Technical Sciences
Lange Kleiweg 137
2288 GJ Rijswijk
P.O. Box 45
2280 AA Rijswijk
The Netherlands

www.tno.nl

T +31 88 866 80 00
F +31 88 866 69 49
infodesk@tno.nl

TNO report

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Numerical simulation of blast loading on Malaysia Airlines flight MH17 due to a warhead detonation

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Appendices

1 Introduction

The Dutch Safety Board (DSB) investigates the crash of Malaysia Airlines flight MH17 which occured on Thursday July 17, 2014 in the Donetsk region (Ukraine). The DSB wants to provide a clear picture of the cause of the crash. A possible cause is fatal damage to the aircraft due to detonation of the warhead of a guided weapon.

TNO was asked to analyse the observed damage on recovered parts of the aircraft, in search for damage that is typically caused by a warhead detonation. TNO was able to establish a probable detonation point for a fragmenting warhead through a combination of damage characterisation and terminal ballistics simulations [1]. A fragmenting warhead causes damage due to impacting fragments and explosive overpressure (blast). The observed damage to the aircraft revealed a pattern of perforations that is typical for a warhead with preformed fragments. Damage due to blast, as far as this could be confirmed, supports the findings.

Fragments with enough kinetic energy are able to destroy critical components deep inside the aircraft. Sufficiently strong blast is able to destroy a wide surface area on the aircraft. Combined effects, such as blast loading on already weakened structures due to fragment impacts or heat from the explosion, may further enhance the damage potential. The DSB wants to know if blast from the warhead is able to damage or destroy parts of the aircraft. To assess the damage potential of blast one must establish the amount of blast loading that is exerted locally on the aircraft, and the aircraft’s response to the load. The research question is about the first step of such an assessment: what is the local blast loading on the aircraft as a result of the detonation of the warhead?

The objective of this investigation is to establish the blast pressure evolution for a number of discrete points on the aircraft contour. This information can be used by the DSB to predict possible failure of the aircraft structure. A so-called Computational Fluid Dynamics (CFD) simulation has been performed to provide high-fidelity quantitative description of the blast loading.

This study uses classified data as described in the *Wet Bescherming Staatsgeheimen*. The text of this report has been inspected and released for publication by the Netherlands Ministry of Defence.

In order to calculate the pressure evolution, a detailed three-dimensional CFD calculation has been performed with the AUTODYN software. In the simulation the warhead is detonated at the probable position and orientation with respect to the aircraft. The setup of the simulations is described in Chapter 2, whereas the simulations results are presented in Chapter 3.

2 Simulation setup

The AUTODYN software version 14.5 [2] was used to simulate the propagation of the blast wave from a warhead near the aircraft and its interaction with the aircraft. The simulation does not account for the response of the aircraft to the blast loading. The software simulates the complete flowfield around the aircraft and the spatial and temporal description of the blast loading on the aircraft is retrieved.

The CFD calculation is built from three elements in order to properly represent the blast loading, namely the warhead, the aircraft and the surrounding atmospheric air. These elements are described in Section 2.2 and the numerical procedure followed for the blast loading simulations is described in Section 2.3. First, in Section 2.1, some introductory information on blast is given.

2.1 Background on the nature of blast

High Explosives (HE) are solid materials with the ability to detonate. During detonation the state of the HE changes extremely rapidly into a hot gas. Typical detonation pressures inside the explosion position are in excess of 20 GPa with a temperature of about 3000 K. A blast wave is formed due to this sudden and large amount of released energy.

The front part of a blast wave is the shock front which causes an instantaneous rise in pressure. This is called the peak pressure. The shock front of the blast wave propagates supersonic, compresses the air and gives a particle velocity increase in same direction as the wave. The mathematical integral over the pressure – time history is called the impulse.

With increasing distance from the detonation position the peak pressure decreases and the duration of the pressure increases for constant charge mass. As long as the propagating blast wave does not hit a body the pressure is called the incident pressure. When the blast wave interacts with a body a reflection occurs giving a local rise in pressure that becomes several times the incident pressure. The loading on a body due to blast differs significantly from static loading:

- The blast loading gives a sharp rise in pressure which is not the case for a slowly applied pressure.
- The duration of a blast loading of a conventional warhead is significantly shorter than for a slowly applied pressure.
- The dynamic behaviour of the blast wave requires obtaining the pressure-time history at specific locations in order to describe the loading.

2.2 Definition of simulation elements

2.2.1 Warhead

In consultation with the DSB, the modelled warhead is type 9N314. The warhead, with a total mass of 70 kg, consists of a steel casing with preformed fragments and a High Explosive (HE) charge [3]. The geometric charge mass shape is approximated by a cylinder. The energy contained in the HE charge is used to break-up the casing, accelerate the fragments and generate an explosive overpressure called *blast*. Hence, only a certain portion of the total HE energy is responsible for the blast. The type of HE used in the warhead model is "Composition B", which consists of 60% RDX and 40% TNT by weight. Open literature provides several different mathematical relationships to calculate the HE energy fraction responsible for the blast wave, or "equivalent bare charge mass". In this study the equivalent bare charge mass was derived from an empirical model using the "modified Fisher" relationships [4]. The derived equivalent bare charge mass represents a worst case situation, i.e. the strongest possible blast emanating from the warhead.

2.2.2 *Aircraft*

A model of the aircraft was obtained from a public source on the internet [5]. The model, shown in Figure 2.1, is a 3D solid structure (21 rigid bodies). The main dimensions of the model were verified against the main dimensions of the actual aircraft (see Figure 2.2). The model was found to be an accurate representation of the aircraft for the purpose of this study.

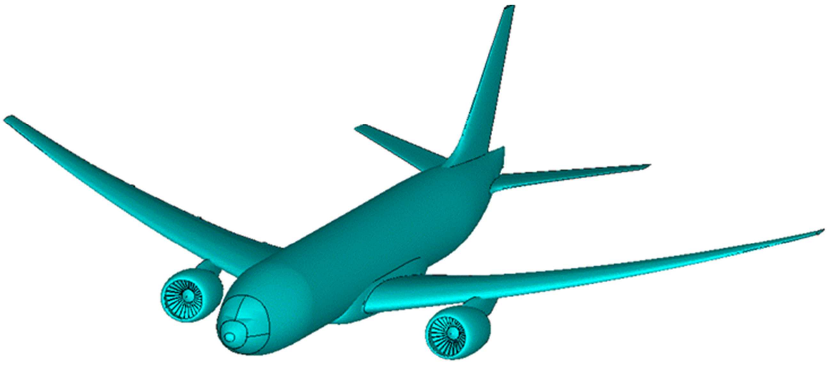

Figure 2.1 Boeing 777 in Solid Works 2012 format. The model is available in the GRABCAD model repository [5]. Note that the model shows the aircraft "in flight": the wing tips are curved upwards due to the lift force.

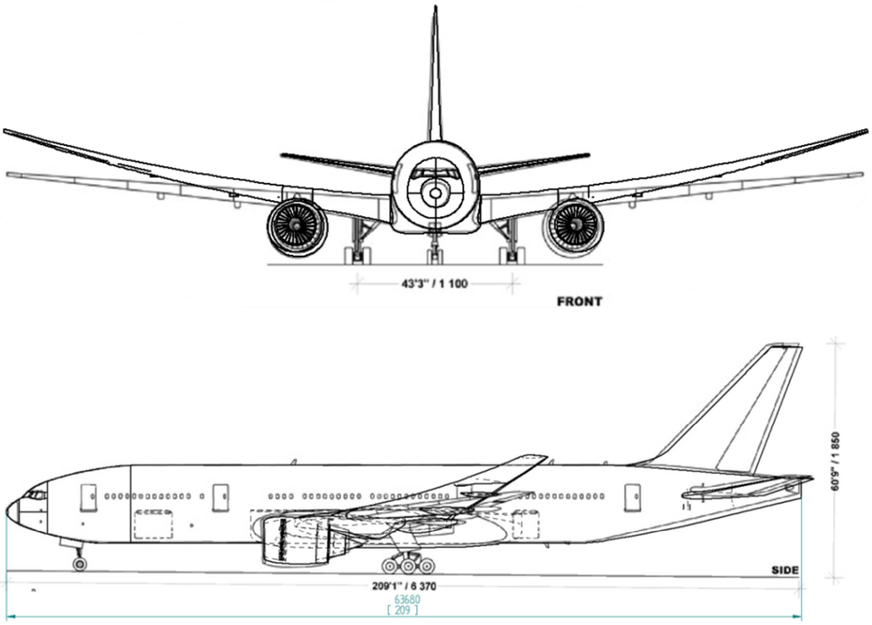

Figure 2.2 Model verification against the main dimension of the Boeing 777-200ER [6]. The GRABCAD model in black was superimposed on the aircraft drawing in grey. The difference in the wingtip locations is 1.3 m.

The time required for the blast wave to propagate along the aircraft is much shorter than the typical time at which the aircraft starts to deform. This allows the aircraft body to be modelled as a rigid body since any material deformation is negligible in the blast timescale. The thus calculated blast load on the outer contour of the aircraft is the maximum load.

2.2.3 *Atmospheric air*

The warhead detonated at an altitude of approximately 10 km (flight level 330). At this altitude the ambient air properties used in the CFD simulation are as follows:

- Density: 0.41 kg/m^3
- Pressure: 26.21 kPa
- Temperature: 223 K

2.3 Numerical procedure

The complete blast event is simulated in two stages, namely the near-field development of the blast wave close to the warhead, and the interaction of the blast wave with the aircraft. In the first stage the blast is simulated over the distance that separates the warhead from the aircraft. The flowfield of this simulation is then re-mapped in a larger domain that includes the complete aircraft. This procedure allows a fine numerical grid (small CFD elements) to be used close to the warhead. This is necessary to properly describe the large pressure gradients across the initial development of the blast wave. The numerical grid of the second stage is made coarser in order to encompass the complete aircraft.

2.3.1 *Near-field development of the blast wave*

Initial conditions for the near-field blast wave are summarised in Figure 2.3. The warhead is moving at a velocity of ~600 m/s [1] and travels through quiescent air. The warhead is detonated from the centre of the charge. The CFD simulation is two-dimensional axisymmetric around the axis of the cylindrical charge mass. The numerical grid used for this simulation is 2000 × 1000 cells and covers a distance of 8 m longitudinally and 4 m radially. Therefore the cell size used is 4 mm. The 4 mm cell size is sufficient to properly resolve the pressure profiles (see Appendix A). The simulation is carried out until the blast front reached a radial distance of 3 m.

The flowfield at that stage is then imported into the larger numerical grid for the second stage including the interaction with the aircraft. The ideal gas equation of state is used for the air and the HE detonation products are modelled using the so-called Jones-Wilkins-Lee (JWL) equation of state. The parameters for air and Composition B are provided in Table 2.1.

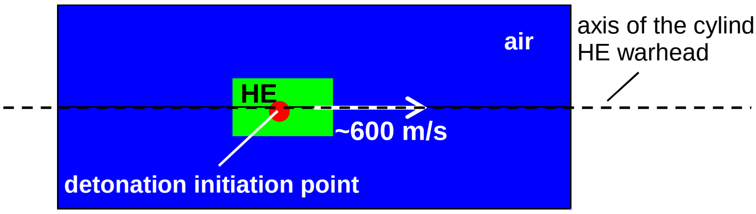

Figure 2.3 Initial conditions for the blast wave development near the warhead. The HE charge mass is shown in green and moving at an initial velocity of ~600 m/s whereas the quiescent air is shown in blue. The detonation initiation point is shown with a red circle and the simulation is axisymmetric around the axis of the cylindrical warhead.

Table 2.1 Equation of state parameters and values for atmospheric air and Composition B.

Ideal gas parameters	Air	JWL parameters	Composition B [7]
ratio of specific heats	1.4	*A* (GPa)	524.23
		B (GPa)	7.678
		R_1	4.2
		R_2	1.1
		CJ detonation velocity (m/s)	7980
		CJ energy (GJ/m^3)	8.5
		CJ pressure (GPa)	29.5

2.3.2 Interaction of the blast wave with the aircraft

For reference Figure 2.4 shows the approximate location of the warhead at the time of detonation with respect to the aircraft. The warhead position and orientation in the reference coordinate system are shown in Figure 2.5. The aircraft and warhead velocities are 254 m/s and ~600 m/s, respectively [1].

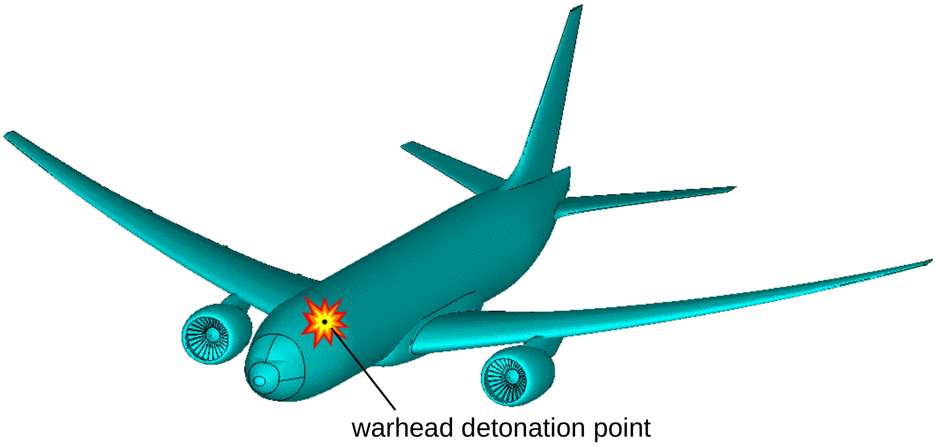

Figure 2.4 At the time of detonation, the location of the warhead with respect to the aircraft is near the left-hand side of the fuselage and close to the cockpit.

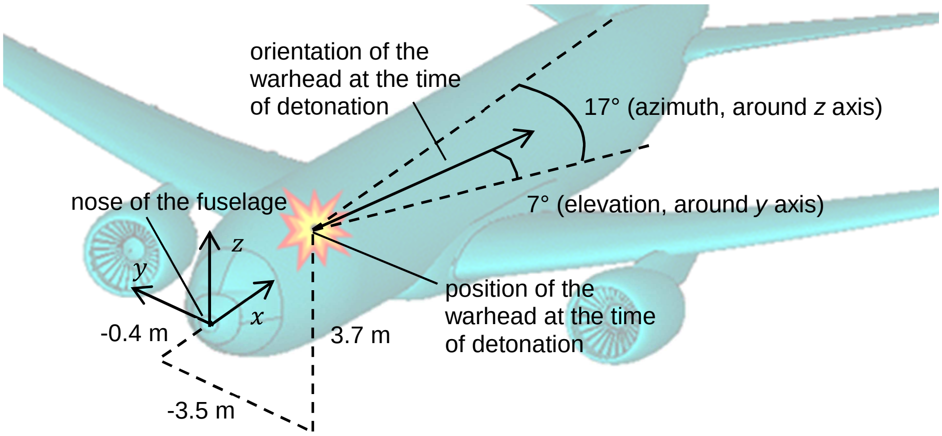

Figure 2.5 Position and orientation of the warhead with respect to the aircraft at the time of detonation. This information is taken from the investigation reported in [1] and involves warhead design I at the initial position and orientation [1, Table A.1].

Note that warhead design I at the initial position and orientation results in a match with the observed fragment hit pattern at the time this blast study was performed (April 2015). In July 2015, new data enabled the exploration of different warhead designs, resulting in a “best match” on a slightly offset location [1]. The different warhead designs affect mainly the fragmentation. The best match is ~1 m closer to the aircraft, resulting locally in a somewhat higher blast loading than presented in this report. The blast loading further away from the point of detonation remains in the same order of magnitude.

At every time step during the simulation the loading applied on the aircraft is recorded by virtual “pressure gauges” on the aircraft. The location of these pressure gauges is presented in Figure 2.6 and Figure 2.7 with red symbols. In the CFD simulation three groups of pressure gauges are defined:

- Top gauges (69 in total), positioned horizontally on the left-hand side of the fuselage at the shortest distance from the warhead position at the time of detonation.
- Lateral gauges (64 in total), positioned horizontally on the left-hand side of the fuselage and closest to the wing attachment to the aircraft.
- A single bottom gauge, located on the right-hand side of the fuselage at the position of panel AAHZ3112NL, which showed damage that is suspected to stem from blast [1].

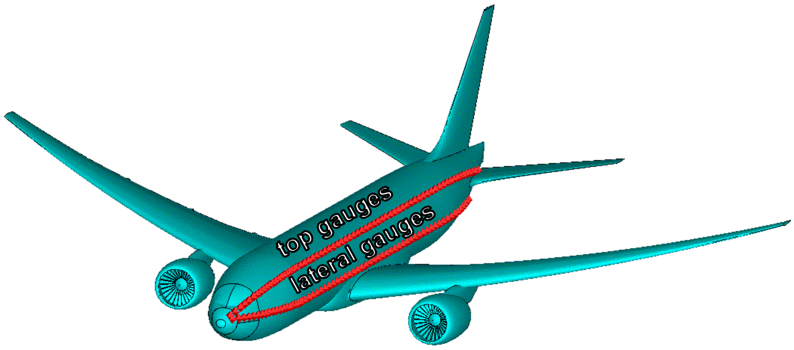

Figure 2.6 Location of the lateral and top pressure gauges on the left-hand side of the aircraft.

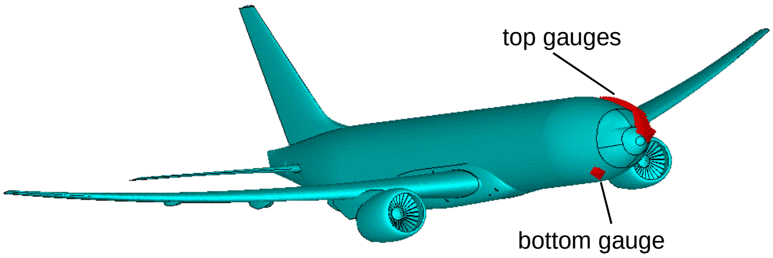

Figure 2.7 Location of the bottom pressure gauge on the right-hand side of the aircraft.

The three-dimensional numerical grid consists of 533 × 267 × 200 cells (along the x, y and z axis, respectively) covering a distance of 160 × 80 × 60 m centred around the warhead detonation point. Non-uniform cell sizes were used in order to provide a finer grid (cell size of 50 mm) at the detonation point and a coarser grid (cell size of approximately 1 m) farthest from the detonation point. This is allowed because the pressure gradient across the blast wave becomes smaller when moving further away from the point of detonation.

3 Simulation results

The outcome of the CFD simulations are presented in this chapter. The results for the near-field development of the blast wave are given in Section 3.1. The results of the interaction of the blast wave with the aircraft are given in Section 3.2.

3.1 Near-field development of the blast wave

The blast generated by the cylindrical warhead is displayed in Figure 3.1 showing the pressure distribution. At 0.91 ms after detonation the blast front has reached a distance of 3.0 m in the radial direction and 3.3 m in the longitudinal direction from the detonation point. In the near-field, the blast is not spherical due to the cylindrical shape of the warhead and due to the fact that the warhead is initially moving towards the right. Non-linear effects will eventually result in a spherical propagation of the blast wave at some distance from the detonation point.

The peak pressure, approximately 1600 kPa, is found in the upwind direction. In downwind direction the peak pressure is approximately 1100 kPa. In radial direction the pressure reaches approximately 1400 kPa. The lowest blast pressure is in the 45° downwind direction, approximately 600 kPa. The non-spherical pressure distribution shows the importance of accounting for the cylindrical shape of the warhead (as opposed to spherical) as well as the velocity of the warhead (as opposed to a static condition). At later times the blast interacts with the aircraft mainly in the radial direction.

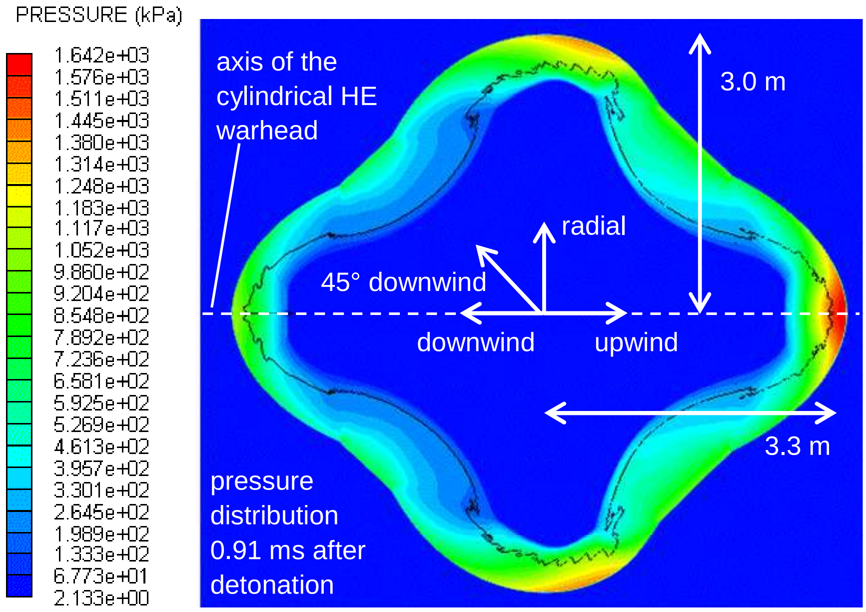

Figure 3.1 Pressure distribution of the blast wave from the warhead 0.91 ms after detonation. At this time the blast front reaches a distance of 3.0 m in radial direction and 3.3 m in longitudinal direction. The blast is not spherical due to the cylindrical shape and the velocity of the warhead. The initial velocity of the warhead points to the right, causing the peak pressure to be highest in upwind direction (approximately 1600 kPa).

The pressure profiles of the blast wave 0.91 ms after detonation along the upwind, downwind, 45° downwind and radial directions are shown in Figure 3.2. The accuracy of the pressure profiles is verified by means of a grid convergence study that is provided in Appendix A.

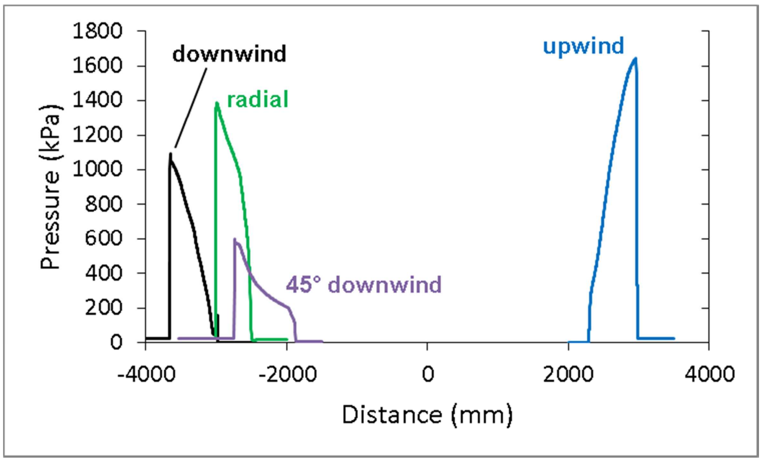

Figure 3.2 Pressure profile (positive phase shown) of the blast wave from the warhead at 0.91 ms after detonation along four directions: upwind, downwind, 45° downwind and radial (see Figure 3.1 for the definition of directions). The peak pressure along these four directions are approximately 1600 kPa, 1100 kPa, 600 kPa and 1400 kPa, respectively.

3.2 Interaction of the blast wave with the aircraft

3.2.1 Blast loading on the fuselage

The flowfield presented in Figure 3.1 and Figure 3.2 is the input for the simulation of the interaction between the blast wave with the aircraft. The transfer of the flowfield conditions from the first stage of the simulation to the second stage is referred to as the remapping procedure. The correct execution of the procedure is verified by tracing the pressure profiles from both stages (see Appendix B for details). The blast loading on the fuselage can then be determined until the blast reaches the tail of the aircraft, or until the magnitude of the blast becomes negligible.

The blast wave is visualised at four different times in Figure 3.3 through Figure 3.6. Viewed from the front (left figures) and the top (right figures) the blast wave is shown using lines of constant pressure. The maximum (red) and minimum (blue) pressures are displayed on each figure. Features that can be observed from the front view is the reflection of the blast from the fuselage (see Figure 3.4) and the propagation of the blast around the fuselage (see Figure 3.5). Features that can be observed from the top view is the blast propagation towards the nose (see Figure 3.4) and towards the leading edge of the wing (see Figure 3.5 and Figure 3.6).

The pressure-time history is provided in Figure 3.7 at four locations along the fuselage: 0 m (at the nose), 2.5 m (at the shortest distance with the warhead), 10 m and 25 m (at the root of the wing's leading edge). The highest calculated peak pressure is 2500 kPa occurring at 2.5 m from the nose. At 10 m and 20 m from the nose the peak pressure decreases to 88 kPa and 41 kPa, respectively. The duration of the blast varies between approximately 3 ms and 7 ms.

The accuracy of the pressure evolution shown in Figure 3.7 is addressed in Appendix C. It is explained that the peak pressure at 2.5 m is underestimated due to a numerical artefact (choice of cell size) whereas the other peak pressures are correctly estimated. With use of the proper cell size at 2.5 m a peak pressure of 5000 kPa is calculated, which is a better estimate.

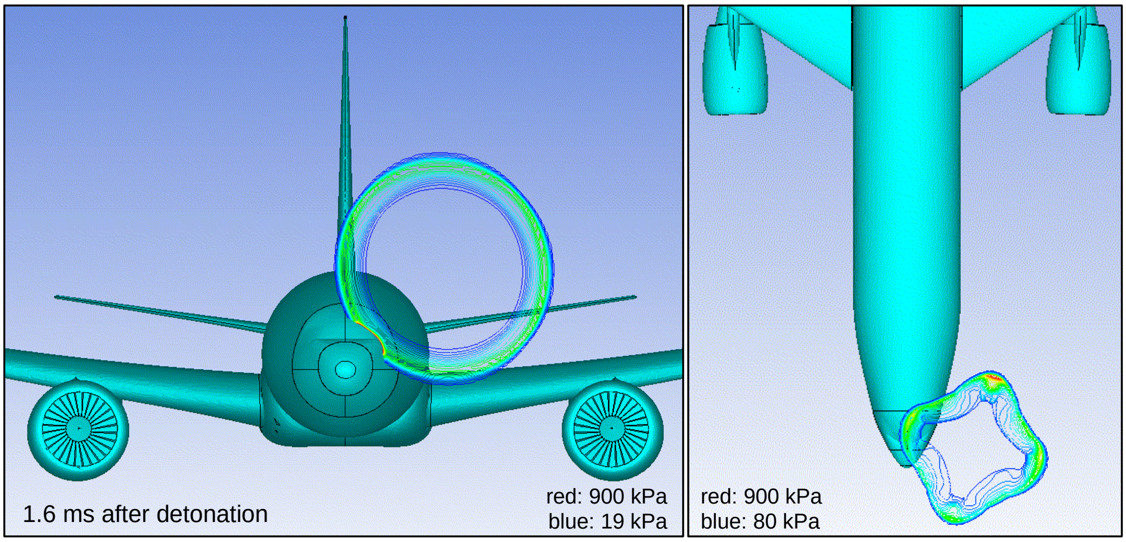

Figure 3.3 Lines of constant pressure 1.6 ms after detonation from the front view (left) and the top view (right). The blast first interacts with the aircraft at the cockpit area. Views include the numeric values of maximum (red) and minimum (blue) peak pressure.

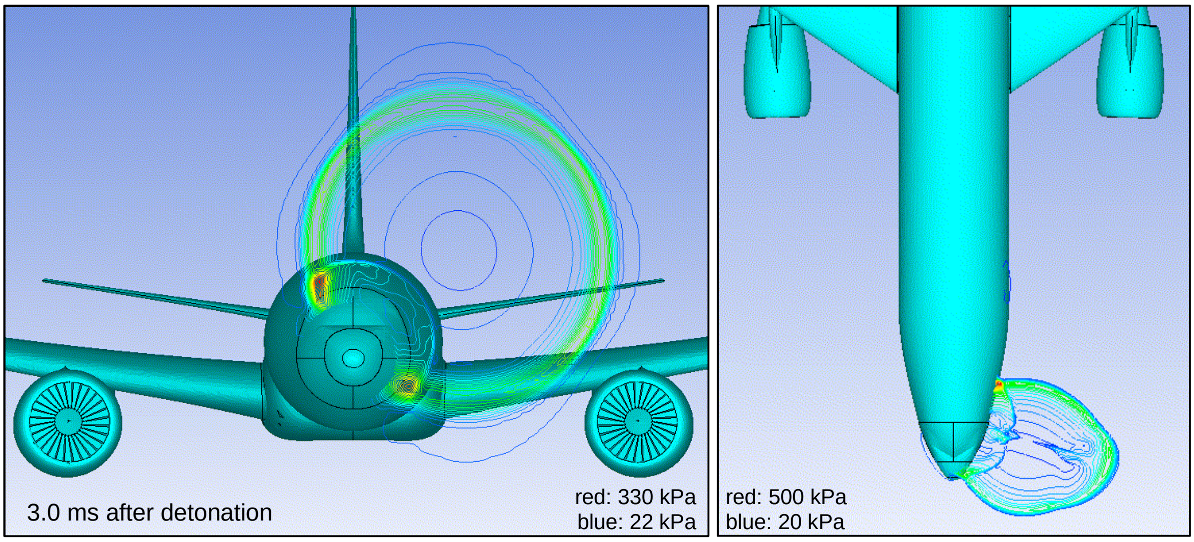

Figure 3.4 Lines of constant pressure 3.0 ms after detonation from the front view (left) and the top view (right). The blast interacts with the aircraft at the cockpit area. Views include the numeric values of maximum (red) and minimum (blue) peak pressure.

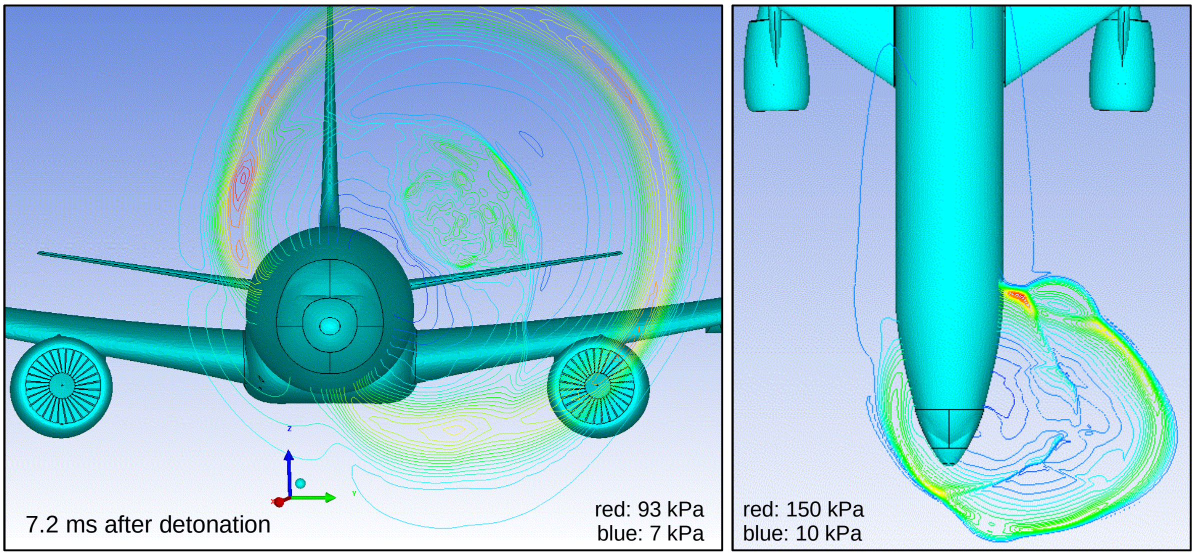

Figure 3.5 Lines of constant pressure 7.2 ms after detonation from the front view (left) and the top view (right). The blast interacts with the entire front section of the fuselage including the right-hand side. Views include the numeric values of maximum (red) and minimum (blue) peak pressure.

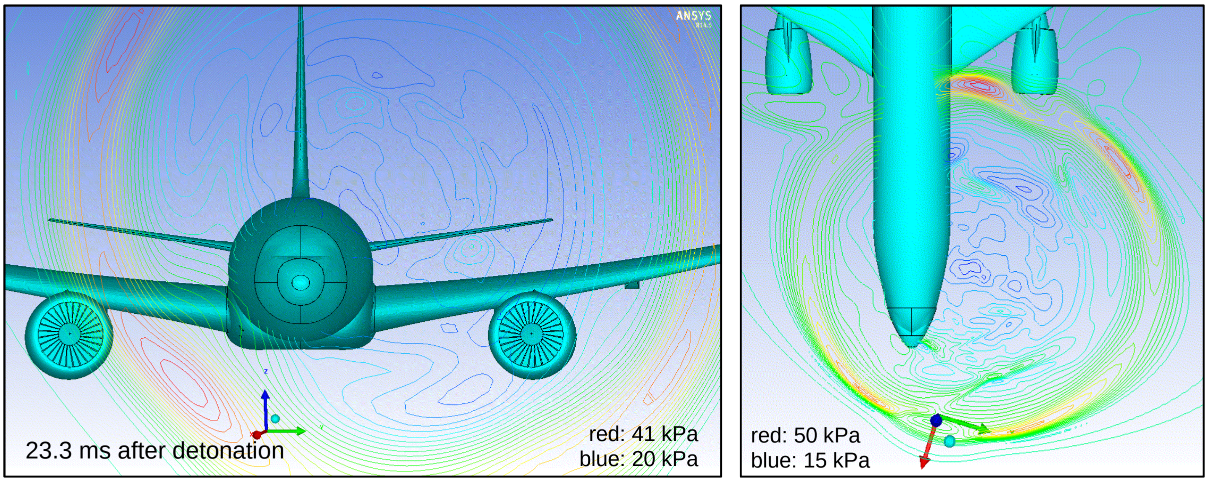

Figure 3.6 Lines of constant pressure 23.3 ms after detonation from the front view (left) and the top view (right). The blast front reaches the leading edge of the wing at the wing root. Views include the numeric values of maximum (red) and minimum (blue) peak pressure.

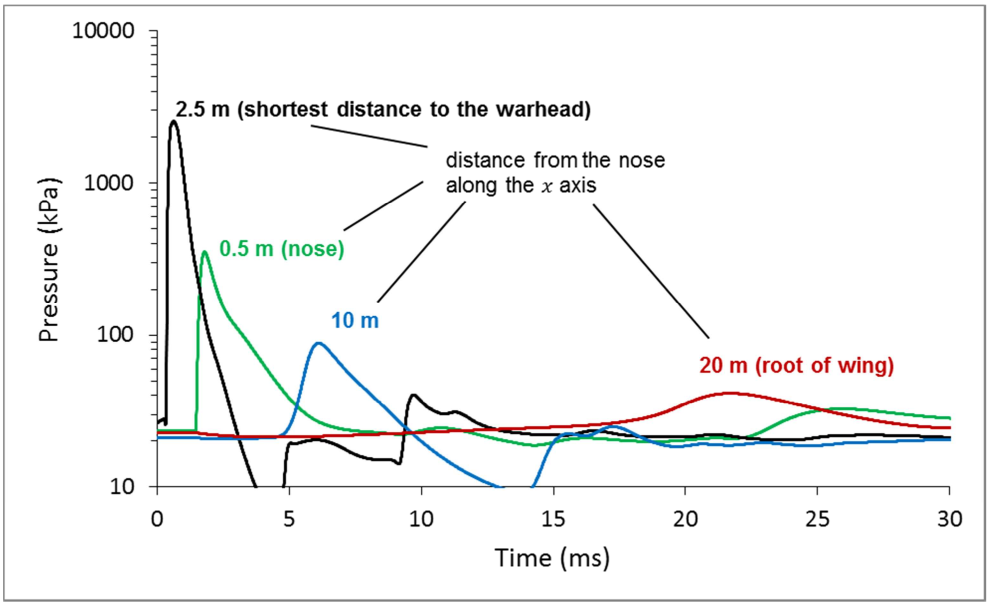

Figure 3.7 Pressure evolution until 30 ms after detonation at four locations: 0.5 m, 2.5 m, 10 m and 20 m from the nose. The peak pressure is the highest 2.5 m from the nose and reaches 2500 kPa with the applied numeric cell size. At 10 m from the nose the peak pressure has decreased to 88 kPa. The duration of the blast varies between approximately 3 ms and 7 ms.

Figure 3.8 shows the peak pressures recorded at each position along the aircraft for the top, lateral and bottom pressure gauges. The highest peak pressure is recorded at 2.5 m from the nose and reaches 5000 kPa. The error bar in Figure 3.8 is added to highlight the uncertainty of the CFD simulation at this particular position on the fuselage (see Appendix C).

The peak pressure decreases with increasing distance from the 2.5 m position and drops below 75 kPa beyond 12.5 m from the nose. In [1], 75 kPa was taken to be the threshold for the mildest form of blast damage (so-called *dishing*). At the leading edge of the wing root (20 m) the peak pressure is in the order of 40 kPa and keeps decreasing until the effect of the blast becomes negligible at approximately 35 m. Beyond this distance from the nose the peak pressure remains at the ambient atmospheric air pressure value of 26.2 kPa.

The peak pressure measured by the bottom gauge on the right-hand side of the fuselage is 43 kPa. The small increase in pressure near the wing's leading edge is caused by blast reflection waves.

In addition to the peak pressure, the impulse exerted on any particular location of the aircraft also characterises the blast loading event. The (specific) impulse at any given location is obtained by integrating the pressure over time as follows:

$$I = \int_0^{t'} (p - p_{atm}) dt$$

where p is the absolute pressure, p_{atm} is the atmospheric pressure at 10 km (i.e. 26.2 kPa) and t' refers to the end of the positive phase of the pressure profile (where the pressure becomes less than the atmospheric value at 10 km). The impulse along the fuselage is presented in Figure 3.9. The highest impulse occurs at 2.5 m from the nose and reaches 1600 Pa·s. The impulse decreases for increasing distance from the nose to approximately 180 Pa·s at the root of the wing. Beyond a distance of 35 m the impulse drops below 100 Pa·s.

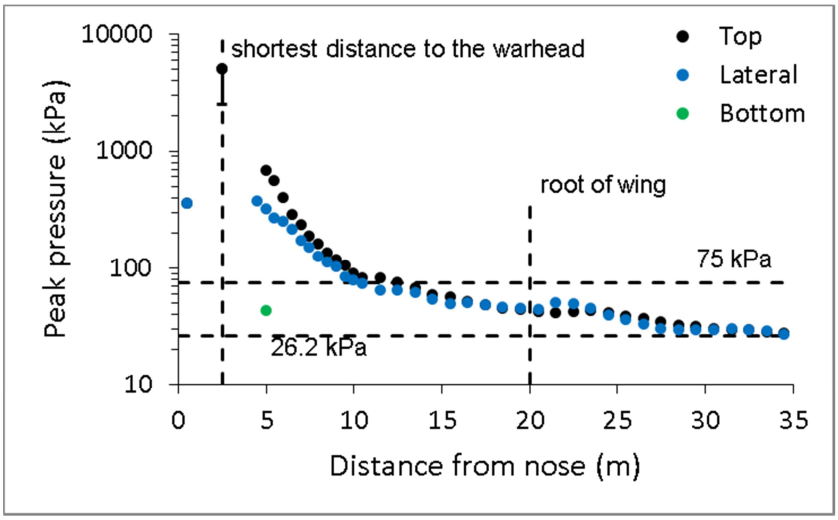

Figure 3.8 Peak pressure along the aircraft measured with the top, lateral and bottom gauges. The highest peak pressure is obtained at 2.5 m from the nose and reaches up to 5000 kPa (see Appendix C). The peak pressure decreases for increasing distance from the nose and drops below 75 kPa (according to [1] a threshold for blast damage) at 12.5 m. At the root of the wing the peak pressure is 40 kPa. Beyond 35 m the effect of the blast wave is negligible.

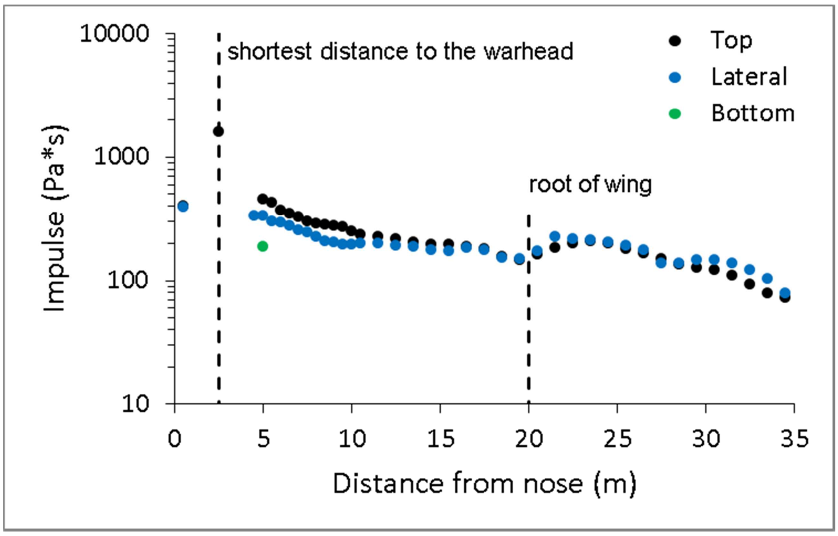

Figure 3.9 Impulse along the aircraft measured with the top, lateral and bottom gauges. The highest impulse is obtained at 2.5 m from the nose and reaches at least 1600 Pa·s. At the root of the wing the impulse is approximately 180 Pa·s. Beyond 35 m the impulse decreases below 100 Pa·s.

3.2.2 *Blast loading on the left nacelle*

The blast loading on the left nacelle has also been investigated, as illustrated in Figure 3.10. The estimated pressure evolution applied on the left nacelle is shown in Figure 3.11. The blast interacts with the nacelle between 20 ms and 35 ms and the pressure reaches a maximum value of 65 kPa.

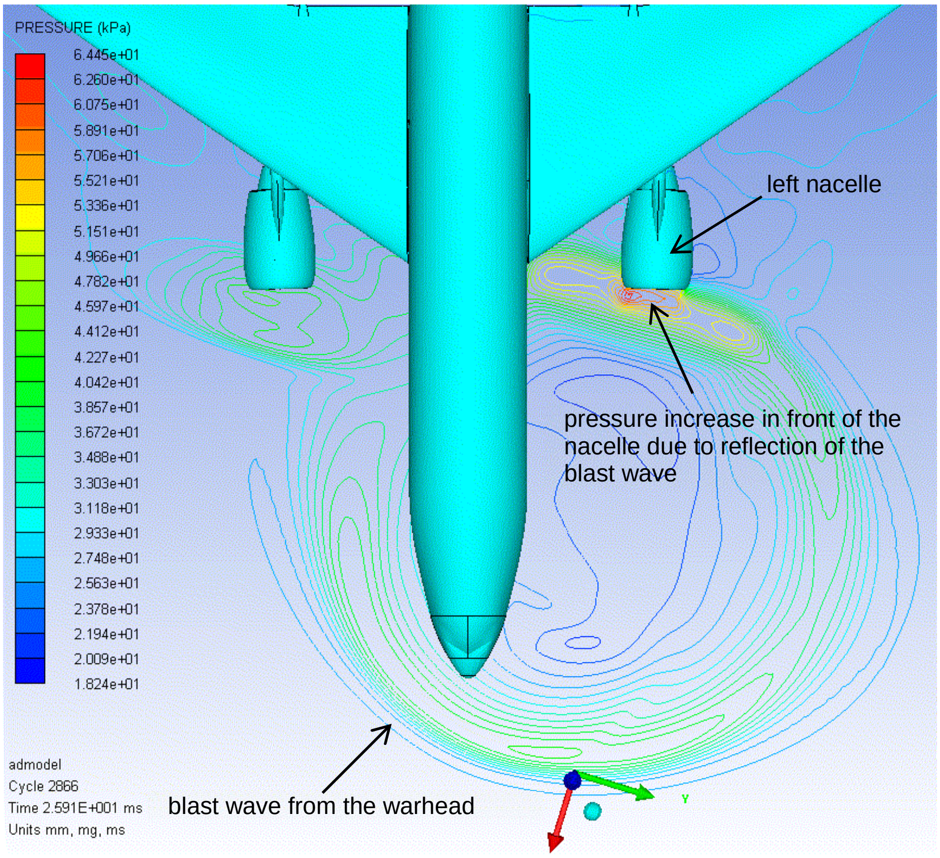

Figure 3.10 Lines of constant pressure showing the interaction between the blast wave and the left nacelle. This interaction produces a peak pressure of 65 kPa in front of the nacelle.

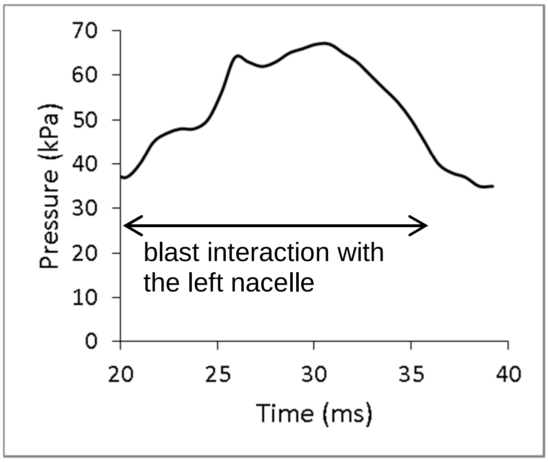

Figure 3.11 Estimated pressure evolution in front of the left-wing nacelle. The blast wave interacts with the nacelle between 20 ms and 35 ms during which the pressure reaches 65 kPa. The ambient air pressure is 26.2 kPa.

4 Conclusions

The Dutch Safety Board (DSB) wants to provide a clear picture of the cause of the crash of flight MH17. A possible cause is fatal damage to the aircraft due to the fragmenting warhead of a guided weapon. A detonating warhead causes damage to the aircraft due to impacting fragments and explosive overpressure (blast). The damage potential of blast is of interest to the DSB, so that TNO investigated the local blast loading on the aircraft as a result of a warhead detonation.

A Computational Fluid Dynamics (CFD) simulation was performed with AUTODYN to determine the blast pressure evolution over time, hence the blast load on the aircraft. The CFD simulation accounts for the altitude, warhead properties, velocity of the aircraft, velocity of the warhead, and shape of the aircraft. The position and orientation of the detonating warhead relative to the aircraft was taken from previous work [1].

The highest peak pressure is approximately 5000 kPa with a duration of 3 ms (corresponding with an impulse of at least 1600 Pa·s), at a distance of 2.5 m from the nose of the fuselage. Beyond a distance of 12.5 m from the nose the peak pressure drops below 75 kPa. This means that beyond this distance the occurrence of blast damage to the aircraft structure is unlikely.

At the root of the wing the peak pressure and impulse are 40 kPa and 180 Pa·s, respectively. Beyond 35 m from the nose the effect of the blast wave is negligible.

The interaction between the reflecting blast wave and the left engine nacelle is noteworthy. The peak pressure in front of the nacelle is estimated to be 65 kPa.

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A Grid convergence of the near-field blast wave

A grid convergence study is performed to ensure that the blast profiles and peak pressures are properly resolved numerically. This was done for the CFD calculation stage involving the near-field development of the blast. The blast wave was simulated using different cell sizes and the resulting blast profiles were compared. Figure A.1 shows the blast profiles at different times after detonation for different cell sizes. A cell size of 8 mm overestimates the peak pressure in the near field (within 1.5 m from the warhead). The peak pressures obtained with the 4 mm and 2 mm cell sizes are quite similar and representative for the blast loading. Therefore, a cell size of 4 mm is chosen for the simulation of the near-field blast from the warhead.

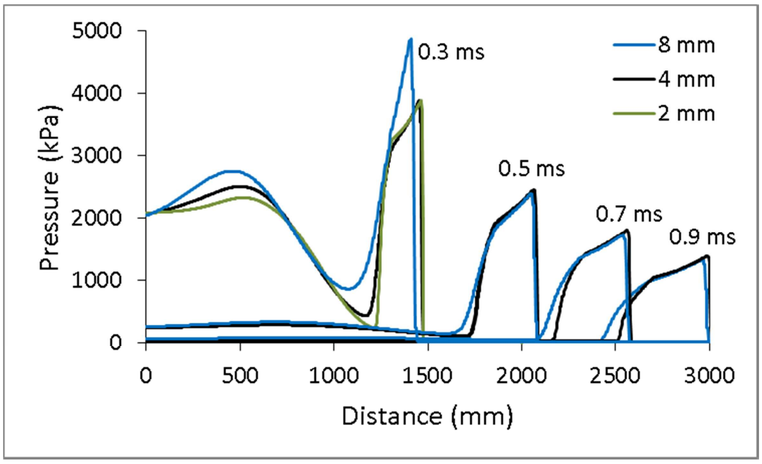

Figure A.1 Pressure profile of the blast from the warhead at different times after detonation using a numerical cell size of 8 mm, 4 mm and 2 mm. The peak pressures obtained with a cell size of 4 mm and 2 mm are very similar. Therefore, calculations have been found to converge at cell size 4 mm.

B Verification of the remapping procedure

The remapping procedure consists of importing the flowfield from the near-field blast wave simulation, performed with a 2D numerical grid and a cell size of 4 mm, into a 3D simulation with a cell size of 50 mm or more.

The remapping procedure is verified by comparing the pressure profiles before (from the 2D simulation) and after (from the 3D simulation) the remapping process. The result is presented in Figure B.1. The pressure profiles before (dashed lines) and after (solid lines) the remapping are very similar. The remapping procedure is therefore considered verified.

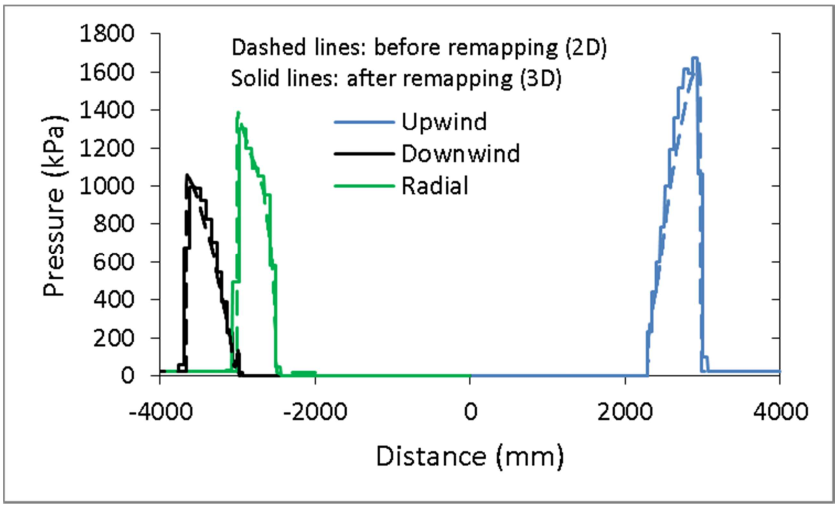

Figure B.1 Pressure profiles from the near-field blast development simulation (dashed lines, before the remapping procedure) compared with pressure profiles from the 3D simulation (solid lines, after the remapping procedure). The comparison shows that the remapping procedure is verified although the effect of the coarser 3D grid (minimum 50 mm cell size) compared with the finer 2D grid (4 mm cell size) can be observed with the step-wise pressure profiles of the solid lines.

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C Grid convergence of the 3D simulation

A grid convergence study for the 3D simulation is performed to ensure that the blast profiles and peak pressures are properly resolved numerically. The aircraft shape was not included for the purpose of this investigation. The flowfield of the 2D blast wave development simulation is incorporated into a 3D numerical grid of cell size varying between 15 mm and 100 mm. The blast is initially located at 3.2 m from the warhead and propagates in the 3D grid up to a distance of 6 m.

Figure C.1 presents the pressure profiles at different times for different cell sizes. The initial profiles show that the peak pressure is well preserved for cell sizes of 15 mm, 25 mm and 50 mm. A substantial loss of peak pressure occurs for a cell size of 100 mm. After the blast propagates for 0.5 ms the discrepancy in peak pressure obtained from the different profiles becomes larger, varying from 720 kPa (15 mm cell size) to 357 kPa (100 mm cell size). The 0.5 ms corresponds to a distance of approximately 4 m from the warhead. At this distance, although a grid convergence is still not fully obtained for a cell size of 15 mm, the finest grid certainly provides the highest accuracy. The discrepancy in peak pressure is considerably less significant at larger distances, as shown by the profiles at 1.5 ms and 2.5 ms. A cell size of 50 mm is considered permissible at distances larger than 5 m from the detonation point.

In the complete 3D simulation, including the aircraft, a cell size of 50 mm is used near the warhead. A cell size of 1 m is used at a distance of 65 m from the warhead for a total of nearly 30 million cells, being the maximum number of cells for this study. This implies that the peak pressure is most likely underestimated only in the near field (up to a distance of 4.5 m from the warhead), but is well-resolved at larger distances.

Since the distance separating the warhead and the aircraft is approximately 4 m, the pressure measured from the gauge located at the shortest distance from the warhead is likely underestimated. For that reason the value of the 15 mm mesh is used for only that location. The pressure measured by the other gauges is sufficiently well-resolved.

The pressure-time profiles from the large 3D simulation (including the aircraft) are shown in Figure C.2 for different distances from the nose of the aircraft. It can be seen that the pressure rise is much steeper close to the warhead than far to it. The pressure profiles at large distances are in contrast with the expected shock wave profile where a discontinuity takes place to reach the peak pressure. The relatively slow rise in pressure is a result of numerical dispersion which is inevitable with CFD simulations. Smaller cell sizes would improve the quality of the pressure profile, but the available resources did not allow such finer numerical grid. The loss of “sharpness” in the pressure profile affects the peak pressure (see figure C.1), but not the impulse: the area under the pressure curve is preserved even if the sharpness is lost.

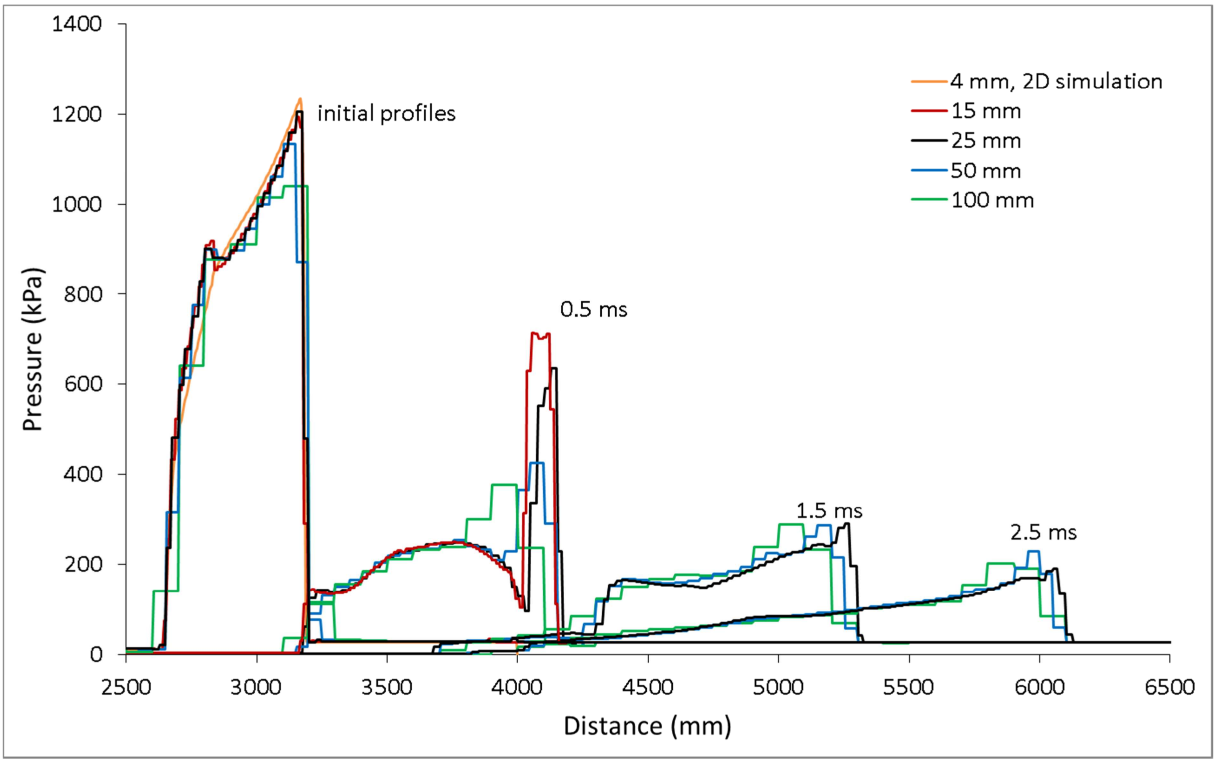

Figure C.1 Pressure profiles of a free-propagating blast wave in 3D numerical grids using cell size varying from 15 mm to 100 mm. The initial blast profile is taken from the 2D blast wave development simulation (shown in orange) and remapped in 3D numerical grids of different cell sizes. The peak pressure of the initial profile is fairly well-preserved for cell sizes of 15 mm, 25 mm and 50 mm whereas a significant decrease of the peak pressure is observed for a cell size of 100 mm. At larger distances the difference in peak pressures is less significant.

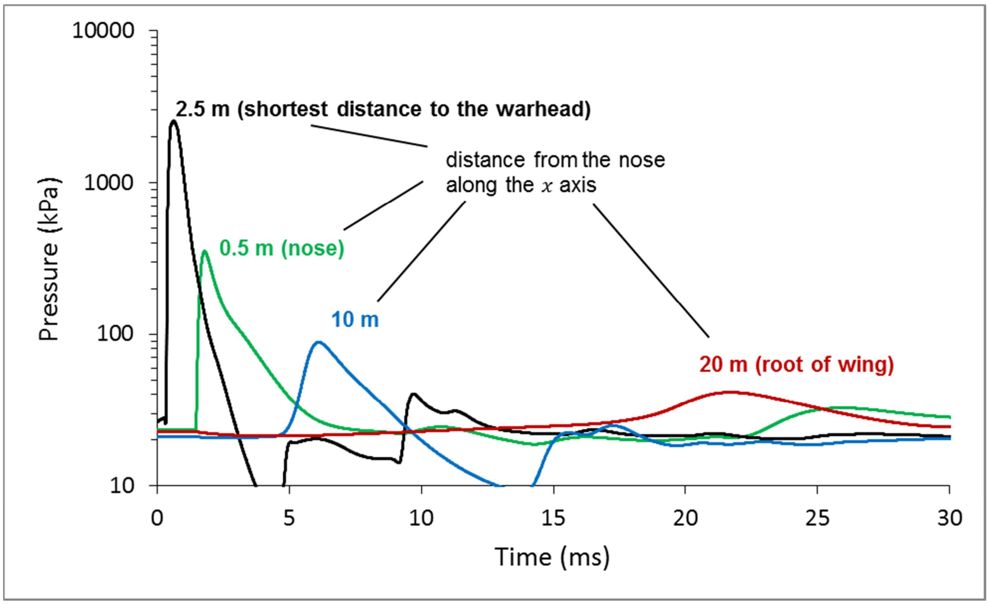

Figure C.2 Pressure evolution of the large 3D simulation including the aircraft (see Section 3.2.2 for the complete analysis).