with dimensions of the order of several meters. Therefore, at the present stage, the main method of studying the RPF effects is testing of full-scale VF constructions for non-stationary loading by explosive and heating devices to simulate thermal and mechanical loads modeling RPF actions [1, 2].

The development of a set of such devices is relevant and of great practical importance [2–5]. However, there is still no set of devices that fully satisfy the requirements of practice. In particular, low pulse submicrosecond load generators are required to provide si-

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multaneous pressure loading the surface of the tested structure. In addition, there are only few devices for modeling the joint thermal and mechanical RPF action. But there are many cases realized during flight, when the FV is subjected to joint multiple thermal and mechanical RPF action, in which its complex character is impotent [5, 6]. The essence of the complexity [6] is that the result of a joint (it's not necessarily simultaneous) action (temperature increase, thermal ablation of material, accumulation of plastic deformations and microdamage, cracking and stratification) is not determined by simply summation of the result of each factor and the principle of superposition of damage is not true. The mutual influence of heating and mechanical destruction is one of the cases of realization of complex RPF action.

An approach based on the joint application of heating devices and explosive generation of mechanical loads is used for strength tests for complex thermal and mechanical RPF action. In turn, the joint use of devices requires the development of universal test benches. The universality of the test bench is understood as: dual purpose (suitable for verification of individual devices and for testing); multifunctionality (applicable for different combinations of RPF actions); wide region of use (in addition to RPF actions, it can be used for any transient effects of heat and power loads that have a complex space-time profiles). Versatility is achieved by modularity of individual modeling devices and their interchangeability in the test bench.

The development of a new set of RPF modeling devices and a universal bench for testing FV constructions for strength to the complex RPF action is the main goal of this work.

2 Thermal RPF action

Gas fluxes (for example, aerodynamic flows or convective and radiant flows from jet flowing from combustion chambers of reactive engines) are an operational sources of thermal action on FV constructions [7]. As a rule, flight heat flows are close to quasi-stationary, and a slowly changing temperature profile is established in the constructions. In addition, aircraft can be subjected to impulse actions of various types of RPF [6].

Some practically important (these are important for the case of thermal action) types of RPF actions and their corresponding energy absorption regimes [6] are given in table 1. It should be noted that, of course, not all possible combinations of the considered types of RPF actions are realized in practice for FV. However, a number of practically important combinations are known when the complex RPF action takes place. Influences of volumetric absorbed radiation (VAR) is the most dangerous for FV construction [2, 5, 6].

The complex action of the VAR, having a hard and soft parts in its spectrum, turns out to be the most noticeable: heating with hard radiation changes the thermodynamic and mechanical characteristics of the material, which affects the formation of a thermomechanical impulse, and the soft part leads to ablation of the material (thermal action) and the formation of the evaporative part of the mechanical impulse. Therefore, even the conditional separation of thermal and mechanical RPF actions is of little use in this case.

Thermal action leads to different temperature profiles depending on RPF parameters and properties of composite materials (CM) (in particular, it depends on free path length of particles in the absorbing material and its temperature conductivity), as well as the thickness of the construction.

At least, when studying the complex thermal and mechanical action, it becomes necessary to create the following set of its thermal states in the thin-walled FV construction before generating a mechanical impulse:

- near-surface heating when the material is warmed to a certain thickness and the rear side of the structure remains substantially cold;

Table 1. RPF influence and corresponding absorption regime

Type of RPF	Spatial regime	Temporary regime
radio radiation of high frequency	volume absorption	gradual absorption
monochromatic radiation of optical range	superficial absorption	gradual absorption
light radiation of a powerful explosion	superficial absorption	gradual absorption
soft X-rays of a powerful explosion or laser fusion reactor	superficial absorption	instantaneous absorption
hard X-rays of a powerful explosion	volume absorption	instantaneous absorption
γ-radiation of powerful explosion or laser fusion reactor	volume absorption	instantaneous absorption
electrons of radiation belts	volume absorption	gradual absorption
neutrons of a powerful explosion or laser fusion reactor	volume absorption	instantaneous absorption
nuclear reactor neutrons	volume absorption	gradual absorption
heavy accelerator ions	volume absorption	instantaneous absorption

- volumetric non-uniform heating when the CM is warmed over the entire thickness of the structure, but with a significant difference in temperatures of the irradiated and rear surfaces;
- uniform heating when the CM temperature over the thickness of the construction is constant.

Near-surface heating is characteristic when CM is irradiated to monochromatic radiation, light pulse of powerful explosion or aerodynamic flows in developed evaporation regime [7, 8]. In this case, the temperature near the ablating (evaporating or sublimating) surface is 1000–2000°C.

Volumetric non-uniform heating occurs when irradiated VAR has photon energy of more than 20 keV and low levels of surface density of energy (mechanical action prevails at high levels of energy, that accompanied by CM destruction). Non-uniform heating can be caused by influence of monochromatic radiation, light impulse, gamma-neutron radiation and aerodynamic flows in thermal conductivity regime. In this case, the temperature varies in the range 100–1000°C. Non-uniform heating is also realized for nozzles made of carbon-carbon CM of operating rocket engines [9]. The temperatures of the nozzle materials are 1000–3000°C.

3 Mechanical RPF action

An approach based on the joint application of heating devices and explosive generation of mechanical loads is used for strength tests for complex thermal and mechanical RPF action. Explosive technologies for reproducing the mechanical RPF action are quite developed and are widely used for testing of construction from CM [1–5, 10]. Therefore, we consider only two relatively new explosive devices from the used set.

As already noted, it is necessary to develop low-pulse devices for modeling the mechanical RPF action. Tape charge [11] and guided initiation charge [12] are the most promising of explosive devices for generating low-pulse loads of microsecond duration.

The tape charge is made of explosive (EX) tapes placed on round tubes (see figure 1). The tubes are equally spaced from the surface of the object to be loaded. The multi-point beam

Figure 1. Tape explosive charge

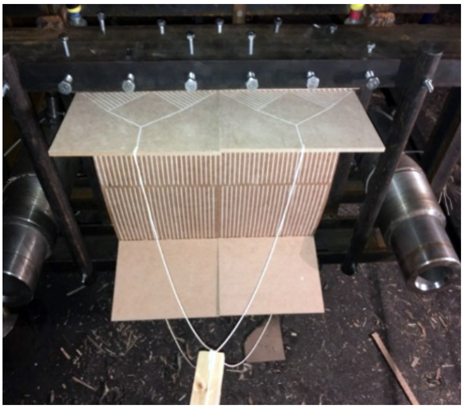

Figure 2. Controlled initiation explosive charge

initiation system from the end of the EX tapes is used to provide the simultaneous applying of the load.

The charge having controlled initiation is made in the form of a thin (≤ 3 mm) shell of hard cardboard with milled channels filled with plastic EX (see figure 2). Placement of EX in channels gives a number of advantages compared to other methods of localizing EX (for example, a continuous layer or sectors on a porous substrate). Controlled initiation is implemented by method adopted from technology of generation of megabar level pressures [13].

The set [2], completed with these new devices, is more capable and is used for testing thin-walled FV constructions for strength to RPF of different physical nature.

4 Complex RPF action on flat packages from CM

Several methods of creating the thermal state of the barrier (using a contact conductive plate, sheet pyrotechnic charges, microwave radiation, etc.) in combination with various types of explosive generators of mechanical loads are used in modeling the complex action on elements of the aircraft structure. The choice of the set of modeling devices depends on the types and combinations of the acting RPF and the characteristics of the test objects.

The temperature distribution in the thin-walled composite plate must be measured to verify the heating devices reproducing the thermal RPF action. Contactless method of temperature profile measurement in structural materials [14] is used. Method consists in formation of channels of different depth in investigated sample. Temperature scanning is carried out through prepared channels by a system of remote infrared pyrometers. Temperature profile in sample is determined by measuring pyrometric information. In this work, temperature measurement is carried out by a non-contact portable pyrometer Raytek Raynger MX.

The non-uniform temperature profile in the flat sample is created by surface heating with the help of a contact plate with current, which varies according to a given law to provide the required temperature distribution in the near-surface layer of the plate. The test scheme is shown in figure 3.

Reproduction of preset flux $q(t)$ of absorbed RPF energy is provided by control of current change in electric circuit. Preliminary estimation of dependence $I = I(t)$ can be made by relation

$$I(t) = \sqrt{\frac{q(t) \cdot S}{\eta R}},$$

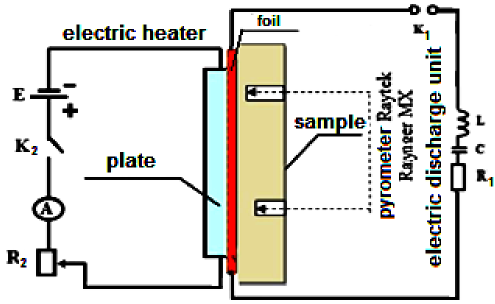

Figure 3. Scheme of testing plate

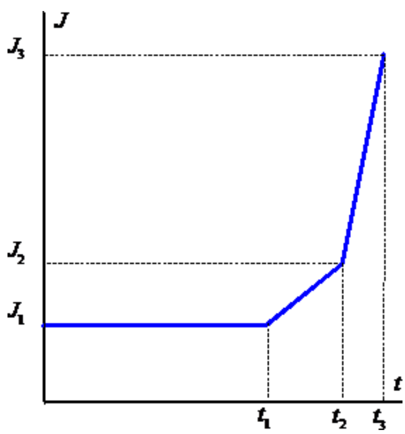

Figure 4. Current-Time Variant

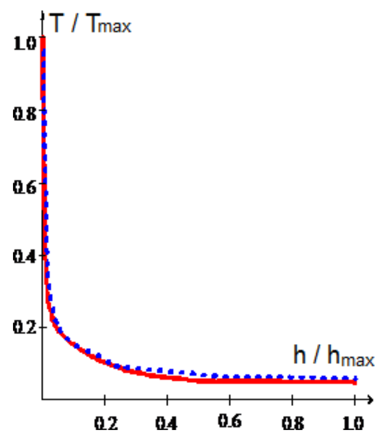

Figure 5. Temperature profile (dashed line is calculation profile at VAR absorption)

where S is heating area (cm^2); R—resistance of current-conducting layer (Ohm); $q(t)$ is density of RPF flux (W/cm^2); η is experimentally determined coefficient of energy transfer from current-conducting layer to sample ($\eta < 1$). Then, the time dependence required to form a given spatial temperature profile is experimentally corrected.

One variation of current versus time is shown in figure 4. Tests showed that the proposed method allows reproducing the required temperature profiles with an error of not more than 15%. Figure 5 shows the comparison of the obtained temperature profile with the one given in the case of simulated RPF absorption.

The considered heating method is applicable for creating monotonically descending temperature profiles from the irradiation surface. In general, combined heating from various energy sources can be used to reproduce more complex temperature distributions in multilayer composite packets.

A version of the combined heating schema from the conductive layer and high-frequency radiation (extremely high-frequency radiation with a wavelength of 1–10 mm) is presented in figure 6.

The result of heating the double-layer sample from the CM according to this scheme is shown in figure 7. It can be seen that the total profile is non-monotonic and experiences a jump at the boundary of the layers, that is characteristic for influence of the a rigid VAR

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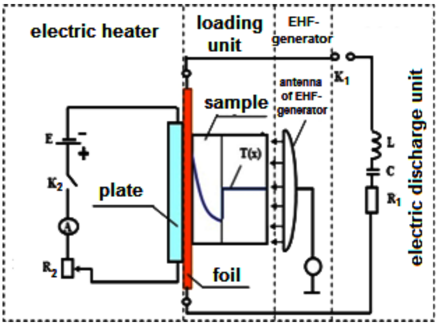

Figure 6. Sample combined heating experiment scheme

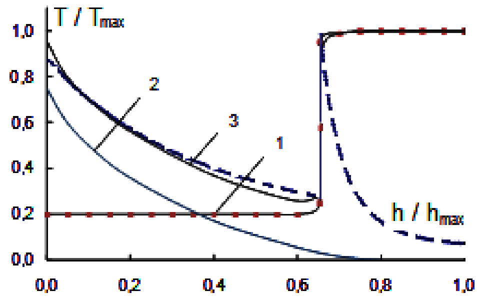

Figure 7. Temperature profiles in the case of combined heating of a two-layer composite plate: 1 is EHF-heating; 2 is electric heating; 3 is total heating; dashed line is simulated profile

(a jump of energy release from the VAR occurs due to a sharp change in the cross sections of the interaction of radiation quants with matter [6]). The simulated temperature profile corresponding to VAR is less than the total profile from heating for the second layer. This means that the thermal action is overestimated compared to what occurs when RPF influence, but it goes to the safety margin of the designed construction.

When required temperature distribution is reached, samples are loaded with pressure pulse formed by the discharge of capacitor bank through metal foils shown in figures 3 and 6.

5 Complex RPF action on FV construction: universal test bench

Tests of full-scale constructive elements of the FV suggest the presence of powerful heating sources and explosive generators of mechanical loading. Equidistant-surface charge (ESC) [2] and charge with controlled initiation (CCI) [12] are the most convenient and suitable devices for modeling the complex RPF action. Thermoelectric heaters (TEH) and pyrotechnic compositions applied to the surface of the tested structure are used to simulate thermal action. Devices that simulate RPF actions are located for joint operation on a universal test bench.

A variant of the universal test bench equipment is shown in figure 8 (it's side view). The tested thin-walled composite cylindrical construction (3) is suspended on a ballistic pendulum (1, 2). It is hermetically closed by two strong steel lids. The construction is heated from one side as a result of combustion of the pyrotechnic composition (5). Change of construction temperature is measured by industrial optical pyrometer (11) and is continuously recorded. Internal pressure (the internal pressure value is measured by the piezoelectric sensor, and is also calculated by changing the readings of the strain gauges) is created simultaneously with heating by burning a bundle of a pyrotechnic composition suspended inside the construction. The stopper (6) opens at the moment of combustion completion (5), and the spring rotary mechanism (7) rotates the construction on the 180° to the position for which the heated part is opposite the explosive loading device of the CCI (4) located stationary. Detonation of device (4) occurs as soon as new position of structure is fixed by stopper (8). Circumferential and longitudinal non-stationary deformations at various points of the inner surface of the tested shell are measured using strain gauges (10) to diagnose the state of the loaded structure. Electric terminals of strain gauges are connected by means of sealed feed-through (9) which is also used for electric ignition of pyrotechnic composition inside construction.

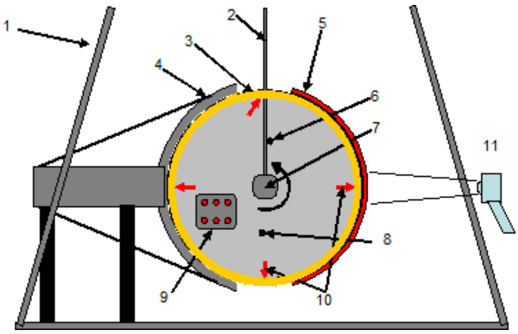

Figure 8. Bench scheme (side view): 1 is pendulum post (top hinge is not shown); 2 is pendulum suspension; 3 is test cylindrical shell with lids; 4 is explosive device (CCI or ESC) located on the stand; 5 is pyrotechnic composition or TEH; 6 is detachable stopper; 7 is spring rotary mechanism; 8 is non-detachable stopper; 9 is sealed feed-through; 10 is locations of strain gauges; 11 is optical pyrometer

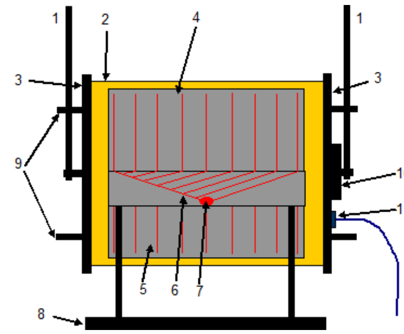

Figure 9. Bench scheme (front view): 1 is pendulum suspension; 2 is test cylindrical shell; 3 hermetic lids; 4 is explosive device of distributed impulse loading, upper part; 5 is explosive device, lower part; 6 is detonation wiring; 7 is initiation point; 8 is explosive loading device stand; 9 are stoppers; 10 is spring rotary mechanism; 11 is sealed feed-through

A view of the test bench from the front is shown in figure 9. Device of impulse loading (it is CCI in the described variant of equipment) is installed on post (8) and consists of upper (4) and lower (5) parts in the form of curved plates having milled channels filled with plastic explosive. Parts are united by detonation wiring (6) transmitting detonation from initiation point (7) to channels on parts (4), (5). Parts (4, 5, 6) are made by milling from hard cardboard.

The bench is original and significantly expands the possibilities for testing FV construction for joint thermal and mechanical RPF action. A distinctive feature and advantage of the bench is the control of reproducible parameters of thermal and mechanical actions during the tests. This is essential, since the stability of these parameters when using explosive and pyrotechnic devices in some cases is insufficient. In particular, control of mechanical action parameters is provided by using the pendulum method to measure the momentum of the force transmitted to the tested construction.

Previous developments were taken into account when creating a universal bench. A previously developed bench rocket engine with a rotation housing [2] was taken as the basis. But a fundamental change that expanded the possibilities of universalization of the bench was made. Previously, modeling devices moved over the tested construction when they were replaced. In the new variant, the tested construction is turned when the heating device simulating the thermal RPF action and flight heat flows is changed to an explosive device for modeling the mechanical RPF action. Rotation of the shell on the 180° provide combustion of the pyrotechnic composition layer (5, figure 8) away from the explosive loading device (4, figure 8), ensuring its preservation.

6 Conclusion

Methods and devices for modeling complex thermal and mechanical RPF action on flat packages from CM and full-scale (with loading area from 2 to 5 m^2) cylindrical composite constructions of FV are proposed and verified.

A universal test bench has been developed to study the strength of cylindrical composite constructions to the complex RPF action.

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