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Implementation of Flying Debris Fatal Risk Calculation in EUROPLEXUS

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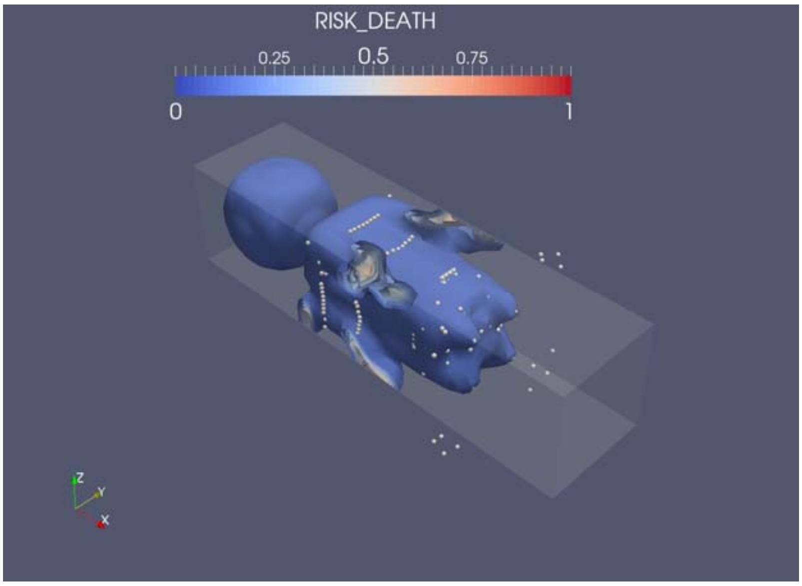

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EUROPLEXUS Software

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1 Introduction

The objective of this report is to present a new procedure integrated in the EUROPLEXUS code in order to calculate the fatality risk caused by the impact of flying debris on the human body. EUROPLEXUS [3] is an explicit computer code for fast transient dynamic analysis of fluid-structure systems jointly developed by the Joint Research Centre (JRC Ispra) and the French Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA Saclay).

The document is organized as follows:

The second chapter describes the applied death risk model. It shows the necessity of including in the death risk calculation the contribution of the projectiles produced after an explosive event. Some injury or fatality criteria are presented from the corresponding bibliography and one is chosen as the most accurate.

The third chapter presents the numerical implementation of the proposed methodology. It refers to the subroutines that are developed for the inclusion of the death risk related to flying debris and the new keywords that activate the new module are discussed. Some particular cases concerning the impact area of the projectiles and the contribution of non-eroded elements (macro debris) are also presented.

The fourth chapter presents the results of several finite element calculations using the debris risk implementation. A simple model is discussed where a tempered glass panel is fragmented and the death risk results are presented. The glass panel is checked also with laminated type in order to present the application on macro-fragments formation. Finally, a study of the influence of the size of the flying debris on the death risk analysis is conducted.

The last chapter emphasizes the main achievements from the new developed methodology. All input files used for the numerical calculations are included in the Appendix.

2 Death risk model

The mechanism of blast injury can be divided into four categories [1] (Figure 1):

- Primary: Injury from over-pressure force of the blast wave interacting with the body surface (eardrum rupture, lung or abdominal haemorrhage, concussion).
- Secondary: Injury from projectiles like bomb fragments or flying debris (penetrating trauma, fragmentation injuries).
- Tertiary: Injuries resulting from the displacement of individuals by the blast wind and the successive collision against hard surfaces (penetrating trauma, traumatic amputations, head/brain injuries).
- Quaternary: All other injuries from the blast (crush injuries, asphyxia, toxic exposure).

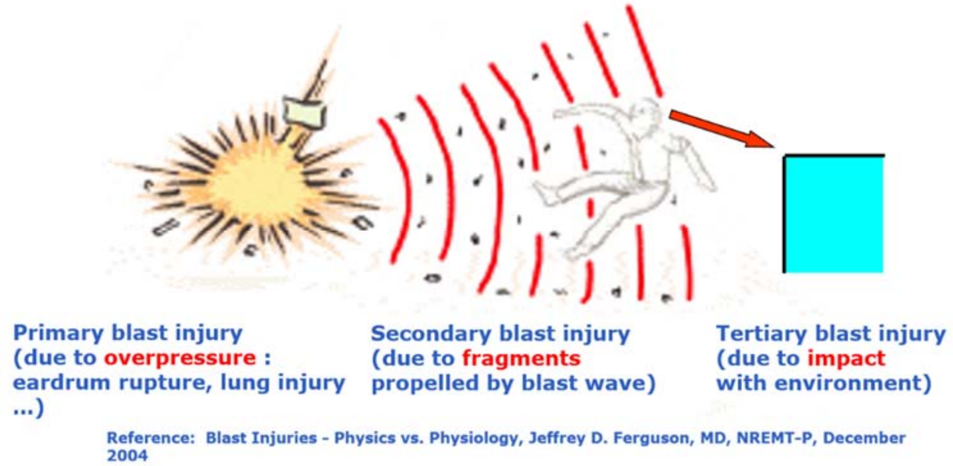


Figure 1: Blast injury mechanism

The risk resulting from the primary injuries is already calculated in EUROPLEXUS [2]. The existing model uses the impulse and the peak overpressure of the air blast to determine the risk of eardrum rupture and the risk of death [4], [5], [6], [7]. In case of an explosive event, it is very possible that the structure that is near the explosion centre will be fragmented and turned into small projectiles with high velocity that can be spread into a very wide area. These particles are able to cause fatal injuries to human beings that are standing in the zone of influence and may extend the area of high death risk significantly. This makes necessary the development of an additional model to determine death risk related to the secondary blast effects.

The flying debris produced by the fragmentation of the structure after an explosion are moving at high velocity and this means that even small-mass particles might have high kinetic energy. A variety of empirical functions of mass and velocity at impact have been proposed as injury criteria [8], [9]. In the relevant literature penetrating and non-penetrating injury data are distinguished. In the current study, the penetrating injury data will be used since they represent the overwhelming majority of the existing models. The penetrating trauma criterion claims that a fragment that causes complete skin perforation (full-thickness skin laceration) is equated to a hazardous condition for the human body. The effect of clothing can be neglected since normal clothing is much less resistant to perforation than skin.

The basic criterion for characterizing the hazard from a moving particle is its kinetic energy. The first approach goes back to 1906 when Rohne set a rough rule of 80 Joule (J) of kinetic energy [10]. A fragment is considered hazardous if it has at least 80 J of kinetic energy when it strikes the target person. This criterion is being used traditionally in many explosive safety standards but for fragments lighter than about 0.1 kg, the velocity that causes lethal injury is overestimated significantly with respect to other approaches (see also Figure 2).

Since the actual area of the fragment is relevant to the fatality of flying debris, a more sophisticated formulation that is taking into consideration this effect has been used for the implementation in EUROPLEXUS. An empirical formula is used for the calculation of the risk due to the impact of flying debris on the human body, which is based on the work of Lewis [11] and involves bare skin penetration as the injury criterion. The objective of [11] was to determine the probability of complete skin perforation since the authors had considered this occurrence as a hazardous condition. They performed several investigations for a big variety of projectiles and of striking velocities on a section of goat skin and they ended with a formula that determines the probability as a function of the test variables. Their model is of the form:

$$P_{debris} = \frac{1}{1 + \exp(-(A + B\ln(\frac{MV^2}{C})))} \tag{1}$$

Where P_{debris} is the probability of death injury (skin penetration), $A = -27.35$, $B = 2.81$ are constants determined after employing curve fitting techniques in the experimental results, M is the mass of the fragment in grams, V is the velocity of the flying debris in m/s and C is the presented area of the projectile in cm². Since a fragment either perforates or fails to perforate the skin, the Walker-Duncan method [12] could be used to estimate the probability in terms of some function of the test variables.

The flying debris death risk probability can be added to the other three already calculated death probabilities for the primary death risk. The final death risk probability for all different cases is simplified by taking the maximum of the four probabilities:

$$P_{death} = \max(P_{head}, P_{body}, P_{lung}, P_{debris}) \tag{2}$$

P_{head} is the death risk probability due to head impact, P_{body} is the probability due to whole body impact and P_{lung} is lung haemorrhage death risk probability. P_{head}, P_{body} and P_{lung} express the three main fatality causes due to primary blast effects.

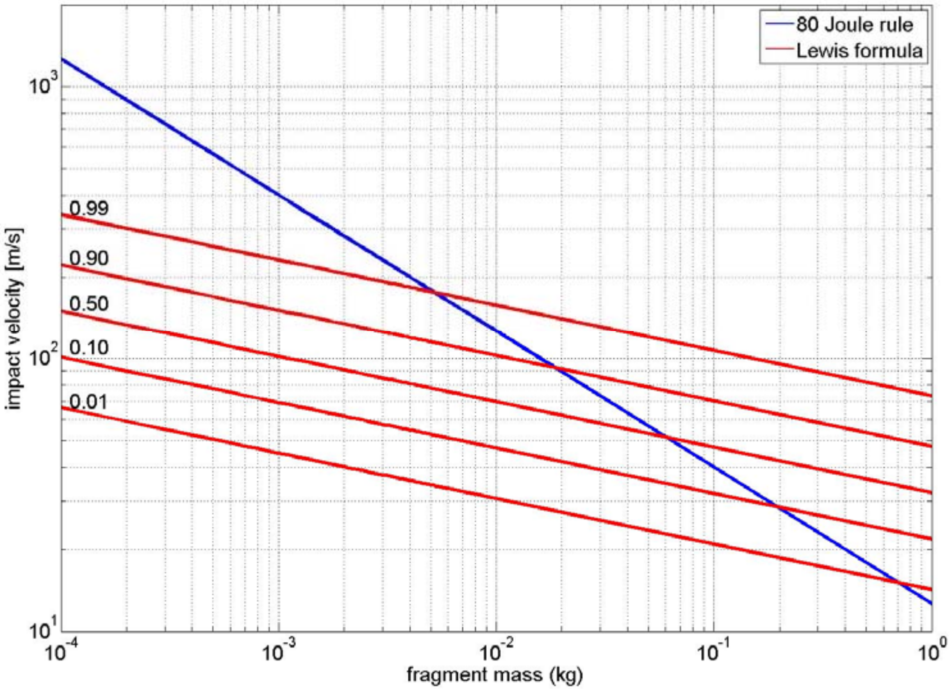


Figure 2: Death risk criteria thresholds

Figure 2 shows the two presented risk criteria relating the impact velocity to the mass of the fragment. The blue line represents the 80 J rule where for a point that is located above the curve the fragment is lethal. This is a threshold with no transition zone, having a probability of injury either 0 or 1. Moreover, penetrating injury research shows that lethal injuries can occur at impact kinetic energy levels significantly less than 80 J. The red curves present the results from Lewis formulation for various values of the probability of death injury. Lewis formulation involves the bare skin penetration as the injury criterion taking into account also the impact area of the fragment. Spherical fragments have been considered for the results of the figure. It is obvious that for a fragment with mass less than 100 g the Lewis formulation gives high death probability for a range of kinetic energy that it is below the threshold of 80 J.

3 Numerical implementation

The formula of the previous chapter concerning the injury due to flying fragments can be numerically implemented in the EUROPLEXUS explicit finite element code. EUROPLEXUS includes structure erosion models where a structural element is excluded from the calculation when a predefined criterion is fulfilled. After the erosion, the element is not participating in calculation as a finite element but it can participate as a flying particle with certain size and with the initial velocity of the eroded (parent) element at the time step of erosion. This procedure is described in [13] and is implemented through the "DEBR" keyword. The debris particles are attached to the structural elements from the beginning of the calculation but they become active only after erosion of the attached structural element. The user defines the number of debris particles that are attached to each structural element, thus identifying the number of fragments that are created after erosion. This is an important input parameter since it determines the mass of each produced fragment. The trajectory of the flying particles is calculated taking into account the initial velocity (the velocity of the parent element just before erosion), the gravity if defined and the drag force exerted by the fluid.

The calculation of the secondary blast risk needs the implementation of the Lewis formula of equation (1) on the flying debris produced after element erosion. Quantities like the initial velocity of the projectile, the mass and (at least) the initial impact area are readily available in most cases so the determination of the debris-related risk is a direct implementation of the risk function. The details of the implementation and the treatment of some special cases are presented in the next paragraphs.

3.1 Debris risk module

The risk variable in EUROPLEXUS is an output variable associated with each fluid element and has two components: one for eardrum rupture injury and one for lethal injury. In the current implementation, the risk of death due to secondary blast effects (equation (1)) is contributing in the determination of the total risk of death as described in equation (2). Therefore, at each time step a value of death risk due the flying debris impact should be calculated for each fluid element. The calculation of the secondary blast effects risk is activated through the risk ("RISK") directive by two additional optional keywords. The keyword "DEBR" includes the contribution of the active flying debris death risk in the final death risk calculation. The keyword "DEBS" goes one step further since it includes in the death risk the calculation not only the active flying debris but also of the the inactive flying debris, as described later on.

In order to handle the cases of the flying debris death risk calculation, two new logical variables have been added to the "M_RISK" module. The "L_RISK_DEBR" is activated when the debris death risk calculation is requested and the "L_RISK_DESP" is activated when also the inactive flying debris should be included in the calculation. Both variables are initially .FALSE. and by specifying the debris death risk keywords they are modified as presented in Table 1.

Table 1: Logical variable values according to the input keywords

Keyword	L_RISK_DEBR	L_RISK_DESP
DEBR	TRUE	FALSE
DESP	TRUE	TRUE

The inclusion of the inactive flying debris that are attached to the (non-eroded) structural finite elements has been considered in order to calculate the death risk of parts of the structure that are not eroded but detached from the main structure, i.e. of macro fragments. The fragmentation of the structure does not always imply that the finite elements are eroded; it is possible that a patch of structural finite elements is detached from the original configuration and moves in space, thus being able to produce damage on other structural parts or injuries on the human beings. This phenomenon is very common for example in the case of laminated glass panels where after the fragmentation large parts of the original panel remain stuck together (because of the PVB layer which glues together the glass splinters). Figure 3 presents two different types of glass fragmentation, the first one is a tempered glass panel where after fragmentation only micro-fragments are produced (the “DEBR” keyword is suitable for that case) and the second one is a laminated glass panel where after fragmentation macro-fragments are produced (the “DESP” keyword is necessary for that case).

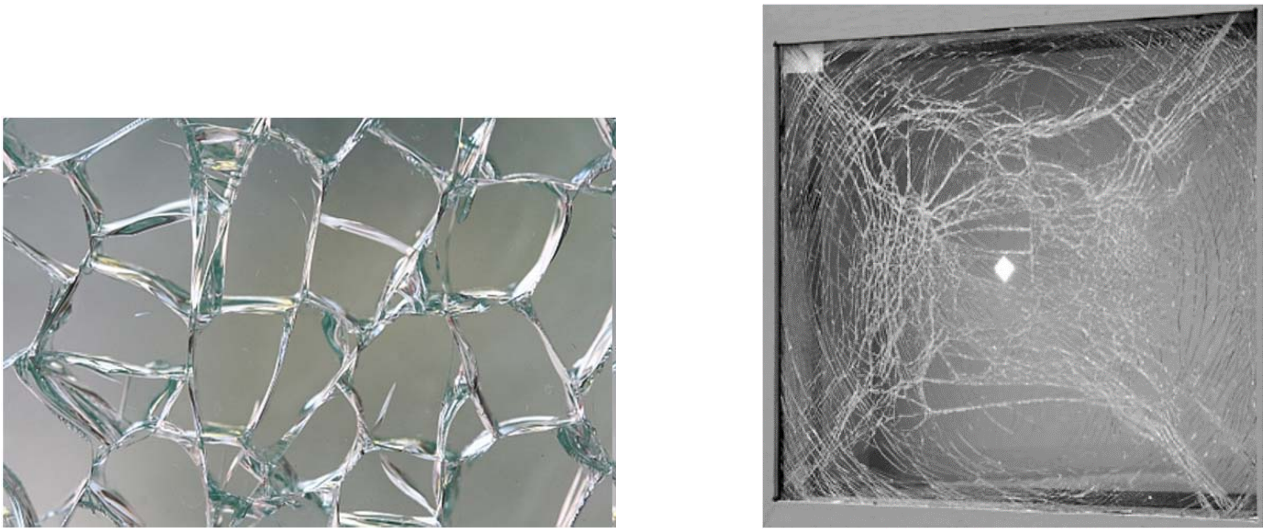


Figure 3: Tempered [23] (left) and laminated [24] (right) glass panel failure/fragmentation.

The main subroutine that calculates the death risk of the flying debris is called “RISK_DEBRIS” and is included in the “M_FLYING_DEBRIS” module. In brief, the organization of the subroutine is described in the following points:

- A loop on the active debris (the inactive debris are also included in the case of “DESP”) is performed and through a fast search algorithm the id number of the fluid element is identified that contains the current (IP-th) particle element for the current time step. This information is stored in the “DEBRIS_PARTICLE(IP)%FLUID_ELEMENT” variable.
- For each debris particle, the velocity is obtained from the global “V” vector and the mass from the global “XM” vector.
- The initial impacting area of the flying particle in most cases is obtained from the variable “DEBRIS_PARTICLE(IP)%FLYIN_AREA” that is calculated at the first step for each debris element. There are also some special cases that are treated differently and are discussed later on.
- After having all the inputs, the death risk is calculated via equation (1) and it is stored in the “RISK_DEBR” vector that is declared in the “M_RISK” module.

The “RISK_DEBRIS” vector that is filled in the above mentioned subroutine is used in the “COMPUTE_THE_RISK” subroutine of the “M_RISK” module. In this subroutine the maximum component (among the head, lung, body and debris risk) of the death risk is selected as the output value.

There is also an older version of the calculation of the total risk which adds all risk components by checking that the final value is not exceeding 1.0. The new (current) version which selects the maximum value of the components is more realistic than the old one, but an even better approach would be to calculate the addition of the four independent risk components according to the probability rules. For two events A, B with probability of occurrence $P(\mathrm{A})$, $P(\mathrm{B})$ that are not mutually exclusive, the probability of occurrence of one of the two events is defined as follows:

$$P(\mathrm{A} \cup \mathrm{B}) = P(\mathrm{A}) + P(\mathrm{B}) - P(\mathrm{A} \cap \mathrm{B}) \tag{3}$$

A similar formulation can be applied to four events. Further investigations are needed to integrated this procedure in a future version of EUROPLEXUS.

At this point, it should be noted that the death risk function is a cumulative non-decreasing variable whose current value is the maximum value that occurred in the fluid element under consideration, until the current time step. In the simulation of explosive events, it is possible that a particle is passing through a fluid element with a certain death risk value and in another time step, another particle with a different death risk value is crossing the same element. EUROPLEXUS is keeping the risk value from the particle with the higher death risk value. It would be more realistic to somehow cumulate the death risk probabilities of all the particles that cross a fluid element but this is a very complicated procedure. In order to achieve this addition it would be necessary to store a relatively big number of data for each fluid element and for each time step since the number of flying debris is typically huge. Taking into account only the "most dangerous" debris for each fluid element is a good compromise between accuracy and efficient calculation.

3.2 Inactive debris particles contribution

When the inactive debris particles are included in the death risk calculation, the subroutine "ACTIVATE_DEBRIS_SP" should be used in order to fill some null variables of the flying debris. The main objective of that routine is to assign the velocity of the particle from the parent element (since it is not active, the particle itself has no velocity). This subroutine identifies the velocity of the parent structural element to which the debris is attached and estimates the velocity of the particle for the calculation of the debris death risk. Actually, the velocity of the particle is the interpolation of the velocities of the nodes that belong to the parent element. This is also the procedure used for the determination of the initial velocity of an active flying debris just after erosion of the structural parent element. It should be highlighted that this procedure is a "spurious" activation of the inactive flying debris, done only for the calculation of the inputs of the debris death risk. For all other procedures these debris are still inactive.

3.3 Impacting area

The formulation of the debris death risk is taking into account the impact area of the projectile. Special treatment is necessary for the definition of this quantity since the shape of the projectile is not fixed. In general, the shape of the produced particle is random so in order to define it some rules are applied, depending on the shape of the parent element. The most common shape that is used for the flying debris is the sphere (which is used when the parent element is solid). After erosion the parent element is divided into the number of flying debris that the user has defined. Each of these debris is assumed to be spherical. The diameter (the volume) of the spherical flying debris is defined according to the conservation of mass and from the fact that the density of the flying particle is known (most of the times it inherits the density of the parent element). For a spherical flying debris, the impacting area is expressed by the equation:

$$Area_{impact} = \frac{\pi}{4} d^2 \tag{4}$$

where d is the diameter of the spherical particle.

When the parent element is a shell element the produced particle is considered as a shell with the same thickness. In that case, the impacting area depends on the position of the flying debris at the moment of collision. There are two extreme scenarios where in the first the impacting area is the surface A on Figure 4 (magenta, minimum value) and in the second is the surface B (blue, maximum value).

In EUROPLEXUS the variation of the area of the debris is defined through the “AFLY” keyword of the “DEBR” directive that determines the data of the flying debris in the calculation. By using the keyword “AFLY” the minimum (afly = 0.0) or the maximum (afly = 1.0) value is used. Values of “AFLY” between 0.0 and 1.0 interpolate linearly between these two values. The default value is 0.5. It should be noted that non-spherical fragments have the tendency to align their large surface across the trajectory because of the drag force. This means that a value of “AFLY” close to 0.0 is more realistic.

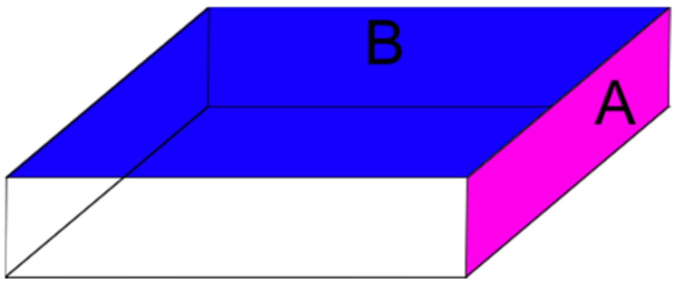


Figure 4: Shell element minimum and maximum impact surfaces

In the case of the inactive flying debris derived from a shell parent element, a special treatment for the calculation of the impacting area has been used. As depicted in Figure 5, the presented area the moment of the impact with the target is the projection of the surface of the shell-shaped particle in the plane normal to the velocity vector. For the calculation of the projected area of the particle, the velocity and the normal to the element surface (particle) vectors are needed.

The velocity of the particle can be inherited from the parent shell element. The normal to the element surface vector can be determined from the nodes of the parent (shell) element by means of the "NORSUR" subroutine. The "NORSUR" subroutine is using the coordinates of the nodes of the surface to compute the normal vector, whose length is equal to the surface of the area. The projection is calculated via the dot product of the two vectors (surface normal and velocity normal) divided by the length of the normal velocity vector as described by:

$$Area_{proj} = \frac{\vec{V}_{normal} \bullet \vec{N}_{surface}}{\left|\vec{V}_{normal}\right|} \tag{5}$$

where $\vec{V}_{normal}$ is a vector normal to the velocity vector and $\vec{N}_{surface}$ is the vector normal to the surface of the element with length equal to area of the surface.

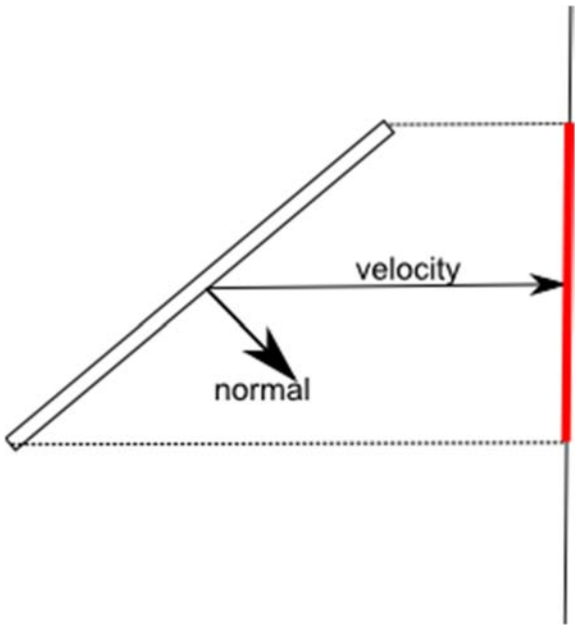


Figure 5: Impact surface for a shell element whose normal vector is different from the velocity vector

Figure 5 presents a shell particle moving in space, whose velocity vector is not normal to its surface. This means that the presented area needed for the calculation of the debris death risk is smaller than the area of the shell particle. The presented area is shown in red and is calculated via the equation (5).

This procedure is used for the inactive flying debris with shell parent elements, while in all other cases of inactive flying debris the desired area is calculated by assuming that the shape of the particle is spherical.

4 Numerical results

This chapter presents the results obtained after the implementation of the debris risk calculation described in the previous chapter. Several numerical simulations of explosive events are performed in order to show the implementation and the importance of the new tool available in EUROPLEXUS. In addition, the influence of some parameters on the results is discussed like for example the size of the produced flying particles. The FLSR technique has been used in order couple the non-conforming fluid and structural mesh [14], [15]

4.1 Simple model with tempered glass panel

The first trial to set up and test the contribution of the flying debris on the calculation of the death risk is taking place on a simple model where a glass panel is embedded in a fluid (air) volume mesh. An explosion is taking place near the glass panel causing the fragmentation of the panel. The model and the most important dimensions are depicted in Figure 6.

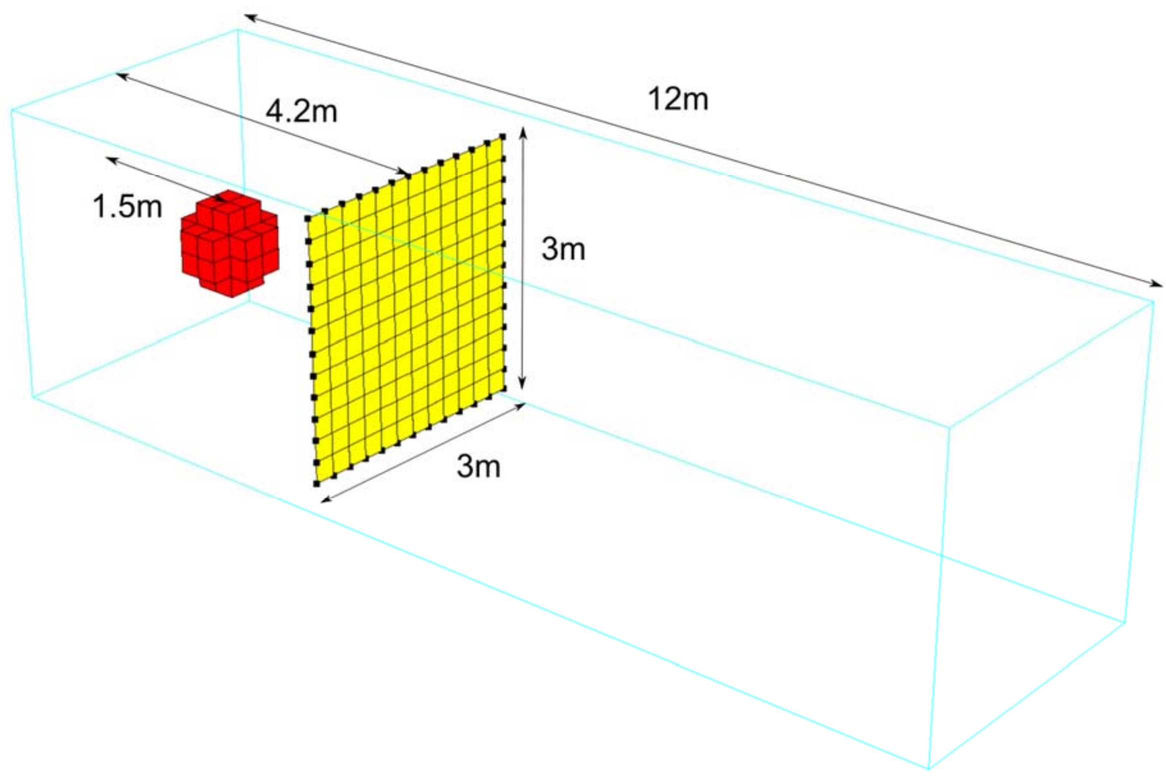


Figure 6: Sketch of the first simple model

The yellow rectangular surface in Figure 6 depicts the glass panel. A 12x12 grid mesh with “Q4GS” quadrilateral elements is constructed for the glass panel where the edge of each element is 0.25m. The thickness of the glass panel is 8mm. On each quadrilateral structural element, four debris particles ("PLEV" = 1) are attached in order to be activated after erosion of the parent element (Figure 7). The nodes on the boundaries of the glass panel are blocked in all directions. The cyan frame on Figure 6 outlines the fluid subdomain (the air) of the model and the red solid elements show the part of the fluid mesh that contains the bomb (through the bubble model, [16]). The fluid mesh is constructed by cubic "FL38" elements where the edge of the cube is 0.25m. along the envelope of the fluid mesh "CL3Q" absorbing elements have been attached, in order to simulate non-reflecting boundaries. Table 2 presents the number of the elements of the adopted finite element model.

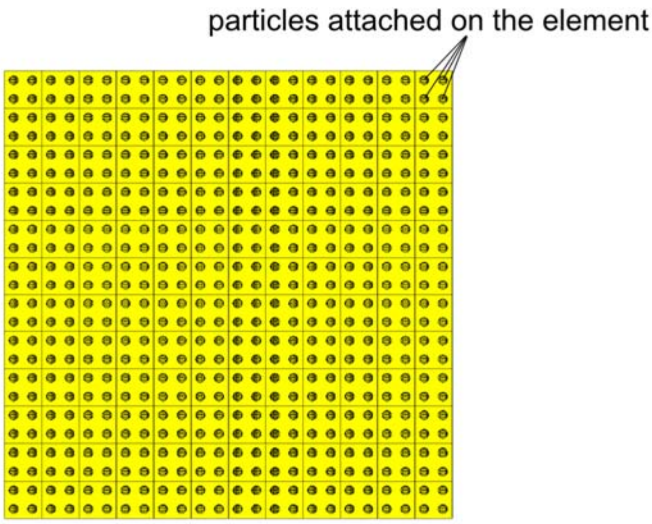


Figure 7: Glass panel with attached debris particles on the quadrilateral elements

Table 2: Element types used for the model

Element type	Number of elements
Q4GS	144
FL38	6912
CL3Q	2592
DEBR	576

The glass panel is made of tempered glass and its properties are listed in Table 3. The failure criterion for the erosion of the glass finite elements is based upon an equivalent constant stress of the duration

60s ("PSAR" keyword) as described in [2]. The fluid mesh consists of air and the material properties are presented in Table 4. The explosive pressure wave reaches the glass panel and causes the erosion of the first structural element at 3.7 ms. 32.9 ms after the initiation of calculation 124 (out of 144) structural elements have been eroded producing 496 active flying particles. The glass projectiles are moving in the fluid mesh with an initial velocity equal to the velocity of the parent element at the moment of the erosion. The drag (drag coefficient equal to 1.0) and the gravity forces are applied on the flying debris. The "AFLY" keyword has been set to 0.0 since shell shaped flying particles are considered, and these tend to align their larger dimension to the trajectory.

Table 3: Material properties for the tempered glass panel

Density [kg/m³]	**Young's modulus [Pa]**	**Poisson's ratio**	**Failure limit [Pa]**
2500	7.1e10	0.23	159.6e6

Table 4: Material properties for air and TNT materials

Material	**Density [kg/m³]**	**Specific internal energy [J/kg]**	**Gamma ratio**	**Reference pressure [Pa]**
Air	1	2.5e5	1.4	1.0e5

The final time of the calculation is 400 ms and the results are presented by the ParaView post-processor [18]. Figure 8 presents a panoramic view of the model. The first image depicts the model before the explosion (at time step zero) where the intact glass panel with the attached (inactive) particles can be observed. The fluid part of the model is depicted in a transparent mode (opacity parameter is set to 0.25) in order to be able to observe the structural parts. The second image shows the state of the model 200 ms after the explosion where the explosive wave has reached and fragmented the glass panel. In the contour plot, an almost spherical part can be identified at the explosion location and this death risk part is a consequence of the primary death effects. The other more geometrically complicated part of death risk contour is the contribution of the secondary effects (debris) to the death risk analysis.

The light grey spherical particles that can be observed in the right hand side image are the active flying debris that were produced after the erosion of the parent structural elements. As already mentioned, the flying debris on that calculation are shell shaped but in the post-processor they are depicted as spherical for a simpler graphical representation.

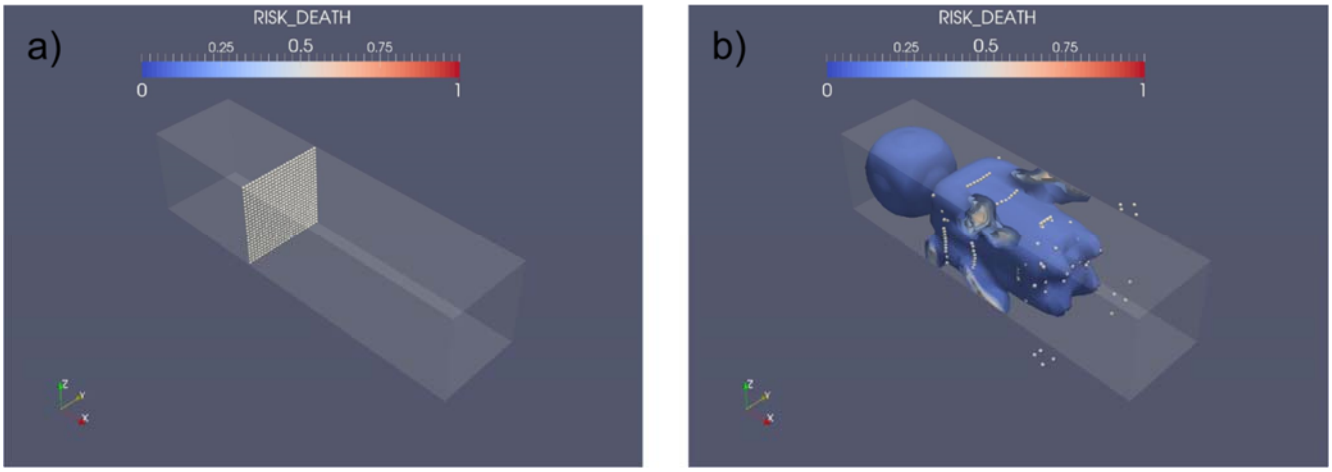


Figure 8: Panoramic view of the model before the explosion and 200 ms after the explosion

Figure 9 presents the death risk evolution at various time instants. The view point is along the Y-axis and the contour plot has been cut in the mid-plane in order to be able to identify the values of the death risk in the fluid part of the model. First, the time step zero is depicted where the glass panel is intact since the explosion has not been initiated yet. The second picture is 100 ms after initiation of the explosion and it is easy to observe that the pressure wave has fragmented the glass panel and death risk areas have already appeared. A circular (spherical in 3D) high death risk area is observed around the explosion location and it is due to the primary blast effects. The glass part is converted into flying debris. They are moving in the fluid mesh and are causing death risk probability. Similar conclusions can be extracted from the other time instants (200 and 400 ms) where the high death risk area extends far from the explosion location because of the trajectory of the hazardous flying particles. In the last instant the high death risk area occupies the whole fluid mesh located after the glass panel.

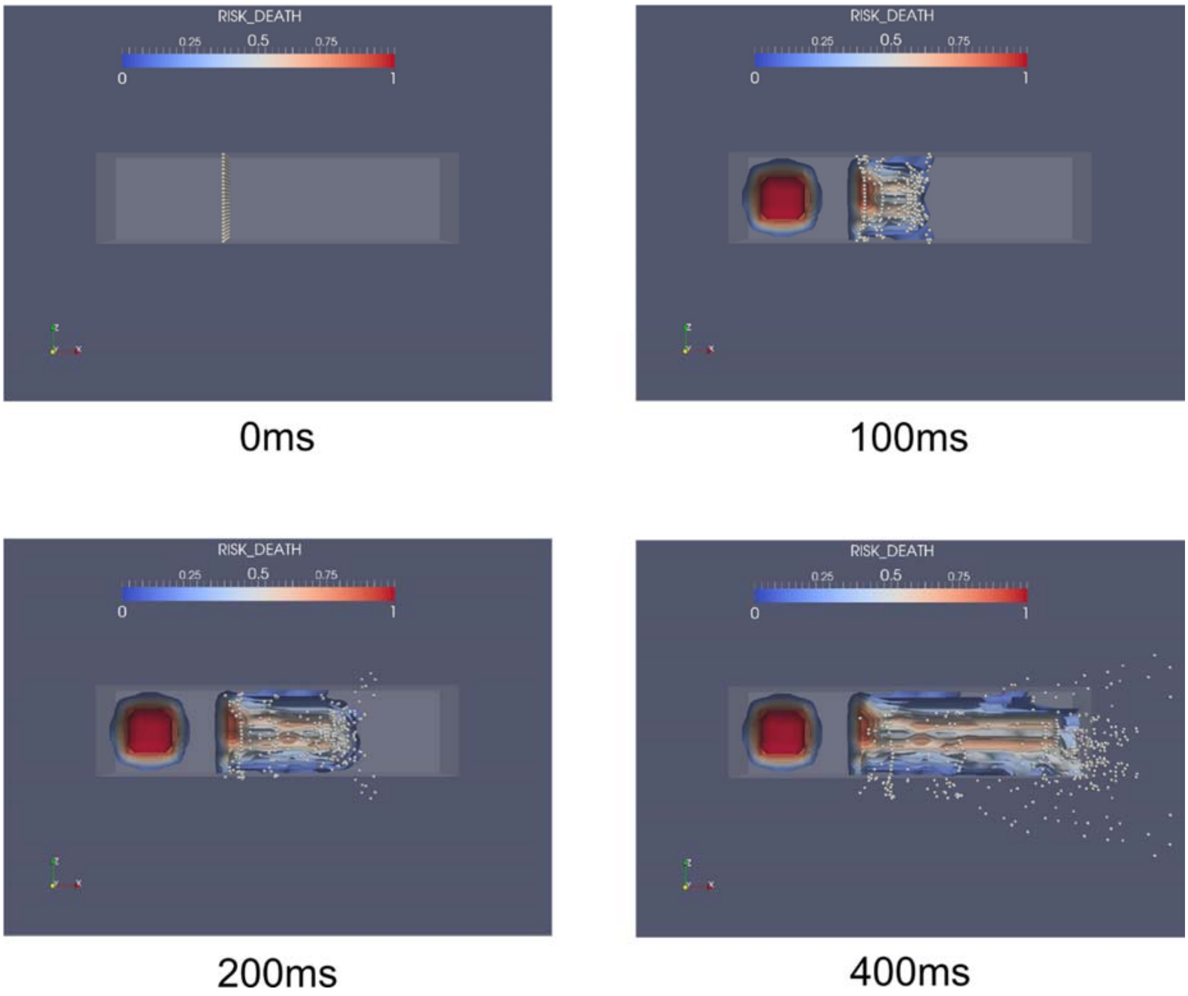


Figure 9: Death risk contour at various time instants

It can be observed that the flying debris on the last instant of Figure 9, are moving out of the fluid mesh. The fluid mesh in that model is restricted in that rectangular area in order to have a relatively small model that can be solved fast enough (less than 10 minutes CPU time). The flying particles on the other hand cannot be restricted in the fluid mesh and they can travel beyond the fluid mesh. The death risk is an output of the fluid elements and is therefore limited to the fluid mesh area. The fact that some projectiles can be identified outside the risk area (fluid mesh) doesn't mean that they are not hazardous. It simply means that there is no fluid element to assign the death risk value to. In a future development it is planned to assign the secondary death risk output directly to the flying debris in order make the risk calculation for some cases independent from the fluid mesh.

Figure 10 presents the comparison of the death risk calculated from primary and secondary blast effects. In the first image, only the death risk caused by direct interaction of the blast overpressure with the human body is depicted. The high death risk is located in a spherical area around the explosion and its radius is less than 1.5 meters. In the second image, the calculated death risk area includes the contribution of the impact of the glass fragments on the human body. It is obvious that the additional death risk is spread in the whole fluid mesh located after the glass part, an area whose major dimension is more than 8 meters. The actual death risk area is even larger since the flying debris are moving outside the fluid mesh with a kinetic energy that is still suitable to cause lethal injury. It can also be observed that the flying particles have higher displacements in the Z direction and this is due to the contribution of the gravity force.

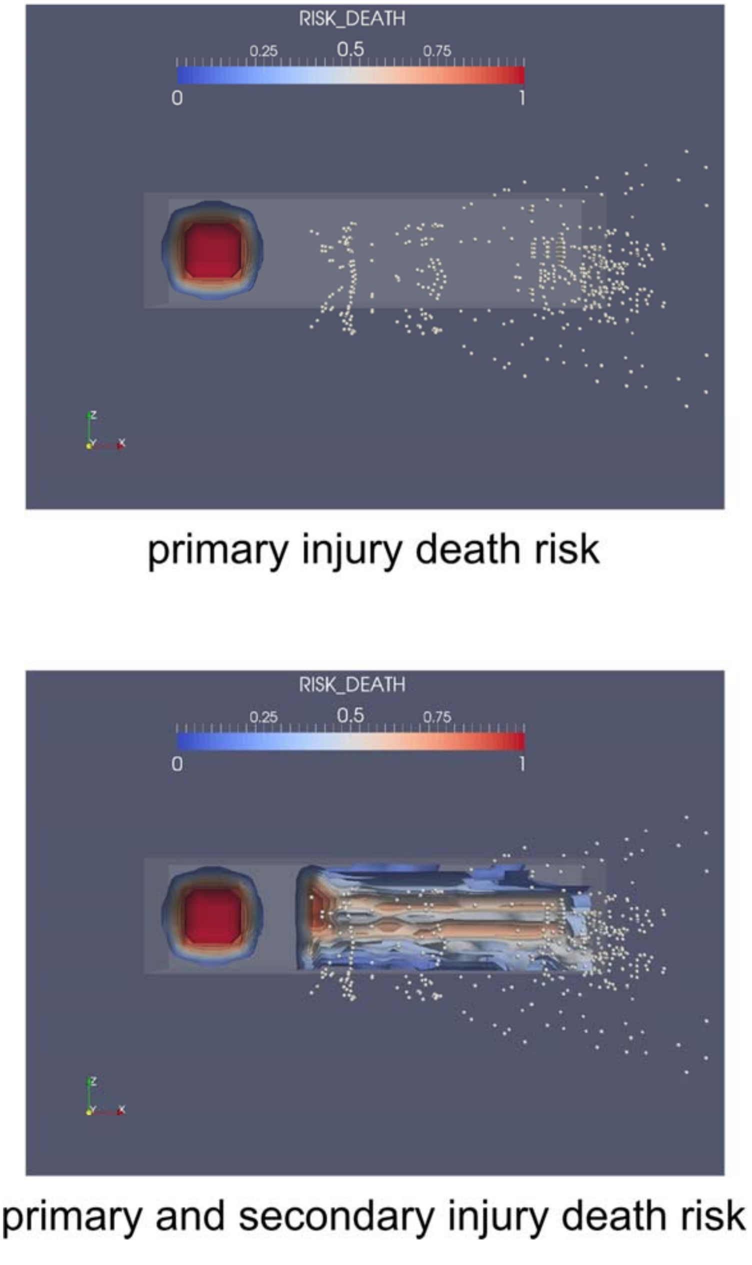


Figure 10: Comparison of death risk between primary and secondary effects

4.2 Simple model with laminated glass panel

The second model is a repetition of the previous one with a different type of glass material properties for the panel. This test is taking place in order to highlight the contribution of the structural elements that are not eroded, on the calculation of the secondary blast effect death risk. The structural panel in this case is made of laminated glass. After the explosion it is moving in the fluid mesh without producing many flying debris. This phenomenon is due to the fact that after the fragmentation of one or both glass layers the PVD layer acts like a glue that keeps the fragmented glass parts (splinters) together.

The laminated glass panel consists of two tempered glass layers (Table 3) separated by a PVB layer. The thickness of each glass layer is 3.2 mm, while the thickness of the PVB layer is 1.6 mm. Table 5 presents the material properties of the PVB material. The erosion model that has been used for this calculation is based on [16], [17], [19]. The erosion criterion is based on the maximum displacement of a given node, usually defined in the centroid of a plane surface. For the implementation of the displacement-based erosion model some extra (compared to the normal erosion criteria) data should be defined. First, the critical point (usually the centroid) of the surface under consideration should be given. Second, the set of finite elements (usually the periphery of the surface) that will be eroded when the criterion will be fulfilled should be determined. Finally, a displacement threshold of the critical point should be given so that when this si reached the candidate elements are eroded. For laminated glass windows, this threshold is set to 30% of the span (distance between the extremities of the window).

Figure 11 presents the preparation of the extra inputs for the implementation of the proper erosion criterion. In this figure, only the candidate elements for erosion are depicted and as it can be observed they are laying on the boundaries of the glass panels. The centroid C of the glass panel can be observed in the figure. The threshold for the erosion is set to 0.1 m in order to reach the element erosion fast enough. When the blast overpressure wave reaches the glass panel, the panel starts to deform. When the displacement of the centroid fulfils the defined displacement criterion, the elements on the boundaries are eroded. The remaining parts of the glass panel move in the fluid mesh due to the inertia at the moment of the fragmentation and to the interaction with the surrounding fluid. The 45 elements that are located on the periphery of the glass panel, are eroded, producing 180 flying debris as depicted in Figure 12.

Table 5: PVB material properties

Density [kg/m³]	Young's modulus [Pa]	Poisson's ratio	Failure strain [%]
1100	3e6	0.46	200

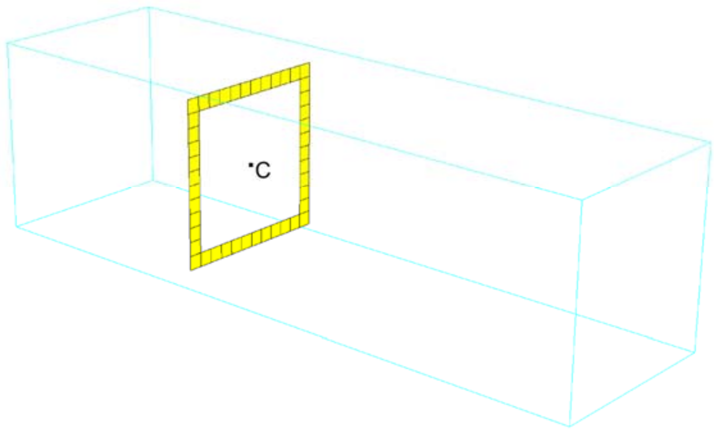


Figure 11: Model preparation for the displacement erosion criterion suitable for laminated glass

The produced flying debris have relatively low kinetic energy (not very likely to cause death injuries) since the velocity of the parent elements is not very high at erosion time. Since these are the only active flying debris, the death risk calculation with the "DEBR" option will most probably not produce any hazardous consequences. On the other hand, the detached flying glass panel is moving with a velocity capable of causing lethal injury on the human body. The use of the "DESP" keyword in this case will take into consideration the death risk that can result from the inactive flying debris that are attached to the non-eroded glass panel finite elements.

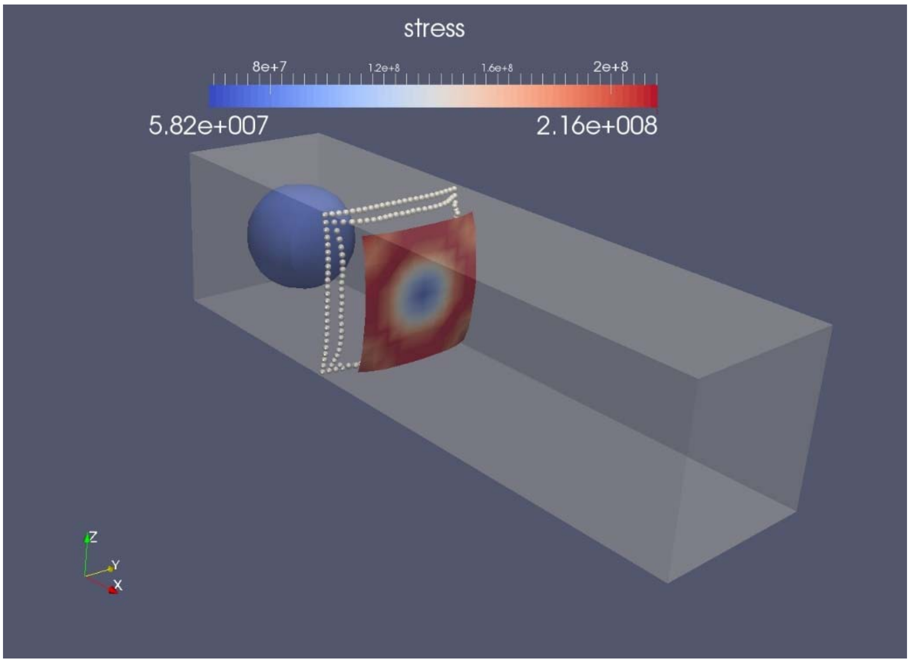


Figure 12: Panoramic view of the fragmentation of the laminated glass panel

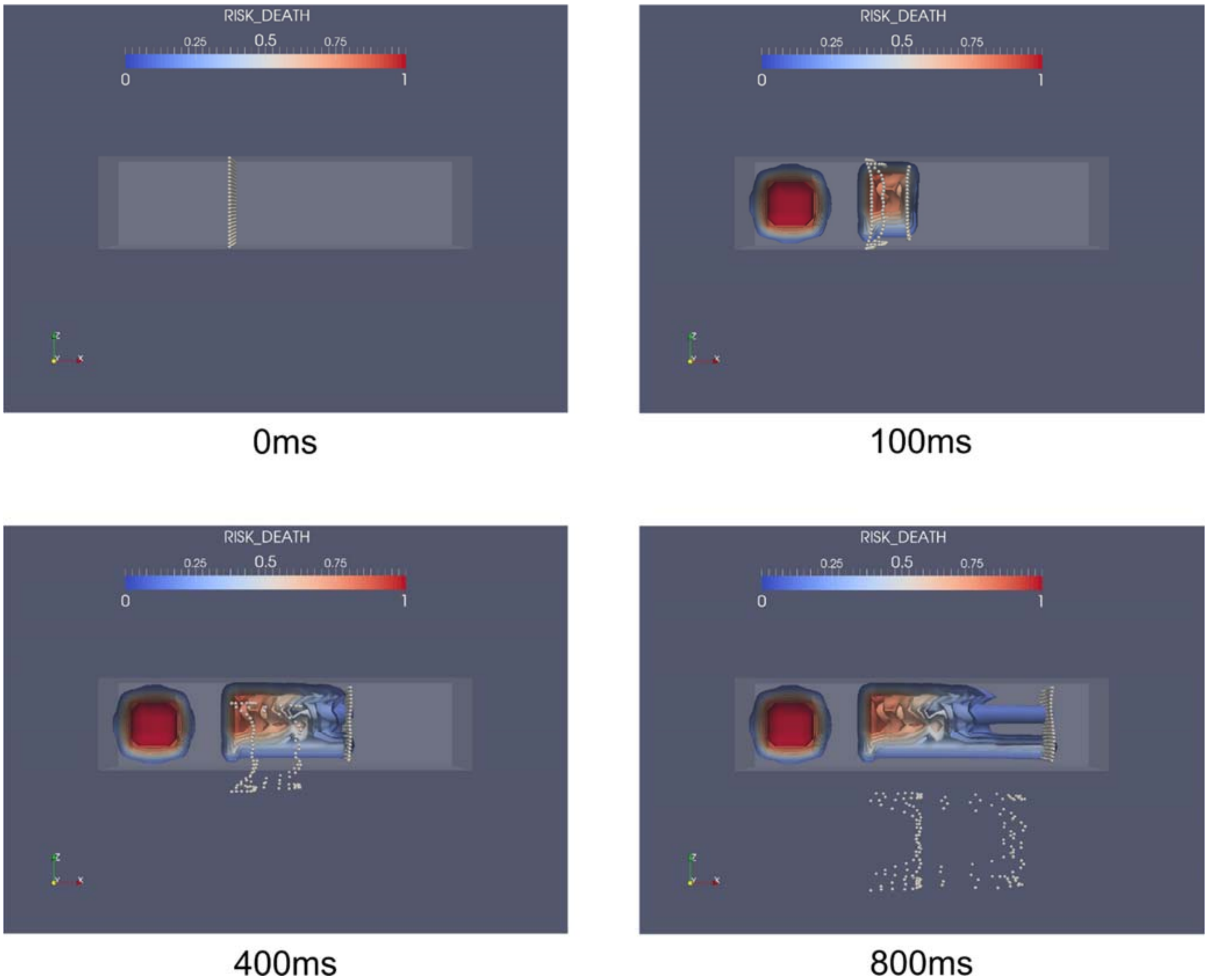
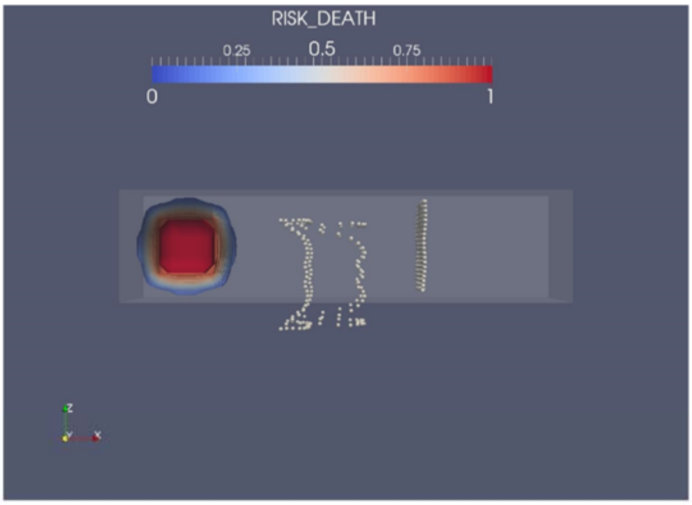


Figure 13: Death risk contour at various time instants

Figure 13 presents the death risk calculation for the current model at several time instants. Again, the spherical high-risk area around the bomb is due to the primary blast effects while the high-risk area beyond the glass panel is due to the secondary blast effects. The boundaries of the glass panel are fragmented 4.26 ms after the initiation of the simulation and the remaining panel starts to move in the fluid mesh with a velocity of 30 m/s. The kinetic energy of the flying glass panel is about 70 kJ, a value high enough to cause lethal injury. Each inactive flying debris has a mass of 0.3125 kg. If we consider that they have the velocity of the parent shell element the kinetic energy of one particle after the fragmentation is about 140J; a value high enough to cause lethal injury.

The velocity of the glass panel is reduced as it moves in the air; the kinetic energy and its lethality are reduced, too. The calculation of the model is performed up to 800 ms since the glass panel is moving slower (higher resistance force because of its shape) than the flying debris of the previous test case and it is taking longer to reach the end of the fluid mesh. At the final time steps only some of the inactive particles are having nonzero death risk value and this is justified by the fact that they are moving with a velocity of 15 m/s and the kinetic energy of about 35 J is not really hazardous. The active flying debris are having big Z-axis displacements because of the gravity force, and this is the reason why they are moving outside the fluid mesh.



death risk calculation with "DEBR" keyword

death risk calculation with "DESP" keyword

Figure 14: comparison of death risk calculation, with and without the contribution of the inactive flying debris

Figure 14 presents the death risk calculation with the two different options of the debris risk analysis. In the first case, the “DEBR” keyword has been used, meaning that only the active flying debris are considered in the debris risk calculation. Since the velocity of the active flying debris is not high enough to cause lethal injury, the risk analysis neglects any secondary blast effect casualties. In the second case the “DESP” keyword has been used, therefore also the inactive flying debris attached to the non-eroded elements are contributing to the risk analysis. It is obvious that the secondary blast effect risk is significant in the zone beyond the initial position of the glass panel since the panel is moving in such a way that it can cause lethal injury. It should be noted that the debris risk analysis is based on Lewis [11] formulation which is extracted from experiments with small projectiles (from 1-10 g), so the validity of the formula for macro-fragments is not clear.

4.3 Parametric study on the size of the flying debris

In the definition of the flying debris produced after the fragmentation of a structural part, there are many parameters of uncertainty like the shape, the size etc. For example, it is impossible to calculate in a deterministic way the shape of the produced projectiles after the fragmentation of a structure. In the literature [20], [21], some studies have developed models that can describe statistically the number and the size of the produced fragments. Although a study of the real size of the produced projectiles after a fragmentation caused by a blast is beyond the scope of the current report, an investigation has been made on the influence of the size of the flying debris on the death risk calculation.

A certain number of flying debris particles are attached to each element that can be eroded. The EUROPLEXUS user defines the number of particles in which the parent element will be split after erosion, through the keyword “PLEV” of the “DEBR” directive. The “PLEV” variable expresses the level of hierarchic subdivisions of the parent element, along each spatial direction in order to generate the particles. For example, a level of 3 means that 2^3=8 particles would be generated along each spatial direction. Therefore, a solid (3D) element will be filled with 8*8*8=512 particles while a shell (2D) element will be filled with 8*8=64 particles. It is clear that as the “PLEV” value is increased the number of particles is increased geometrically. Hence the user should take into account that with high values of “PLEV” it is possible to increase significantly the computational time and the required memory.

For the calculation presented the previous section, the value of “PLEV” was set to one, which means that on each quadrilateral element four particles are attached. This value is considered as a fair choice in order to have a realistic representation of the flying debris without having a huge number of particle elements. The length of each edge of the quadrilateral elements of the glass panel model is 0.25 m. This value is fairly high to perform an analysis of the fragmentation of a glass panel but it was selected in order to reduce the size of the model. Based on the size of the parent element of the model and the conservation of the mass the data of the produced particles are defined in Table 6 for various values of the hierarchy level.

Table 6: Hierarchic data for the produced particles

Hierarchy level	Number of debris per element	Mass per debris [gr]	Equivalent sphere radius [mm]	Velocity for 50% death risk [m/s]
0	1	781.4	42.1	34.7
1	4	195.3	26.5	43.7
2	16	48.8	16.7	55
3	64	12.2	10.53	69.4
4	256	3.1	6.6	87.4

The table shows the number of the parent element subdivision, the mass of each produced particle and the equivalent sphere radius. The particles that are produced from a quadrilateral element have quadrilateral shape but an equivalent sphere is calculated. In the last column of the table the particle velocity is presented that can cause 50% of death risk probability according to Lewis formulation. For the calculation of this critical velocity, the particles are considered spherical, so the impacting area is πR^2, where R is the radius of the sphere. The shape of the particles for quadrilateral elements in EUROPLEXUS is rectangular so the impacting area depends also on the "AFLY" value.

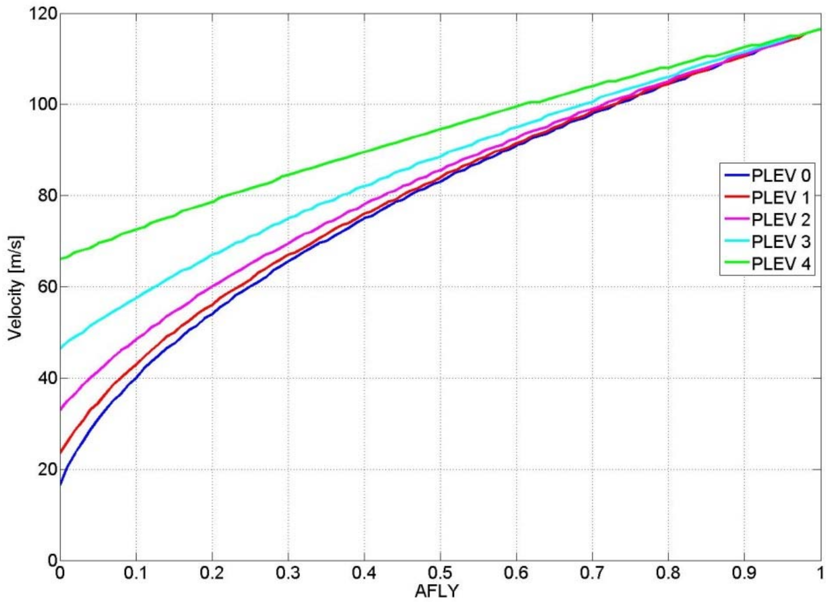


Figure 15: Influence of "AFLY" on the critical velocity for various "PLEV" values

Figure 15 depicts the influence on the death risk analysis of the “AFLY” value for several levels of hierarchic subdivision of the parent element. In the Y-axis of the plot is depicted the velocity of the particle that will cause 50% of death risk probability, while the in the X-axis the variation of the “AFLY” value is recorded. Five curves are depicted for five different values of the “PLEV” variable. “AFLY” equal zero results into the minimum impacting area, while “AFLY” equal one results into the maximum. It is obvious that the smaller the impacting area is (for the same particle mass) the lower the critical velocity (that produce 50% death risk) becomes.

As the level of subdivision (“PLEV”) increases, the variation of the critical velocity is getting smaller, hence for “PLEV”=4 (small particles) the critical velocity varies from 65 m/s to 118 m/s while for “PLEV”=0 (big particles) it varies from 18 m/s to 118 m/s. For “AFLY”=1 the critical velocity is independent from the level of subdivision. From a comparison of the values of the critical velocity of Table 6 (corresponding to a spherical particle) with the curves of Figure 15 it can be seen that a spherical particle corresponds to an average value of “AFLY” (0.4-0.5). Finally, it should be noted that “AFLY” value closer to zero is more realistic since the quadrilateral particles tend to align their larger dimension with their trajectory.

5 Conclusions

The objective of this work is to introduce the concept of secondary blast effects risk into the EUROPLEXUS explicit finite element code. The risk analysis module for the primary blast effects had already been developed in EUROPLEXUS and the objective of the present study is to enhance it by including the contribution of the flying fragments death risk.

The review of the literature concerning the human injuries caused by projectiles produced for example after a detonation clarifies the parameters that influence the death risk analysis. The main quantity that characterizes the hazardousness of a flying particle is the kinetic energy, since it couples the mass with the velocity. It has been found that also the impacting area of the projectile is essential for defining the severity of the injury that can be caused by a projectile on the human body.

An empirical formula that combines the kinetic energy and the presented area of the projectile has been implemented for the determination of the debris death risk in EUROPLEXUS. All the implementation details have been discussed thoroughly in order to clarify the selected strategy in the calculation. The debris risk module is able to estimate the fatalities caused by the macro-fragments during a simulation. There are cases where the fragmented structural parts are forming mainly macro-fragments, each composed by a patch of finite elements.

The results of the simulations that include the debris death risk highlight the necessity of the current development. The comparison of results with and without the contribution of the flying debris on the death risk analysis shows huge differences. There are many uncertainties in the determination of the produced projectiles after an explosive event. The influence of the size and the shape of the flying debris on death risk analysis has been discussed.

Further investigations are needed to determine the size and the shape of glass fragments in case of explosive events. The impact of these fragments and the influence of size, shape and orientation on human bodies should be investigated more in detail in order to generate more realistic results.

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7 Appendix

7.1 Simple test

test1.dgibi

```
opti echo 1;
opti dime 3 elem cub8;
opti sauv form 'test1.msh';
opti trac psc ftra 'test1_mesh.ps';
*
camD = 100.0;
oelz = 0 0 camD;
oel = camD camD camD;
oelm = (0 - camD) (0 + camD) (0 - camD);
tol = 1.E-3;
dx = 12.0;
dy = 3.0;
dz = 3.0;
Elfl = 0.25;
Elst = 0.25;
p1 = 0 0 0;
p2 = p1 PLUS (dx 0 0);
*p3 = p1 PLUS (dx dy 0);
p4 = p1 PLUS (0 dy 0);
*
nxf = ENTI ((dx + 0.01) / (Elfl));
nyf = ENTI ((dy + 0.01) / (Elfl));
nzf = ENTI ((dz + 0.01) / (Elfl));
list nxf;
list nyf;
list nzf;
*
nys = ENTI ((dy + 0.01) / (Elst));
nzs = ENTI ((dz + 0.01) / (Elst));
c1 = p1 D nxf p2;
s1 = c1 TRAN nyf (0 dy 0);
*
v1 = s1 VOLU TRAN nzf (0 0 (0+dz));
*
fluid = v1;
elim tol fluid;
*
absor = enve fluid;
dxs = 4.2;
*
c2 = p1 D nys p4;
c2n = c2 PLUS (dxs 0 0);
OUBL c2;
smesh = c2n TRAN nzs (0 0 dz);
sb = cont smesh;
coco = cont smesh;
mess(mesu coco);
Glp1 = smesh elem appuye largement coco;
LIST (NBEL Glp1);

Glb1 = smesh point proc(smesh bary);
LIST (NBEL smesh);
elim (smesh) 1e-4;

fmesh = fluid et absor;
*!!!! OBLIGATORY
TASS smesh NOOP;
*!!!! OBLIGATORY
fmesh = fmesh coul turq;
*TASS fmesh NOOP;
TRAC qual cach fluid;
LIST (NBEL fluid);
LIST (NBNO fluid);
*
LIST (NBEL smesh);
elim tol smesh;
mesh = smesh ET fmesh;
elim tol mesh;
TRAC oel CACH QUAL ( smesh );
TRAC oel CACH QUAL ( mesh );
TRAC oelm CACH QUAL ( mesh );
TASS mesh NOOP;
SAUV FORM mesh;
*
fin;
```

test1.epx

```
TEST1 (STRUCTURE + FLUID)
ECHO
 CONV WIN
CAST mesh
EROS 0.0
RISK DESP
TRID ALE
DIME
  DEBR 576
  NALE 1
  NBLE 1
TERM
GEOM Q4GS smesh FL38 fluid CL3Q absor TERM
COMP EPAI 0.008 LECT smesh TERM
     DEBR
     ROF 1.0                        ! let
particles move in vacuum
     FLUI LECT fluid TERM HGRI 0.251 ! grid
size > fluid Smesh size
     FILL PLEV 1                      ! select
the level
         RO 2500 DRAG 1.0 COUP AFLY 0.0 OBJE
LECT smesh TERM
     GROU 3 'bomb' LECT fluid TERM
                   COND SPHE XC 1.5 YC 1.5 ZC
1.5 R 0.5
            'air'  LECT fluid DIFF bomb TERM
            'CATOUS'  LECT TOUS TERM
                   COND ZB LT 1.5
                   COND YB LT 1.5
     COUL ROUG LECT bomb TERM
          JAUN LECT smesh TERM
          TURQ LECT air TERM
GRIL LAGR LECT smesh _DEBR TERM
     EULE LECT fluid TERM
MATE
     GLAS RO 2500 YOUN 7.E10 NU 0.23
          CORR 16 FAIL PSAR LIMI 159.6E6
          LECT smesh TERM
     FLUT RO 1.0 EINT 2.5E5 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL
0.5
          CQ 2.56 PMIN 0 NUM 1 PREF 1.E5
          LECT air bomb TERM
     BUBB MASS 5.0
          LECT bomb TERM
     IMPE ABSI LECT absor TERM
LINK COUP SOLV SPLI
          SPLT NONE
     BLOQ 123456 LECT sb TERM
     FLSR STRU LECT smesh _debr TERM
          FLUI LECT fluid       TERM
          R    0.2175 ! 0.87*H_FLUID = 0.87*0.5
          HGRI 0.3  ! > THAN BIGGER STRUCTURAL
ELEMENT !!!
          BFLU 2 ! BLOCK FLUXES
          FSCP 1 ! COUPLE ALONG ALL DIRECTIONS
CHAR CONS GRAV 0.0 0.0 -9.81
               LECT _DEBR TERM ! gravity acts
only on debris particles
ECRI VITE CONT ECRO TFRE 50.E-3
          POIN LECT 1 TERM
          ELEM LECT 1 TERM
     FICH SPLI ALIC TFRE 5.E-3
OPTI NOTE
```

```
     CSTA 0.8
     LOG 1
     FLS CUB8 2 ! to avoid problem with cub8
inverse mapping ...
CALC TINI 0 TEND 400.E-3
FIN
```

test1L.epx

```
TEST1L (STRUCTURE + FLUID)
ECHO
 CONV WIN
CAST 'test1.msh' mesh
EROS 0.0
RISK DESP
TRID ALE
DIME
  DEBR 576
  NALE 1
  NBLE 1
TERM
GEOM Q4GS smesh FL38 fluid CL3Q absor TERM
COMP EPAI 0.008 LECT smesh TERM
     SAND 3
     FRAC 0.4 0.2 0.4
     NGPZ 2 1 2
     LECT smesh term
     DEBR
     ROF 1.0                       ! let
particles move in vacuum
     FLUI LECT fluid TERM HGRI 0.251 ! grid
size > fluid Smesh size
     FILL PLEV 1                     ! select
the level
         RO 2500 DRAG 1.0 COUP AFLY 0.0 OBJE
LECT smesh TERM
     GROU 3 'bomb' LECT fluid TERM
                  COND SPHE XC 1.5 YC 1.5 ZC
1.5 R 0.5
           'air'  LECT fluid DIFF bomb TERM
           'CATOUS'  LECT TOUS TERM
                  COND ZB LT 1.5
                  COND YB LT 1.5
     COUL ROUG LECT bomb TERM
          JAUN LECT smesh TERM
          TURQ LECT air TERM
FAIL DISP 1e-1 NODE LECT Glb1 TERM OBJE LECT
Glp1 TERM
EROS 0.0 LECT Glp1 TERM
GRIL LAGR LECT smesh _DEBR TERM
     EULE LECT fluid TERM
MATE
     LSGL RO 2500 YOUN 7E10 NU 0.23 CORR 16.0
     LECT smesh TERM
     laye lect 1 3 term
     VM23 RO 1100. YOUNG 2.2E8 NU 0.495 ELAS
11E6
     TRAC 3 11e6 0.05 30e6 2.25 172e6 20.
     LECT smesh TERM
     laye lect 2 term
     FLUT RO 1.0 EINT 2.5E5 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL
0.5
          CQ 2.56 PMIN 0 NUM 1 PREF 1.E5
          LECT air bomb TERM
     BUBB MASS 5.0
          LECT bomb TERM
     IMPE ABSI LECT absor TERM
LINK COUP SOLV SPLI
          SPLT NONE
     BLOQ 123456 LECT sb TERM
     FLSR STRU LECT smesh _debr TERM
          FLUI LECT fluid       TERM
          R    0.2175 ! 0.87*H_FLUID = 0.87*0.5
          HGRI 0.3  ! > THAN BIGGER STRUCTURAL
ELEMENT !!!
          BFLU 2 ! BLOCK FLUXES
          FSCP 1 ! COUPLE ALONG ALL DIRECTIONS
CHAR CONS GRAV 0.0 0.0 -9.81
               LECT _DEBR TERM ! gravity acts
only on debris particles
ECRI VITE CONT ECRO TFRE 50.E-3
          POIN LECT 1 TERM
          ELEM LECT 1 TERM
     FICH SPLI ALIC TFRE 5.E-3
OPTI NOTE
     CSTA 0.8
     LOG 1
     FLS CUB8 2 ! to avoid problem with cub8
inverse mapping ...
CALC TINI 0 TEND 900.E-3
FIN
```

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Abstract

This study presents a numerical approach for the calculation of fatality risk caused by the impact of flying debris on the human body. Following an explosion, the formation of a large number of high velocity flying fragments, especially from glass panels, is very possible. The velocity, the mass and the shape of these projectiles define their hazardousness. The developed numerical approach is integrated into the fluid-structure techniques, commonly used for the determination of the behavior of a structure under blast loading. The implementation of the numerical approach in the EUROPLEXUS code is described thoroughly.

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