Ensuring Blast Resistance of Critically Important Buildings and Constructions in Case of Air Crash

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Abstract. Introduction. The paper is focused on improving blast resistance of critically important buildings and constructions exposed to a deflagration explosion due to an aircraft (A/C) crash in their vicinity, by improving methods of the explosion effects calculation. The main tasks include: 1. considering the physical processes that occur during an aircraft crash, which causes the formation of a highly explosive cloud; 2. quantifying the parameters affecting explosion loadings; 3. provide insights into modern procedures for calculating effects of a deflagration explosion caused by an A/C crash; 4. giving an example of calculating the loadings on a critically important building or construction in a crash deflagration explosion. Methodology and calculations. The article presents a methodology for calculating the maximum parameters of explosion loadings on buildings and constructions arising from aircraft crash situations. The calculations are performed with the help of author’s and generally accepted methods by the numerical method with the use of MatLab software complex. Results and discussion. As a result of calculations, the proposed methodology allows to obtain: the fuel mass values capable of forming highly explosive mixture; to choose the appropriate scenario for the development of an aircraft crash: an igneous ball or a deflagration explosion of a fuel-air mixture; to determine the time dependence of the fuel vapor concentration in the air; to evaluate the maximum apparent flame front speed; to determine the dynamic parameters of the fireball and the time dependences of the overpressure at points in the space adjacent to the explosion site; to build up a maximum pressure field created by this deflagration explosion; to obtain the explosion loading integral parameters: the maximum and minimum explosion overpressure, the compression phase pulse, the probability of destruction of buildings; to evaluate vibration loading on the building from a deflagration explosion. Conclusion. The methodology presented in the article can be used to calculate the loadings on buildings and structures during a deflagration explosion that occurs when an aircraft crash.

1. Introduction
Aircraft crashes, despite their low probability, pose a great danger to any facilities located near the aircraft crash site. This is due to the presence on board of any aircraft of a large amount of fuel in a liquid or gaseous state. The damage effects in an aircraft crash, in addition to the impact of a glider or engines, are the fire of the jet fuel spillage, heat loadings from an igneous ball, as well as loadings from a compression wave during a deflagration explosion of fuel vapor.
The loadings arising from an aircraft crash are not of particular interest for civilian facilities due to the low probability of such an event. However, when designing such critically important constructions as nuclear power plants (NPPs), it is necessary to determine the parameters of explosion loadings that occur when an aircraft crashes within the NPP site [1]. At the same time, the most conservative ideas about the development of an aircraft crash are used [2]. In this regard, they consider the crash within the site of a NPP of a large commercial aircraft such as Boeing-747, Airbus A-320 or Antonov An-124 [3, 4].

Such regulatory documents as RD 03-409-01 “Methodology for assessing the consequences of crash explosions of fuel-air mixtures” or RB G-05-039-96 “Guidelines for analyzing the danger of crash explosions and determining the parameters of their mechanical impact” use the TNT equivalent as the basis for calculating loadings from deflagration explosions, which significantly overestimates the calculated loadings [5–7]. Some aspects of crash deflagration explosions were considered in works [8–12], but they did not fully reveal the processes of formation of a fuel-air explosive cloud in the atmosphere and the effect of its explosion on the construction design of buildings and structures.

This article describes the basic principles and some research results of this problem. A large commercial aircraft — Boeing-747 is considered as a source of danger. The paper is aimed at improving blast resistance of critically important buildings and constructions exposed to a deflagration explosion due to an aircraft (A/C) crash in their vicinity, by improving methods of the explosion effects calculation. The main tasks include considering the physical processes that occur during an aircraft crash, which causes the formation of a highly explosive cloud; quantifying the parameters affecting explosion loadings; provide insights into modern procedures for calculating effects of a deflagration explosion caused by an A/C crash; giving an example of calculating the loadings on a critically important building or construction in a crash deflagration explosion.

2. Methodology and calculations
Let us consider the physical processes that occur during a plane crash, which causes the formation of a highly explosive cloud.

The following conditions are necessary for an explosion: fuel vapor formation with a combustible liquid, the mixing of the formed vapor with air in certain proportions, and the appearance of an ignition source.

When a plane crashes, the main source of fuel vapor is the heated parts of its engine. We assume that all the aircraft engine parts can be heated to an average of 460 °C. The engine weight of Boeing-747 is 4,300 kg. Then the total heat of one engine will allow evaporating no more than 1,520 kg of fuel. The alleged crashing aircraft has 4 engines. Therefore, when the plane crashes, the maximum amount of fuel capable of forming a fuel-air explosive cloud will be no more than \( M_f = 6,080 \) kg [6].

Some specialists use the amount of vapor that can be in an explosive state in the aircraft fuel tanks as the basis for calculating the potential explosive hazard of an A/C. Given that the total fuel tank capacity of a heavy commercial aircraft is about 300 m³, we obtain that no more than 100 kg of fuel can be involved in explosive combustion with this approach. However, in conservative calculations of the potential explosive hazard of an A/C crashing within a nuclear power plant, it is necessary to take into account the amount of vapor that can form when it evaporates from the red-hot parts of the engine. This amount of vapor is much greater than can be found in the empty fuel tanks of any A/C.

The ignition of the resulting cloud of explosive mixtures is possible from the hot parts of the same engine or from sparks that occur at the moment of the impact. For example, it is known that a crash or
a hard touchdown of an aircraft on soft ground is not always accompanied by deflagration and fuel explosion.

During the deflagration of the cloud formed, it creates an overpressure caused by the rapid heat release and combustion products, a fireball (area of heated combustion products) is formed, which rises quickly enough under the influence of the Archimede force. It should be noted here that there are two different concepts: “fireball”, which is an upward-moving mass of explosive combustion products, and “igneous ball”, which is a surface burning mass of re-enriched fuel mixture. In the first case, an explosion of an explosive mixture occurred, accompanied by overpressure, and in the second case, surface burning of the re-enriched mixture took place, which is not accompanied by a noticeable overpressure. At the same time, an outside observer can classify both phenomena as two identical ones. This is due to the fact that deflagration time of 100 ms or a surface burning time of several seconds is equally fast for a person, and for a pressure propagating at a speed of about 340 m/s, these are two fundamentally different processes. In the first case, blast pressure arises, since the explosion products “did not have enough time” to leave the fire location, and in the second case, there is practically no pressure, since the explosion products “managed” to leave the fire location.

Therefore, in a scenario involving the appearance of an ignition source immediately after the plane crash, an igneous ball emerges, which is formed as a result of burning fuel vapor and dispersed drops of kerosene, which occurs as the fuel mixes with air. This scenario for the development of the accident will conditionally be called the first one.

With a certain delay of the ignition source (for a few seconds), a fuel-air mixture forms that is capable of exploding, which is accompanied by overpressure of significant intensity. In other words, when a source of ignition manifests itself with a certain delay, the deflagration explosion of a part of the fuel in an explosive concentration first occurs, and after that (with the supply of oxygen) the remaining fuel burns out in the form of an igneous ball and a spillage fire. This scenario for the development of the accident will conditionally be called the second one.

Let us take a closer look at the second scenario of the crash. It was previously shown that the maximum amount of vapor that can be generated by the heated parts of one engine of the aircraft can be no more than $M_f = 1,520$ kg.

Let us calculate the formation process of a highly explosive cloud. We will consider the most unfavourable scenario for the development of the crash.

Figure 1 shows the lines of equal concentrations of the mixture 10 seconds after the vapor release. The isolines correspond to the following volumetric concentrations of the resulting vapor-air mixture: 1% vol. (outer isoline), 2%, 5%, and 10% vol. The situation was calculated when at the initial moment of time, there was a mixture of fuel vapor and air, that is, at the initial moment of time there is not a mixture of vapor and air fragments near the crashing engines, but an “enriched” mixture with a volume concentration of 27%.
Figure 1. The initial vapor cloud position (a) and vapor cloud position in 10 seconds after vapor discharge (b).

When performing the calculations, it was assumed that there is an intensive mixing of fuel vapors with air, that is, the crash is accompanied by significant gas-dynamic flows and the crash occurs at the high values of the turbulent diffusion coefficient. The turbulent diffusion coefficient was assumed to be 0.5 m$^2$/s, which corresponds to the values observed in similar situations. In the figures, the green dots indicate the initial discharge limits, the position of which was determined for each moment. This allows us to judge the degree of deformation of the initial cloud due to gas-dynamic flows accompanying the aircraft crash. Besides, the figures show vectors of flow velocities.

Figure 2 shows the time dependencies of vapor concentration at five points, the position of which is shown in Figure 1.

Figure 2. Vapor concentration time laws at five points.

Figure 3 shows the time law of the vapor mass having a concentration in a mixture with air from 1% vol. to 5% vol.
Figure 3. The time law of vapor mass ratio with volume concentration from 1% vol. to 5% vol. ($M_b$) to the total vapor mass ($M$).

The calculation results analysis showed that the initial conditions (the presence or absence of a large building near the site where the aircraft crashed; the initial state of the discharge: the discharge consists of vapor fragments or is already well mixed, etc.) have a negligible effect on the initial stage of the highly explosive cloud formation. In all the cases or in all the scenarios of the development of the aircraft crash causing a deflagration explosion at the time of the crash (the second scenario of the development of the aircraft crash), the maximum amount of vapor capable of creating conditions for deflagration does not exceed 7% of the initial vapor discharge mass. Given that the maximum amount of vapor that can be generated by the heated parts of one aircraft engine is not more than $M_b = 1,520$ kg, we obtain that the maximum vapor mass capable of involving a deflagration explosion, developing according to the second scenario, can be no more than $M = 106.4$ kg.

For the obtained value of the maximum vapor mass capable of exploding, we obtain the maximum radius of the fireball. Let us remember that that the fireball is the area of the explosion products and, accordingly, is determined by the boundary of the explosion products, and the igneous ball is the area of burning of the “enriched” mixture that burns as soon as the oxygen contained in the air is available. The weight of 106.4 kg of vapor (under normal conditions) is 16.45 m$^3$. The explosive mixture will have a volume of 822.5 m$^3$. Accordingly, the explosion product volume will be about 6,580 m$^3$. Assuming that the explosion products at the time of explosion completion will be in the form of a half cylinder mounted on the ground, we obtain that the maximum radius of the fireball will be no more than $R_S = 19.5$ m.

In order to determine the maximum apparent flame speed occurring during an explosion, it is necessary to determine the radius (length) at which the initial acceleration of the combustion process occurs due to the hydrodynamic instability of the mixture. Taking into account that a part of the combustion products (about 50%) will be required to expand the area of initial vapor discharge, we obtain that the main acceleration of the flame is carried out only at the last 4.9 m from the fireball boundary.

Based on the obtained values of parameters characterizing a fireball capable of forming in the process of a deflagration explosion, let us estimate the maximum apparent flame speed.

Following the recommendations of RD 03-409-01, we obtain that the maximum value of the apparent flame speed in deflagration explosion $M = 106.4$ kg of fuel will not exceed: $W = 43M^{1/6} = 93.6$ m/s.
Following the methods adopted in [13-19], the maximum visible flame speed in a deflagration explosion is defined as the product of the apparent flame speed performed under the conditions of hydrodynamic instability of the mixture (or turbulent combustion velocity) \( W_P \), and the coefficients characterizing the way the mixture is initiated \( k_1 \) and the nature of the surrounding area where the explosion occurred \( k_2 \), that is \( W = W_P k_1 k_2 \). Expert coefficient values \( k_1 \) and \( k_2 \) are given in [16,17].

Using an empirical ratio to determine \( W_P \) [16, 17], we obtain that

\[
W_P = U_N \left[ 1 + A \left( \frac{R_P}{\Delta} \right)^{3/8} \right] = 11.3 \text{ m/s},
\]

where \( U_N \) — laminar apparent flame speed \( (U_N = 3.67 \text{ m/s}) \); \( A \) — empirical proportion coefficient \( (A = 0.34) \); \( \Delta \) — average size of detonation cells of mixtures with air of lower hydrocarbons \( (\Delta = 0.131 \text{ m}) \); \( R_P \) — flame acceleration distance (in our case \( R_P = 4.9 \text{ m} \)).

When using a ratio that has some theoretical justification [18], we obtain that

\[
W_P = U_N \left( \frac{R_P}{R_K} \right)^{1.38} = 15.05 \text{ m/s},
\]

where \( R_K \) — critical distance of transition of the laminar combustion to the turbulent one \( (R_K = 0.432 \text{ m}) \); \( R_P \) — flame acceleration distance (in our case \( R_P = 19.5 \cdot 0.95 = 18.525 \text{ m} \)). It must be emphasized that in this situation, the value \( R_P \), used in [16, 17], is different from flame acceleration distance \( R_K \), which is used in [18].

For further calculations, we take the maximum value of the turbulent combustion speed \( W_P = 15.05 \text{ m/s} \).

For conservative calculations, we accept the maximum expert values of the coefficients \( k_1 \) and \( k_2 \) [16, 17]: \( k_1 = 1.8 \), which corresponds to the case of initiation of the mixture by turbulent ignition sources, and \( k_2 = 4.0 \), which corresponds to a case of considerable clutter of space.

As a result, we obtain that the maximum apparent flame speed in our case does not exceed the value \( W = 108.4 \text{ m/s} \).

Using the obtained values of the maximum explosion parameters, the explosion dynamic characteristics were calculated, which can occur during the development of an accident according to the second scenario.

With the accepted parameters of deflagration, the flame front dynamic characteristics will have the form shown in Figure 4. Figure 4 shows the dynamic parameters of the fireball, the dynamics of the apparent flame speed, and the velocity characteristics of the flow accompanying the explosion, which are taken as the initial data: the maximum radius of the fireball will be no more than \( R_S = 19.5 \text{ m} \) and the maximum apparent flame speed does not exceed the value \( W = 108.4 \text{ m/s} \).

For these dependences of the flow dynamic parameters, the time dependences of the overpressure were calculated at the points in the space adjacent to the explosion site. The calculations were performed according to the method described in [13] and simulating the formation of an explosive pressure field from an expanding sphere according to the law shown in Figure 4.
Figure 4. Dynamic dependences of the fireball parameters, the apparent flame speed and the flow velocity at the fireball’s boundary: 1 — flame front coordinate versus time characteristic; 2 — apparent flame propagation speed from the flame front position; 3 — dependence of the apparent flame propagation speed versus time parameter; 4 — dependence of the flow velocity at the fireball’s boundary versus time parameter.

As a result of the calculations, the field of maximum pressures created by this deflagration explosion was determined [20, 21]. Figure 5 shows isolines of equal maximum pressure, which can emerge in a crash developing according to the second scenario.

Figure 5. Isolines of equal maximum pressure $\Delta P(X, Z)$ in a crash.
The numerical values of isolines are 6, 8, 10, 12, 14 and 16 kPa. Figure 5 shows the position (highlighted in green) of the fireball at the moment of the explosion completion (the area of the explosion products), the crashing plane, a schematic representation of the standardized power unit building, as well as 5 points on the facade of the power unit building, for which the dynamic parameters of the explosion loading are shown in Figure 6.

![Figure 6](image_url)

**Figure 6.** The dynamic parameters of the explosion loading at five points located on the building facade.

The integral parameters of the explosion loading at 5 points of the building facade have the following values (see Table).

| Parameter name                         | Explosion loading parameters at points of the facade (see Figure 5) |
|----------------------------------------|---------------------------------------------------------------|
|                                        | 1    | 2    | 3    | 4    | 5    |
| Maximum explosion pressure $\Delta P_{\text{max}}$, kPa | 16.4 | 15.7 | 11.6 | 8.4  | 6.4  |
| Minimum explosion pressure $\Delta P_{\text{min}}$, kPa  | -7.21| -6.89| -5.10| -3.67| -2.79|
| Compression phase impulse $I$, Pa·s       | 749.9| 716.6| 530.6| 382.2| 290.7|
| Probability of complete destruction $V_1$, % | 4.30 | 3.60 | 0    | 0    | 0    |
| Probability of medium destruction or loss of life $V_2$, % | 44.4 | 40.5 | 18.5 | 5.26 | 1.49 |

The exposure time of the positive phase of the explosion loading, reduced to a triangular shape, will be about 92 ms.

Conditional probabilities of destruction were determined by the methods given in GOST R 12.3.047-2012 OSSS “Fire safety of technological processes”.

Figure 7 shows the narrow-band (bandwidth 10 Hz) spectrum of the explosion loading, which is realized at point 1 (the closest point of the building facade to the explosion site, see Figure 5). Figure 7
shows that the vibration loadings are quite high at low frequencies (up to 200 Hz): from 130 to 175 dB. These loadings are quite dangerous for the appliances available in the building. At higher frequencies, sound or acoustic loadings, that is, the noise that witnesses to the crash explosion can hear, will have an intensity of no more than 120 dB, which will be perceived by wider public as a low-frequency hum.

Figure 7. Narrow-band spectrum (10 Hz bandwidth) of explosion loading at point 1, located on the building facade (see Figure 5).

3. Results and discussions

As a result of calculations and based on the correct initial data, the methodology proposed in the article allows:

- obtaining values of the fuel mass capable of forming a highly explosive mixture;
- choosing an appropriate aircraft crash scenario: igneous ball or deflagration explosion of vapor-air mixture;
- determining the time dependence of the fuel vapor concentration in the air;
- evaluating the maximum apparent flame front speed;
- determining the fireball dynamic parameters and the time dependences of the overpressure at points in the space adjacent to the explosion site;
- building up a maximum pressure field created by this deflagration explosion;
- obtaining the integral parameters of the explosion loading: the maximum and minimum overpressure of the explosion, the compression phase pulse, the probability of destruction of buildings and loss of life;
- evaluating vibration loadings from a deflagration explosion.

The calculation results analysis showed that the initial conditions (the presence or absence of a large building near the site where the aircraft crashed; the initial state of the discharge: if the composition consists of vapor fragments or is already well mixed, etc.) have a negligible effect on the initial stage of the highly explosive cloud formation. In all the scenarios of the development of the aircraft crash causing a deflagration explosion at the time of the crash the maximum amount of vapor capable of creating conditions for deflagration does not exceed 7% of the initial vapor discharge mass.

The calculations showed that the proposed methodology allows us to obtain more accurate values of the maximum apparent flame speed, compared with the methods described in the existing Russian regulatory documentation.
From the above calculations (using Boeing-747 as an example), it follows that in the most unfavorable scenario of a plane crash near or directly onto a reactor building, the loadings arising from the deflagration of a fuel-air cloud will have the parameters not exceeding the following values:

- maximum explosion pressure will not exceed $\Delta P_{\text{max}} = 16.4 \text{ kPa}$;
- minimum explosion pressure will not exceed $\Delta P_{\text{min}} = -7.21 \text{ kPa}$;
- compression phase pulse does not exceed $I = 749.9 \text{ Pa} \cdot \text{s}$;
- maximum probability of complete destruction will not exceed $V_1 = 4.30\%$, and the probability of average destruction of buildings and structures (or loss of life) will not exceed $V_2 = 44.4\%$;
- exposure time of the positive phase of the explosion loading, reduced to a triangular shape, will be not more than 92 ms.

The vibration loadings created by the explosion will have rather high values at low frequencies (up to 200 Hz): from 130 to 175 dB. At higher frequencies, sound or acoustic loadings will have an intensity of not more than 120 dB, which will be perceived by wider public as a low-frequency hum.

The obtained values of explosion loadings arising during any crash of a heavy commercial aircraft are quite severe, but safe for building envelopes of first safety category buildings of nuclear power plants designed for explosion loadings of up to 30 kPa [22].

4. Conclusions

This work presents the most modern methodology for calculating the damage effects of a deflagration explosion associated with crashing an aircraft (A/C). Such calculations are carried out when assessing the consequences of a plane crash near major civil, industrial and energy facilities (such as NPPs).

The article discusses the physical processes that occur during an aircraft crash, which causes the formation of a highly explosive cloud; the methodology for the quantitative assessment of parameters affecting explosion loadings is indicated; the methods of calculating the damage effects of a deflagration explosion during an aircraft crash are presented. When describing the methodology, an example was given of calculating the loadings from a deflagration explosion that occurs when a heavy civilian Boeing-747 crashes onto the NPP site.

The results of calculations carried out according to the methodology described in the article were used to assess the consequences of an aircraft crash on the sites of nuclear power plants in Russia (Novovoronezhskaya, Beloyarskaya, Leningradskaya NPPs), as well as in Hungary (Paks II NPP) and Egypt (El-Dabaa NPP) and were used at the design stage of these facilities. Thus, this methodology has been tested and can be used to calculate the loadings on critically important buildings and structures during a deflagration explosion that occurs when an aircraft crashes.

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