FFI-RAPPORT

18/00556

Blast injuries to people inside buildings

Knut B. Holm

Blast injuries to people inside buildings

Knut B. Holm

Norwegian Defence Research Establishment (FFI) 18 December 2018

Keywords
Luftsjokk
Numerisk analyse
Risikoanalyse
Dødelighet

FFI-rapport
18/00556

Prosjektnummer
5279

ISBN
P: 978-82-464-3044-7
E: 978-82-464-3045-4

Approvers
Morten Huseby, *Research Manager*
Halvor Ajer, *Director of Research*

The document is electronically approved and therefore has no handwritten signature.

Copyright

Summary

When a building is struck by a blast wave, people inside can get injured both from impact of parts from the damaged building and by the pressure transferred into the building through openings.

By numerical simulations the pressure inside a building is found for a series of incident blast waves with different values of peak pressure and specific impulse. Then the velocity of the human chest wall is found from the pressure-time histories by Axelsson's model, and the lethality is estimated from the maximum chest wall velocity.

The results from the simulations show that in concrete structures the blast injury is significant compared to injury from building debris at incident pressures down to 500 kPa. The lethality can be estimated by *PI*-curves fitted to the results. In wooden constructions the injury from building debris is much larger, and the blast injury can be neglected for incident pressures below 3 MPa.

Simulations of blast tests against a construction in scale 1:25 give inside pressure values in good agreement with the tests. Experiments in full scale and in scale 1:5 are also fairly well simulated. The results show that modelling windows as rigid bodies is a good approach when the pressure load is considerably larger than the window capacity. An experimental verification of the similar approach for the front wall is also achieved.

Sammendrag

Dersom en bygning blir truffet av en trykkbølge, kan mennesker i bygningen bli skadet både ved å bli truffet av deler fra den skadete bygningen og av trykket som trenger inn gjennom åpninger i bygningen.

Ved hjelp av numeriske simuleringer har vi funnet det innvendige trykket fra innfallende trykkbølger med en rekke ulike verdier for maksimaltrykk og spesifikk impuls. Vi har brukt Axelssons modell til å beregne hastigheten trykket gir på brystveggen til et menneske. Deretter har vi estimert dødeligheten fra den maksimale hastigheten.

Resultatene fra simuleringene viser at trykkskaden i betongkonstruksjoner vil være betydelig sammenliknet med skaden fra bygningsdeler ved maksimalverdier på den innfallende trykkbølgen ned til 500 kPa. Dødeligheten kan estimeres ved hjelp av *PI*-kurver som er tilpasset resultatene. I trebygninger er skaden fra bygningsdeler mye større, og trykkskaden kan neglisjeres ved trykkverdier mindre enn 3 MPa.

Simuleringer av sprengningsforsøk mot en konstruksjon i skala 1:25 gir trykkverdier som er i god overensstemmelse med forsøksresultatene. Eksperimenter i fullskala og i skala 1:5 er også simulert med rimelig godt samsvar. Resultatene viser at det er holdbart å modellere vinduer som stive legemer når trykkbelastningen er betydelig større enn vinduets kapasitet. Det er også bekreftet eksperimentelt at frontveggen kan modelleres på en liknende måte.

Contents

1 Introduction

For several years FFI has been developing and improving models for use in quantitative risk analysis of ammunition storages, principally for use in the Norwegian-Swedish computer tool, AMRISK [1]. In recent years the effects of air blast against humans have been extensively studied, not only in the context of ammunition storages, but also for general applications [2-7].

The air blast from an explosion may cause injuries to people both outdoors and indoors. People inside buildings can get injured from impact by building parts if the blast wave damages the building. In addition the blast wave propagating into the building through openings can cause injuries similar to primary blast injury in free-field. A goal of this work is to establish an injury model for implementation in AMRISK. Such a model should incorporate injuries from building damage, including window breakage.

The small openings originally in the exterior of a building (e.g. ventilation) only allow a relatively slow pressure build-up inside. However, if the building damage caused by the blast wave creates larger openings, the subsequent part of the blast wave can easier propagate into the building. Inside the building the pressure wave will be reflected and thereby enhanced.

One of the few existing models for estimating blast injuries inside buildings is described in chapter 3. There are more models for estimating the inside pressure [8-12], but to estimate the lethal effect against humans it is not sufficient to know the peak pressure. Except for simple shock waves the pressure-time history is highly significant, as will be explained in chapter 2.

Numerical simulations can give the time history of the pressure and the dynamic pressure at any position in a building. The interaction between the blast wave and the surface of the human body can be included as well as the dynamic response of the building. A series of such simulations is performed as described in this report.

The numerical calculations are verified by comparing the results with results from experiments.

2 Blast injury models

For people exposed to blast two injury mechanisms are normally considered [2]. The first one is the direct or primary effect against the body and particularly the lungs. The second is the indirect effect of impact of the body against the ground or a wall after being accelerated by the blast wave.

2.1 Direct effect

In 1968 Bowen et al [13] published a model for estimating the probability of lethal damage to humans exposed to blast waves. Bowen's model is based on experiments with simple shock waves. A recent study [14] has adjusted Bowen's model by taking into account that a standing person is initially loaded by the reflected pressure before relaxation waves reduce the load to the stagnation pressure.

Inside a building the pressure wave may have a complicated shape and be without a sharp shock front, in which case Bowen's model cannot be used. To be able to estimate the direct effect of such complex blast waves, mechanical models of the chest have been developed. Based on a given pressure load they give values of physical quantities that are correlated with a damage measure. The model of Axelsson and Yelverton [15], which is the most prevalent, describes the movement of the chest or the chest wall in a single degree of freedom model. The chest wall is subject to the external pressure of the blast wave and the internal pressure in the lungs, and the movement is damped elastically and viscously.

The damage indicator of the model is the calculated chest wall velocity. A relationship was found between the damage index ASII (Adjusted Severity of Injury Index) and the maximum chest wall velocity, v_c:

$$\mathrm{ASII} = \left(0.124 + 0.117\, v_c / (\mathrm{m/s})\right)^{2.63} \qquad (2.1)$$

The ASII values correspond to the damage levels shown in Table 2.1.

Table 2.1 Correlation between damage levels and the ASII damage index [15]

Damage level	ASII
No injury	0.0-0.2
Trace to slight damage	0.2-1.0
Slight to moderate damage	0.3-1.9
Moderate to extensive damage	1.0-7.1
> 50 % lethality	>3.6

A value of ASII may correspond to more than one damage level. This reflects the way ASII is calculated as a sum of damage values for different organs.

In the tests used to calibrate Axelsson's model, pressure values were registered at four positions evenly distributed around the circumference of a cylinder (called a Blast Test Device, BTD). The cylinder was at the same position relative to the explosive charge as the animals used in the tests. From the measured pressure-time histories the maximum chest wall velocity was calculated by Axelsson's model. The quantity v_c is the average of the four values.

When pressure registrations from a BTD are not available, values of the incident pressure wave can be used to calculate v_c. Teland et al [3] have shown that the results from this simplified method to a large extent agree with the results achieved by use of a BTD.

A model similar to Axelsson's model is developed by Stuhmiller et al [7, 16, 17]. The version presented in [17] describes the movement of the front and the two sides of the human chest. The normalised irreversible work, *W*, made by the pressure on the lungs, is calculated from this movement. A correlation between *W* and the probability of a damage level was found by adjusting the parameters b_0 and b_1 in the logit function

$$z = b_0 + b_1 \ln W \qquad (2.2)$$

to experimental data. The function applies to one exposure. The probability *P* of damage above a given level is then given by the logistic distribution,

$$P = \frac{1}{1 + e^{-z}} \qquad (2.3)$$

The parameter values for lethal damage is b_0 = 8.4547 and b_1 = 3.3828.

In [7] it is pointed out that the models of Stuhmiller and Axelsson are calibrated to the same tests. By comparing the results from the models' calculations of v_c and *W* in these tests, it is found that the relation

$$v_c = 50.62 \text{ m/s} \cdot W^{0.4786} \qquad (2.4)$$

is in good agreement with the results.

With the relations above the damage probability can be calculated from v_c. Figure 2.1 shows resulting values.

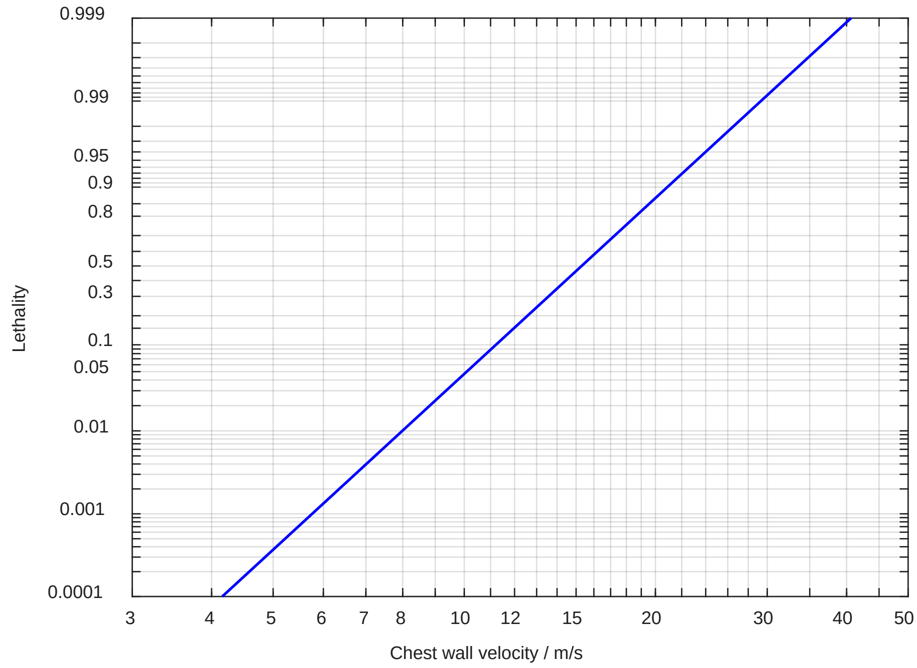


Figure 2.1 Lethality as a function of chest wall velocity found from combining Axelsson's and Stuhmiller's models

A velocity of 15.3 m/s gives a lethality of 50 %. Axelsson suggests that the median value of the velocity is 12.8 m/s.

2.2 Indirect effect

When a person in a building is accelerated by a pressure wave, injuries may arise when the body bumps against the floor, walls or other hard surfaces. An established damage criterion is the probit function [18]:

$$z = -7.136 + 2.541 \ln v \tag{2.5}$$

where v is the velocity given in m/s and z is the quantile of the lethality, assuming a standard normal distribution. The formula is based on fall accidents. Special criteria for the head also exist [19].

The velocity of the body can be found from numerical hydrocode simulations. Alternatively it can be estimated by air drag calculations, see for instance [2].

3 Models for calculating blast injury to people in buildings

Most models for calculating injuries to people in buildings exposed to a blast wave do not consider blast injuries separately [20]. In some cases these injuries are included in the estimated total number of injuries inside a building. However, the present version of DDESB Technical Paper 14 [21] includes a model for calculating blast injuries indoors. The method is implemented in the risk-based siting tool SAFER.

According to the model the pressure and impulse inside a building is found by multiplying the incident pressure and impulse by a reduction factor. The factor is in the range of 0.5-1.0 and depends on the percentage of glass in the walls, the ratio of the vent area and the building volume, the incident pressure and an effective charge weight. The nominal vent area is 2.5 % of the wall area, in addition comes the window area.

At low charge weights the model is overly conservative, while at high charge weights and large scaled distances it underestimates the pressure reduction [22]. Therefore a new method has been suggested for implementation in the next version of Technical Paper 14 (Revision 5).

This method [22-24] is based on the model described in UFC 3-340-02 [10]. The model assumes that the openings are so small (e.g. vents and ducts) that the shock front will not develop inside the structure, and that the maximum applied blast pressure is less than 1 MPa. The average inside pressure, p_{i}, is then changed according to the relation

$$\delta p_{\mathrm{i}} = C_L \left(p - p_{\mathrm{i}} \right) \frac{A_0}{V_0} \delta t \qquad (3.1)$$

where p is the outside pressure, A_0 is the area of openings, V_0 is the structure volume and C_{L} is a coefficient depending on the pressure difference, $p - p_{\mathrm{i}}$, see Figure 3.1. In appendix B test results are compared with results found by this model.

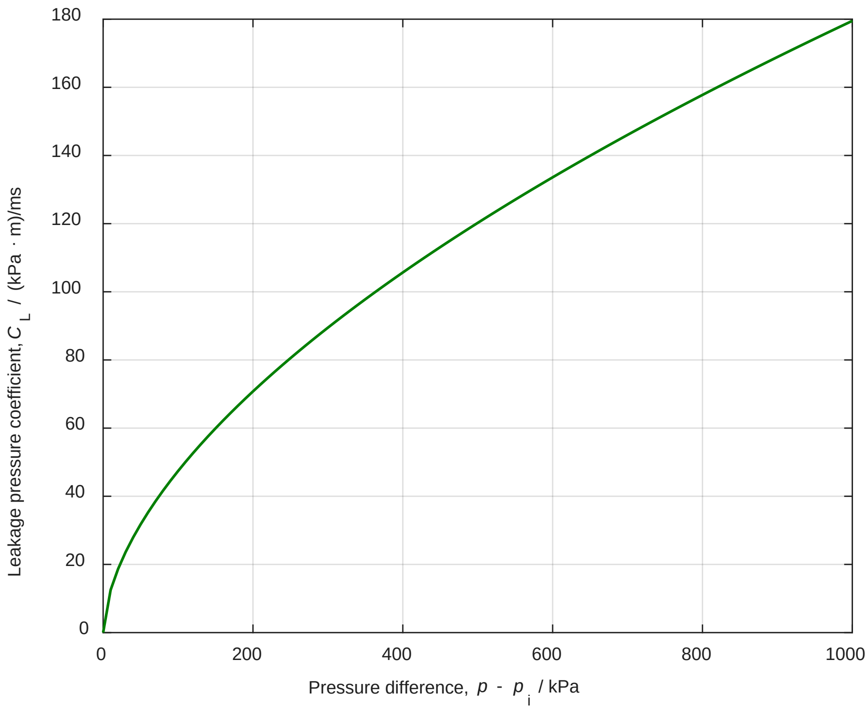


Figure 3.1 Coefficient for pressure leakage into structures [10]

By equation (3.1) a series of calculations have been made [22] with combinations of five structure sizes and eleven opening area ratios (5 % - 100 %) subject to pressure-time histories from seven different charges (45 kg – 450 tonnes) at scaled distances from 0.8 – 40 kg/m^3. The resulting ratio of peak overpressures inside and outside is described by the equation [22]

$$\frac{p_i}{p} = A\left(\frac{A_0}{A_g}\right)^3 + B\left(\frac{A_0}{A_g}\right)^2 + C\left(\frac{A_0}{A_g}\right) + D \tag{3.2}$$

where A_g is the area of the building wall facing the explosion and *A*, *B*, *C* and *D* are quantities depending on the distance from the charge and an adjusted charge weight. The adjustment depends on the ammunition type, in what kind of structure the ammunition is stored and possibly the orientation of the storage [21].

A, *B*, *C* and *D* are calculated by equations containing 48 coefficients. A set of those were fitted to the results for each of the five structure sizes and for two ranges of scaled distances.

The ratio of the internal and external specific impulse, i_i/i, is found from the relation [22]

$$\frac{i_{\mathrm{i}}}{i} = 1.81 \frac{p_{\mathrm{i}}}{p} \qquad (3.3)$$

From the pressure and impulse the direct effect against people in buildings is calculated by established models based on Bowen's model for blast injury. The injuries from impact of the whole body and skull fracture are similarly estimated by models developed from calculations of body acceleration and the criteria described in chapter 2.2. The three effects are considered independent. These models are also used to estimate outdoor blast injuries, but then the pressure is the free-field pressure.

4 Injuries from building damage

In addition to blast injuries, people inside a building can get injured from impact by building parts. If the lethality from blast injuries is insignificant compared to the lethality from building parts, blast injuries can be neglected.

The lethality caused by building damage can be estimated by the *PI*-curves developed by ACTA [25]. The curves show the combinations of pressure and impulse that lead to a certain lethality and are defined by the expression

$$(p - A)(i - B) = C \qquad (4.1)$$

The parameters A, B and C are given for a set of lethality values and for different building types. The lethality can then be found from the pressure and impulse by interpolation between the curves. The curves are constructed by detailed calculations of building response and more simple estimates of the resulting lethality. This method is also the basis of the model in TP 14 [21].

The *PI*-curves in [25] are given for several types of buildings, see also [20] for more information about the types. We are considering two of them. The first is the small wood structure of about 230 m^2 with wood stud walls and roof. The second structure type is the small reinforced concrete building. The area of the building is similar to the wood structure, and the wall thickness is 20 cm. This is the strongest building type described in [25], and it will have a substantially higher blast resistance than a wooden house. However also in this type of building the windows are easily shattered, and then the pressure wave can propagate inside and injure people. Compared to the injuries from building damage, the blast injuries will therefore have a larger effect than in weaker buildings.

5 Numerical simulation of blast propagation into buildings

To predict the blast injury to a person in a building the time-dependent pressure at the person's position must be known, see chapter 2.1. This pressure is the result of the propagation of an external blast wave into the building, and it can be found by numerical simulations.

We have made such simulations by use of ANSYS Autodyn [26]. Appendix A contains descriptions of the methods and models employed in the simulations. The first part of the simulations is made by a 1D-model that describes the formation of a shock wave after a TNT charge is detonated and the subsequent propagation of the shock wave forward to the house. The properties of the air in front of the house are then remapped from the one-dimensional simulation, and the further propagation through openings into the house is simulated in three dimensions.

The model for simulating the blast propagation into buildings was developed stepwise, making it possible to evaluate different parts of the numerical calculations by comparing numerical and experimental pressure registrations.

The first simulations are made of experiments with little or no building damage, and the simulation model does not need to take account of the response of the building walls. However, as will be shown in the next chapter, the incident blast that results in injurious pressure levels inside a building will also damage the building and create larger openings. The final simulation model therefore includes building damage and is compared with blast tests that caused such damage.

The building model used in most of the simulations is based on the house Lykkebo, a wooden standard house typical for residential use in Norway [27], see Figure 5.1. Lykkebo was used as test subject in three trials in Australia [28, 29], where charges of 40, 27 and 5 metric tons were detonated at different distances from the house.

Figure 5.1 The Lykkebo house [28]

5.1 Blast propagation

A series of blast tests was accomplished with a model of Lykkebo in scale 1:25 [30]. The house model was constructed by rigid plastic components. Figure 5.2 shows a drawing of the ground floor with the positions of the pressure gauges. In addition the free-field pressure was measured beside the house.

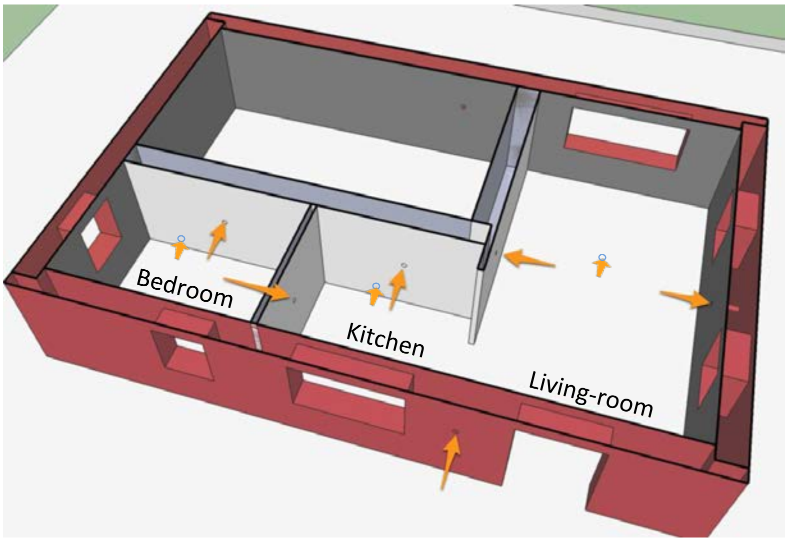


Figure 5.2 Ground floor of Lykkebo scale 1:25 where the arrows show the positions of the pressure gauges [30]

The internal dimensions of the rooms were in agreement with the full-scale house, but the outer walls were thicker.

Several of the tests were made with plates of plastic or cardboard placed in the window and door openings. The area density of the plates was about 0.8 kg /m^2, which is 1/25 of the value of 2 x 4 mm window panes. The plates were held in place only by the friction against the walls.

In the tests charges of 0.32 kg and 2.0 kg C4 were set off at different distances at the front and the back side of the house, see Table 5.1. A more detailed description of the tests and the results is given in [30].

Table 5.1 Tests with Lykkebo in scale 1:25

Test no.	Charge weight / kg	Distance / m	Scaled distance / m/kg $TNT^{1/3}$	Windows
1-2 3-4	0.32	2.2	2.9	 x
5-6 7-8	0.32	3.76	5.0	 x
9-10 11-12	0.32	7	9.5	 x
13-14	2.0	3.5	2.5	
17-18 19-20	2.0	5.67	4.1	 x
21-22 23-24	2.0	10.08	7.3	 x
30-31	0.32	-3.76	5.0	
32-33	0.32	-2.2	2.9	

The simulations of these tests are made with a rigid house model. The window plates are assumed rigid, and there is no interaction between the plates and the house.

In Figure 5.3 the results from the tests with 0.32 kg C4 detonated 2.0 m from the house are compared with simulation results. The simulation of the experiment without window plates gives at some positions larger values of the peak pressure than the tests. At the other positions there are only minor differences, and the pattern of the pressure wave in the experiments is easily recognized in the simulations. For the tests with window plates the correspondence is also quite good. The details are not perfectly reproduced, but there are also significant differences between the two tests.

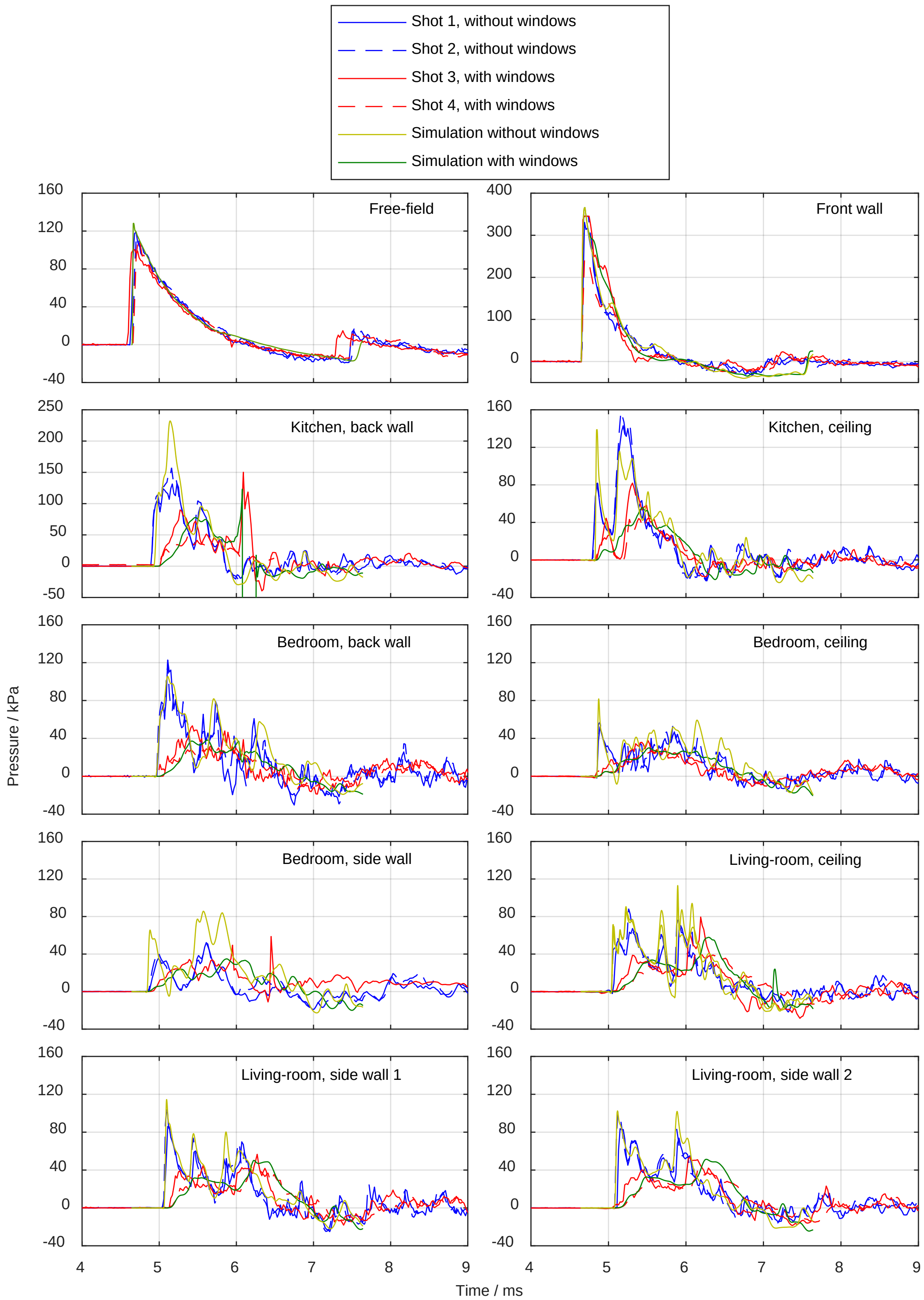


Figure 5.3 Test and simulation results from detonation of 0.32 kg C4 2.2 m from Lykkebo 1:25

Similar comparisons with the other tests are shown in appendix A.3.1. Generally the agreement is good, particularly when there are no window plates.

A comparison can also be made between the chest wall velocities calculated from the measured and the calculated pressure. Here we are considering only the tests without window plates because the velocities from the tests with plates give very low lethality values. When the pressure is put into the Axelsson's model with times scaled up to full scale, the results become as shown in Figure 5.4.

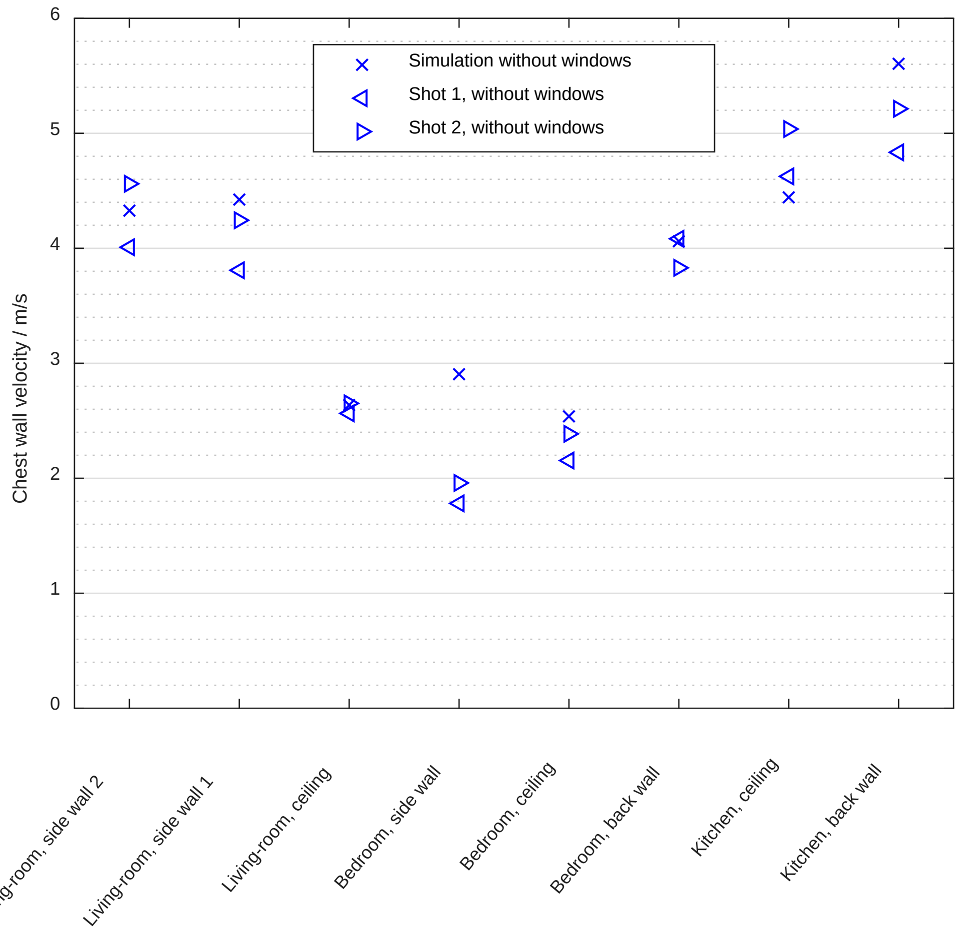


Figure 5.4 Maximum chest wall velocity calculated from pressure values from simulations and experiments with 0.32 kg C4 detonated 2.2 m from Lykkebo

The values from the tests are in good agreement with the simulation results. If we look at the details, the simulation gives a larger chest wall velocity at the bedroom side wall than the tests do. The value of the first pressure peak, which gives the maximum velocity, is larger at the ceiling than at the side wall both in tests and simulation, but in the simulation the shape of the pressure wave gives the largest velocity at the side wall. It can also be seen that the large difference between the pressure at the kitchen back wall in the simulation and the experiments only give a small difference in the chest wall velocity. The average lethality calculated from the chest wall velocities by equations (2.2)-(2.4) becomes $1.7 \cdot 10^{-4}$ when using the simulation values and $0.9 \cdot 10^{-4}$ and $1.6 \cdot 10^{-4}$ with the values from shot 1 and 2 respectively.

Overall the results show that the simulations are in good correspondence with the experiments. The simulation model is able to reproduce the pressure propagation into a rigid building with openings, also when there are plates in the openings.

5.2 Window response

The modelling of the window plates as unconstrained rigid plates was further assumed to be applicable also for real windows.

This assumption was first examined by simulating the test in Australia with 5 tonnes of explosives detonating 177 m from the Lykkebo house [29, 31]. In the test all the windows in the front wall were blown inside, see Figure 5.5.

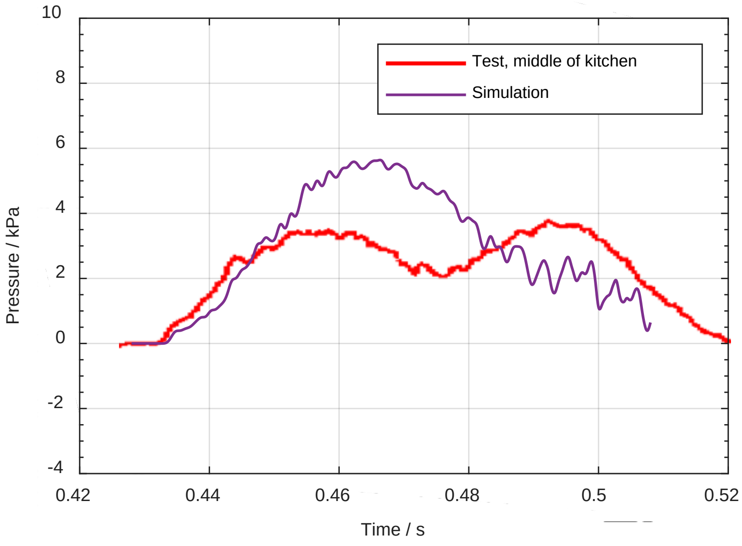
Figure 5.5 Front wall of Lykkebo after the five tonne trial [29]

Half of the windows in the side walls were broken [29]. The windows in the back wall were undamaged, excluding one that probably was broken by pieces falling from the plaster board in the ceiling. There was some damage to the panel of the front wall facing the blast and the roof, but little damage to the load bearing components of the structure.

Except for the veranda door at the front side the window panes consisted of two layers of 4 mm annealed glass with 16 mm air between the layers. The incident pressure in the trial is estimated to 14.2 kPa [30].

In the simulation of the test the walls and the roof are modelled as rigid and unmoveable. The small movement of the front wall in the test is assumed to be insignificant for the internal pressure. The windows in the simulation model consist of 8 mm rigid and freely moving plates.

Inside the house the pressure was measured in the middle of the kitchen and the bedroom, 1.2 m above the floor. Figure 5.6 shows pressure values from the test and the simulation.



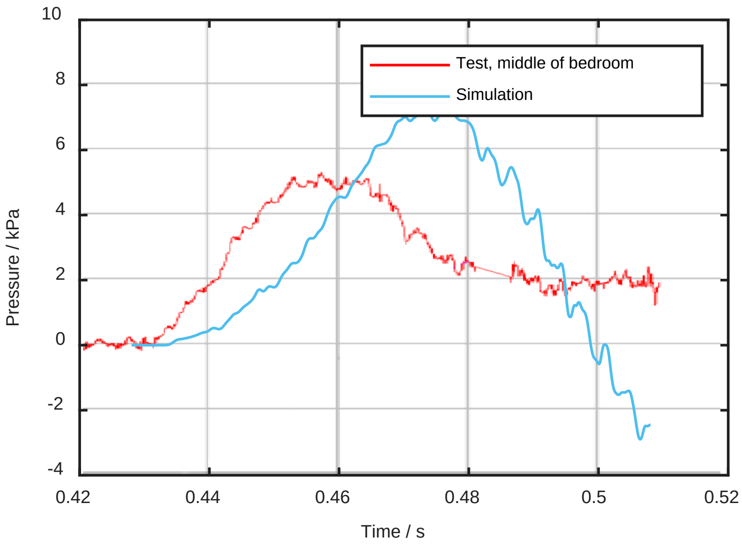


Figure 5.6 Pressure values in the kitchen and the bedroom in Lykkebo from the five tonne trial and the simulation of the trial

The simulation gives somewhat higher pressure values than the test. A possible reason is that the structural resistance and the attachment to the frame is not included in the model of the windows.

From experiments the breakage limit for the window type is found to be 100 Pa·s for impulsive loads and 12 kPa for quasi-static loads [32]. In the five tonne trial the pressure load on the side walls with a peak pressure of 13.8 kPa and 380 Pa·s impulse [31] caused 50 % breakage to the windows. Hence this load is also at the breakage limit. The pressure on the front wall in the test was 33 kPa and the impulse 630 Pa·s [31]. The load on the bedroom and kitchen windows is thus not very much larger than the limit load. The numbers suggest that a considerable part of the energy of the blast load on the bedroom and kitchen windows was spent on breaking the windows, and the internal pressure was reduced accordingly.

The approach of modelling windows as rigid bodies without interaction with the rest of the building was also assessed by another test. In the test performed by NDEA [33] 400 kg TNT was set off 25 m from a chamber with a window, see Figure 5.7. The window opening in the middle of the front wall was 1 x 1 m, and the window was made of 6 mm annealed glass. The glass pane was clamped to a steel frame, and a wooden frame between the glass and the steel frame was glued to the glass.

The inside of the chamber was 2 m wide, 2.5 m high and 3 m long. The side walls, roof and floor were constructed of 20 mm steel plates and 270 mm h-beams. The front wall and the back wall consisted of 40 mm steel plates. On each side and on top of the front wall concrete elements were assembled, forming an 11.7 m wide and 4.0 m high wall. In the simulation the building is modelled as rigid and stationary.

Figure 5.7 Test structure with chamber and concrete walls [33]

Inside the chamber gauges recorded the pressure in the ceiling, on the back wall and on a side wall. In addition the pressure was measured on the outside front wall and in free-field.

The measured peak free-field pressures at two positions 25 m from the charge were 93 kPa and 101 kPa, whereas the simulation gave a value of 90 kPa. The difference is larger for the impulse values, but it should be noted that in the test there was a secondary pressure wave, possibly caused by reflections from the structure, which contributed to the impulse. The pressure on the front wall is somewhat larger in the simulation than in the test.

In Figure 5.8 test recordings of the pressure inside the chamber are compared with results from the simulation. The times from the experiment are shifted to fit the simulation.

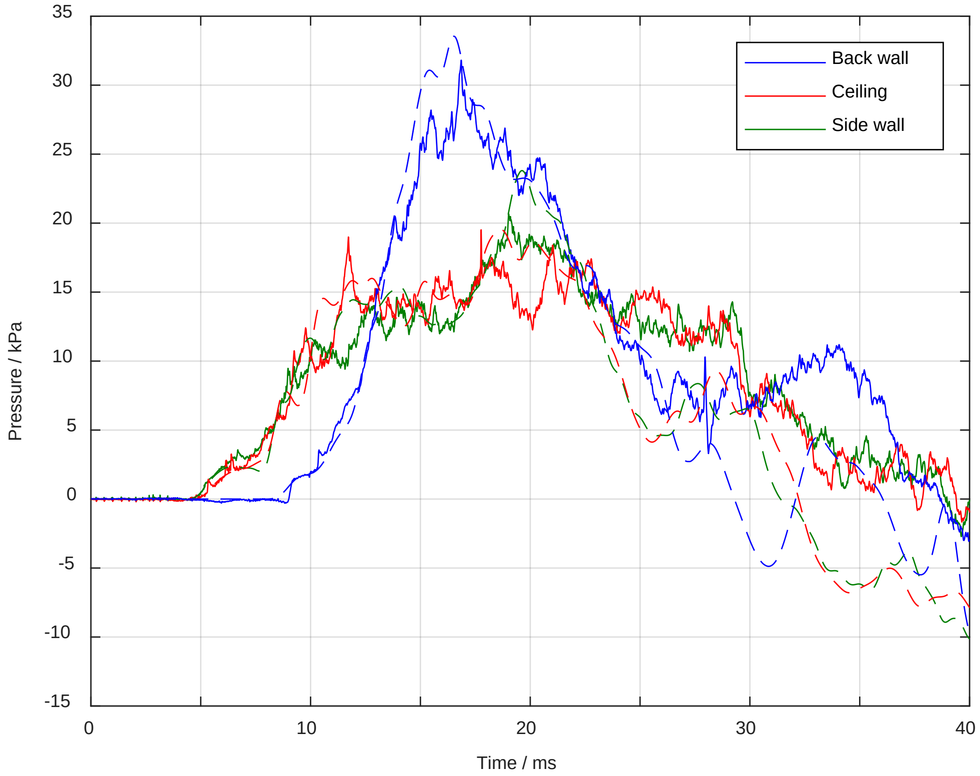


Figure 5.8 Pressure values in a chamber from experiment [33] (solid lines) and simulation (dashed lines) with 400 kg TNT detonated 25 m from the chamber

Up to 25 ms the agreement between experiment and simulation is very good. The blast injury estimated by the extended Axelsson's model (chapter 2.1), is determined by the pressure values during this time period. At later times the simulation pressure descends too fast. This is also the case for the pressures in free-field and at the front wall.

Based on values in [34] the breach limit for a window of this type is estimated to 37 Pa·s for impulsive loads and 8 kPa for quasi-static loads. In the test the peak pressure and impulse of the blast load on the front wall was 214 kPa and 1150 Pa·s. Consequently the load was much larger than the window capacity. Neglecting the structural resistance of the windows in the simulations should therefore be a reasonable approximation, which is confirmed by the simulation results.

It can be concluded that modelling windows as unconstrained, rigid plates gives results in good accordance with experiments as long as the pressure load is considerably larger than the window capacity.

5.3 Building response

In the final step of the development of the simulation model damage to the building was included. The building damage is described by dividing the front wall into several, movable parts. The rest of the house is fixed. Contact forces are defined between the front wall elements and the side walls, the adjacent inner wall and the first floor. Then the only resistance by the front wall against the blast load is this interaction and the mass of the wall elements. The resistance against deformation and failure is not taken into account. Figure 5.9 shows the front wall sections.

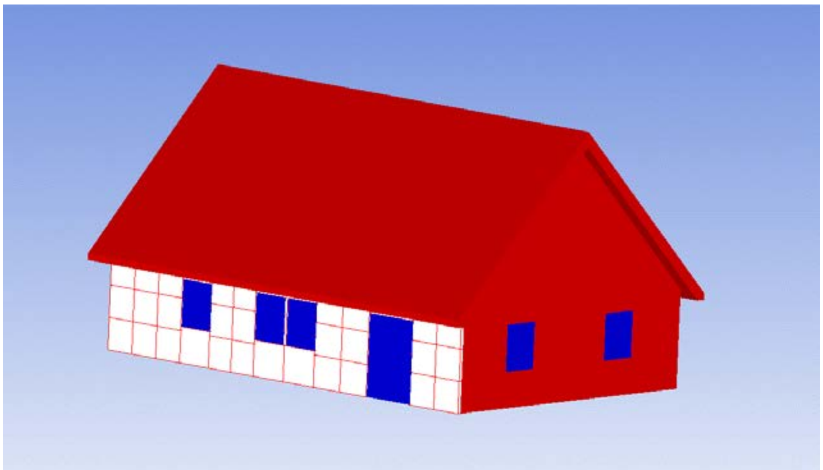


Figure 5.9 Drawing of the Lykkebo model with front wall elements

The windows are modelled as rigid bodies as in the previous simulations.

A verification of the model was made by simulating a blast test against a model of Lykkebo in scale 1:5 [30]. The house model was constructed similar to the full-scale house using downscaled building parts including wood elements, tiles and windows see Figure 5.10. The window panes were single and 2.15 mm thick. Some internal walls and doorways in the full-scale house were left out in the model, such as the doorway between the living-room and the hall.

Figure 5.10 Lykkebo in scale 1:5 at the test site

Three detonation tests against the house were carried out [30]. In the two first tests TNT charges of 40 kg and 240 kg was detonated 34.1 m and 45.4 m from the house.

The test considered here is the third test where 350 kg Texit vas detonated at a distance of 35 m from the house. The building damage from the blast was extensive, as shown in Figure 5.11. The front wall was blown inside, and the side walls were destroyed. The roof facing the charge was heavily damaged. The internal back wall of the bedroom and kitchen was removed. The windows in the side wall of the living-room were not broken, similar to the windows in both side walls in the first floor. The windows in the living-room facing away from the charge were broken. Overall the house was beyond repair.

Figure 5.11 Lykkebo in scale 1:5 after detonation of 350 kg Texit 35 m from the house

To simulate a detonation in ANSYS Autodyn it is required to know the parameters of the equation of state of the detonation gases, see appendix A.1. The parameters for Texit are unknown, but if we compare free-field pressures from a simulation using 400 kg TNT with the test recordings, the agreement is good, see Figure 5.12. At 35 m the pressure was not measured, but the simulation results are included in the figure. Table 5.2 shows the peak pressure, duration and impulse of the blast waves in the test and in the simulation.

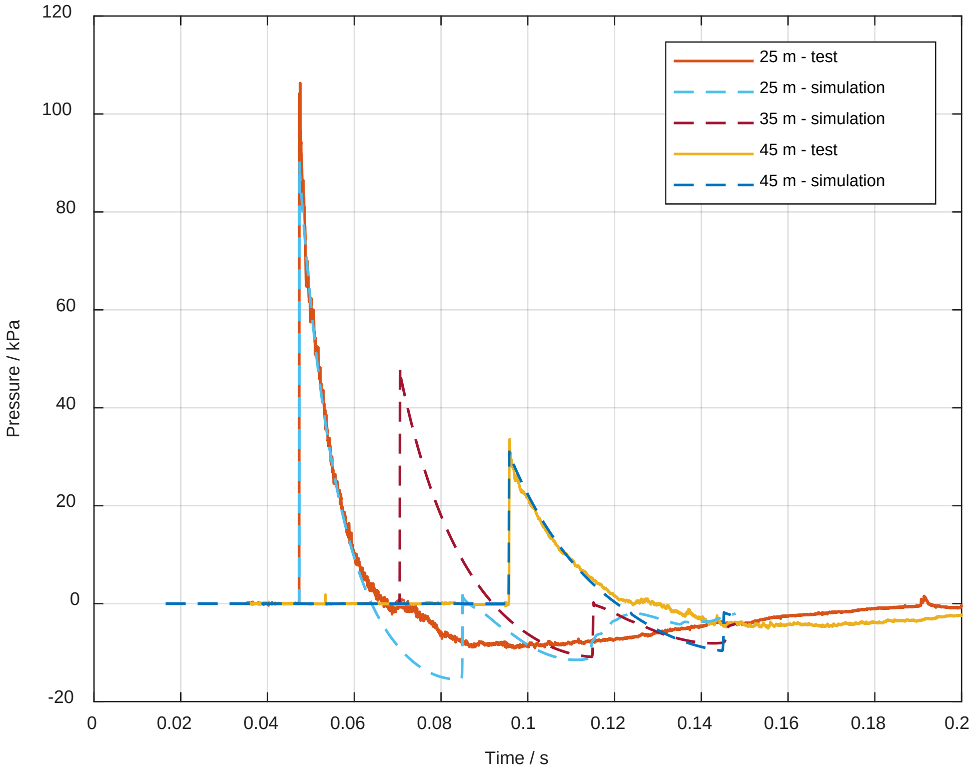


Figure 5.12 Pressure values registered at different distances from the detonation of 350 kg Texit [30] and the simulated detonation of 400 kg TNT

Table 5.2 Blast wave parameters from detonation of 350 kg Texit and from the simulation of detonation of 400 kg TNT

Distance / m	Peak pressure / kPa		Duration / ms		Specific impulse / Pa·s	
	Test	Simulation	Test	Simulation	Test	Simulation
25	106	90.3	19.5	16.8	551	519
45	33.6	31.2	28.4	25.1	306	307

The simulation gives in general shorter durations than the test, and the measured peak pressures are higher than the simulation values. Still large parts of the blast waves are very similar in the test and the simulation.

The simulation gives an incident peak pressure at 35 m of 48 kPa. The reflected pressure of 126 kPa, which was measured on the outer wall, corresponds to an incident pressure of 52 kPa according to standard relations for shock waves in air.

Because of the good agreement the detonation of 350 kg Texit was simulated using 400 kg TNT as the explosive charge.

In addition to the measurements in free-field the pressure was registered on the front wall of the building, the side wall of the living room and the kitchen back wall. The position of the pressure gauges is similar to the positions shown in Figure 5.2 for the tests in scale 1:25, with the gauge in the living-room at the internal wall at the left side of the room. Figure 5.13 shows the test recordings together with results from the simulation.

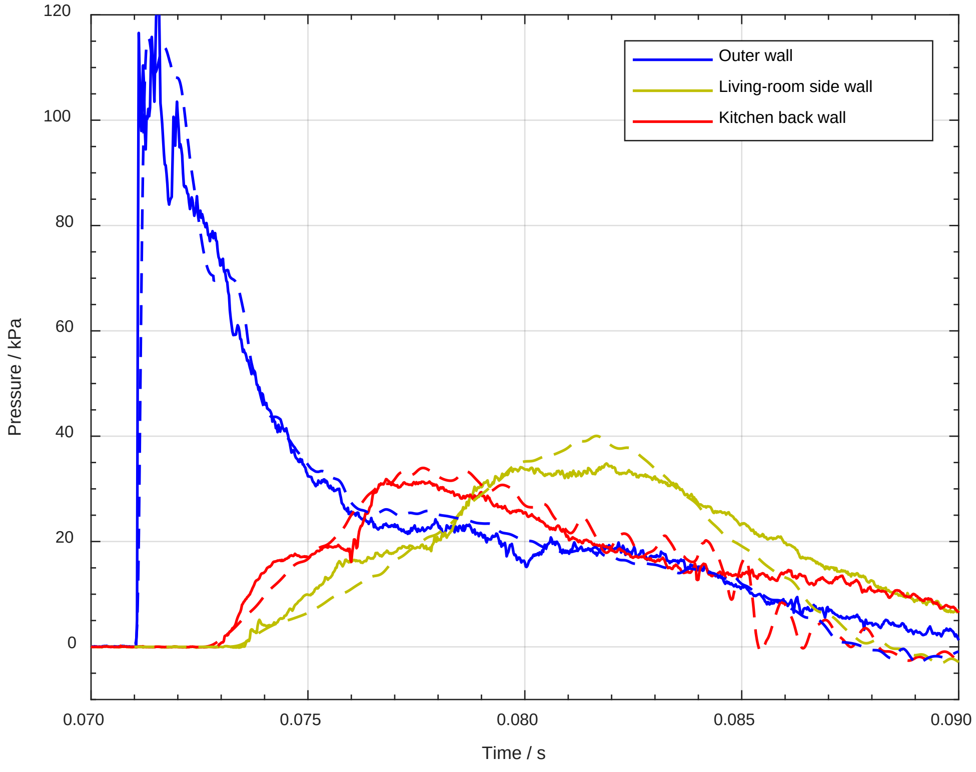


Figure 5.13 Pressure values from test (solid lines) and simulation (dashed lines) with 350 kg Texit detonated 35 m from the Lykkebo house in scale 1:5

The pressure on the front wall is reproduced very well in the simulations. Inside the pressure initially rises more rapidly in the test than in the simulation, but then the simulation catches up and reaches a bit higher than the experimental values. In general the agreement is good.

Figure 5.14 shows the building response given by the simulations. The damage to the side walls is not included, but the damage to the front wall is not very different from the test results.

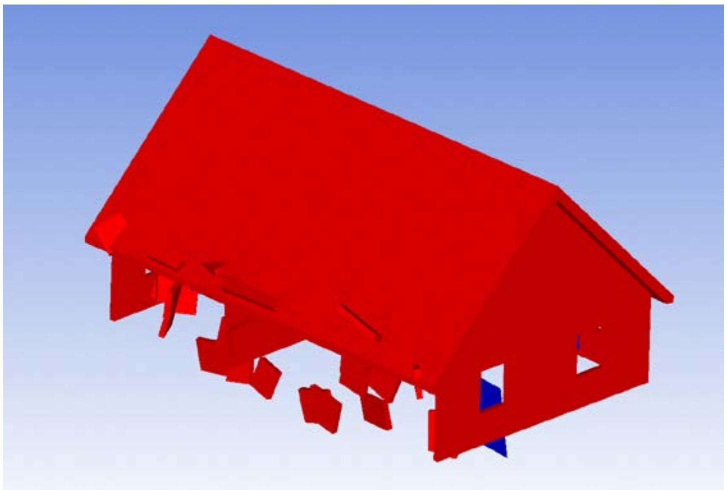


Figure 5.14 Image captured from the end of the simulation with 350 kg Texit detonated 35 m from the Lykkebo house in scale 1:5

A simulation made with a fixed front wall gives a maximum pressure of 35 kPa on the living-room side wall and 27 kPa on the kitchen back wall. The corresponding values in Figure 5.13 from the simulation with a moving wall are 40 kPa and 34 kPa. These numbers show that the main part of the pressure ingress goes through the window openings, also when the front wall can move. Taking account of the structural resistance would therefore not reduce the pressure substantially.

According to Swedish building damage predictions [20] a timber walls structure will get wall collapse and cracks with an impulsive load exceeding 600 Pa·s which corresponds to 120 Pa·s in scale 1:5. For a quasi-static load the capacity is 20 kPa. The blast load on the outer wall had a peak value of 120 kPa and an impulse of 514 Pa·s. Also this suggests that the energy spent on deformation and breakage can be neglected.

If the simulation is run with no contact forces between the front wall elements and the adjacent parts of the house, and all the elements can move freely, there is only a minor increase in the resulting pressure compared to the simulation with contact forces. However the behaviour of the wall observed in the test is best described by the simulation with defined contacts.

Another simulation was made with the front wall elements divided into more and smaller elements. The side lengths were about 3/5 of the lengths of the elements shown in Figure 5.9. The result of this simulation was inside pressure values considerably higher than the test values.

5.4 General model

The results presented above show that the building model used in the simulation of the test with Lykkebo in scale 1:5 gives inside pressure values in good accordance with the experiment. A full-scale version of this model is therefore chosen as the general model in our calculations of internal pressures. This means a rigid construction except for the rigid and movable front wall elements and windows. The thickness of the walls is 16 cm, and the area density 65 kg/m^2. The windows are 8 mm thick.

Simulations are also made with a model of a concrete structure. The dimensions of the structure are similar to Lykkebo, and the area density of the front wall elements is set to 500 kg/m^2, which corresponds to a 20 cm thick concrete wall.

A model for predicting air blast damage to persons in a building should cover different building types and sizes. The properties of the pressure wave inside the building strongly depend on the geometry and the size of the openings in the building. Our basis for a general model is Lykkebo, where the three rooms taken into consideration have quite different sizes and designs. Still, for buildings very different from Lykkebo the model is of limited applicability.

6 Estimation of blast injuries in buildings

By the methods described above the lethality caused by blast injuries inside a building can be found. First the detonation of a TNT charge and the subsequent propagation of the blast wave into the building are simulated numerically using the general building model. The lethality from direct blast injuries is calculated from the internal pressure values by the extended Axelsson's model. The indirect blast injuries are estimated by including a human body model in the simulation. The lethality is then calculated from the obtained body velocities.

The calculation procedure can be explained in more detail by looking at an example. We assume that 22,000 kg TNT is detonated 27 m from the Lykkebo house of wood or concrete. When the blast wave from the detonation arrives at the house, the amplitude is 960 kPa, the duration 21 ms and the impulse is 3,800 Pa·s.

6.1 Direct blast injuries

To estimate the direct blast injuries inside pressure values are collected during the simulation from 316 gauge points distributed across the rooms, 1.2 m above the floor. The peak overpressures in the example become as shown in Figure 6.1. The colour of an area is given by the pressure registered by the gauge in the centre of the area. In addition to results for a concrete wall and a wooden wall the results for a rigid wall are included for comparison.

The pressure values are in general comparatively high just inside the windows and the door in the front wall. Further it can be seen how the reflection on the back wall increases the pressure, particularly in the kitchen. The average peak pressures are 520 kPa with a rigid front wall and 540 kPa with a concrete wall. The small difference implies that the pressure wave is mainly entering the concrete building through the window openings and only to a small extent through the openings formed by the movement of the front wall. With the lighter wooden walls the average pressure becomes 610 kPa, thus a little higher than with concrete walls.

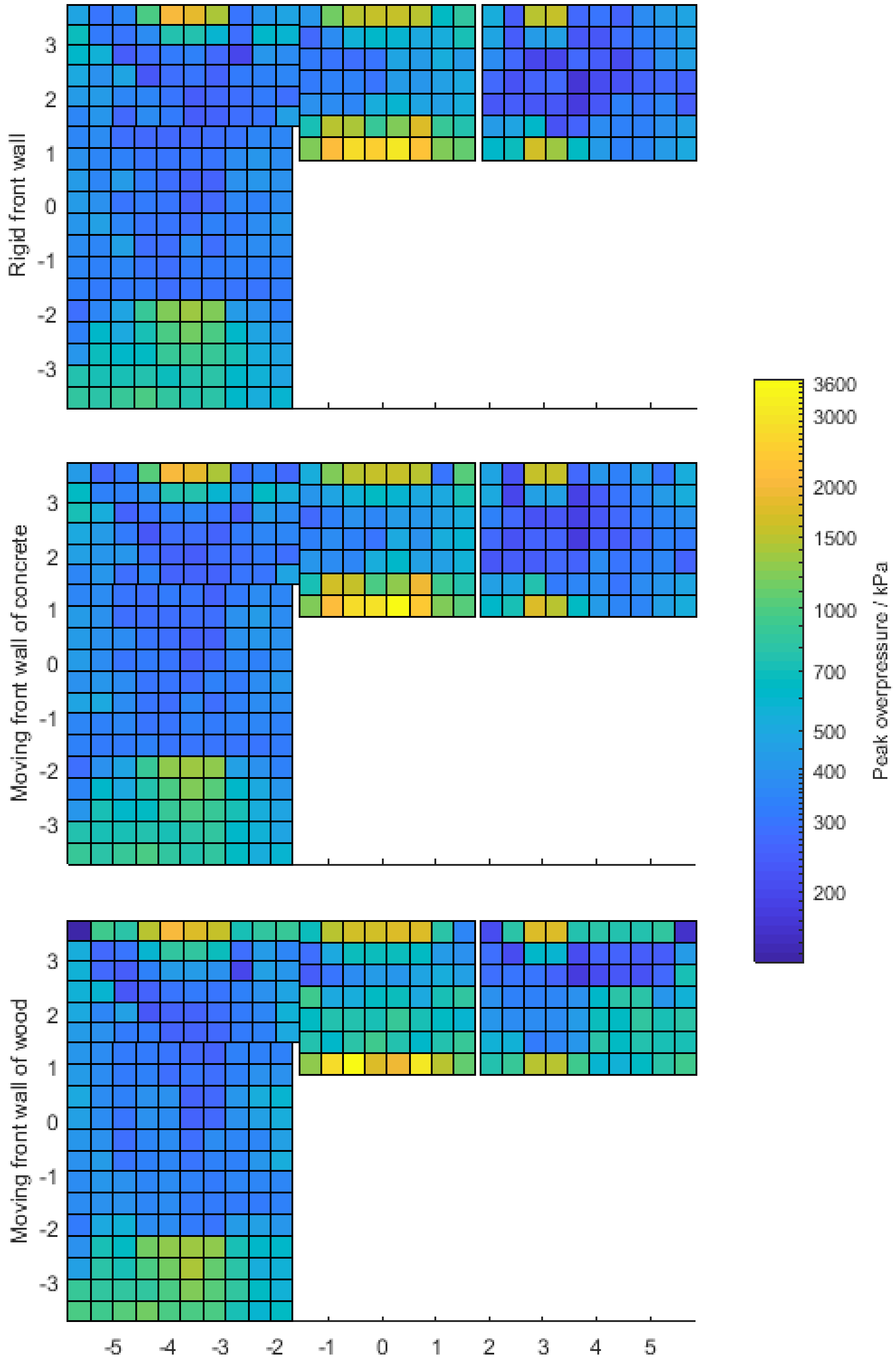


Figure 6.1 Peak pressures inside the Lykkebo model with different front wall types when a pressure wave of 960 kPa peak pressure and 3,800 Pa·s impulse hits the house

The lethality caused by direct blast injuries is calculated from the pressure by the extended Axelsson's model, see chapter 2.1. The lethality inside the two building types becomes as shown in Figure 6.2.

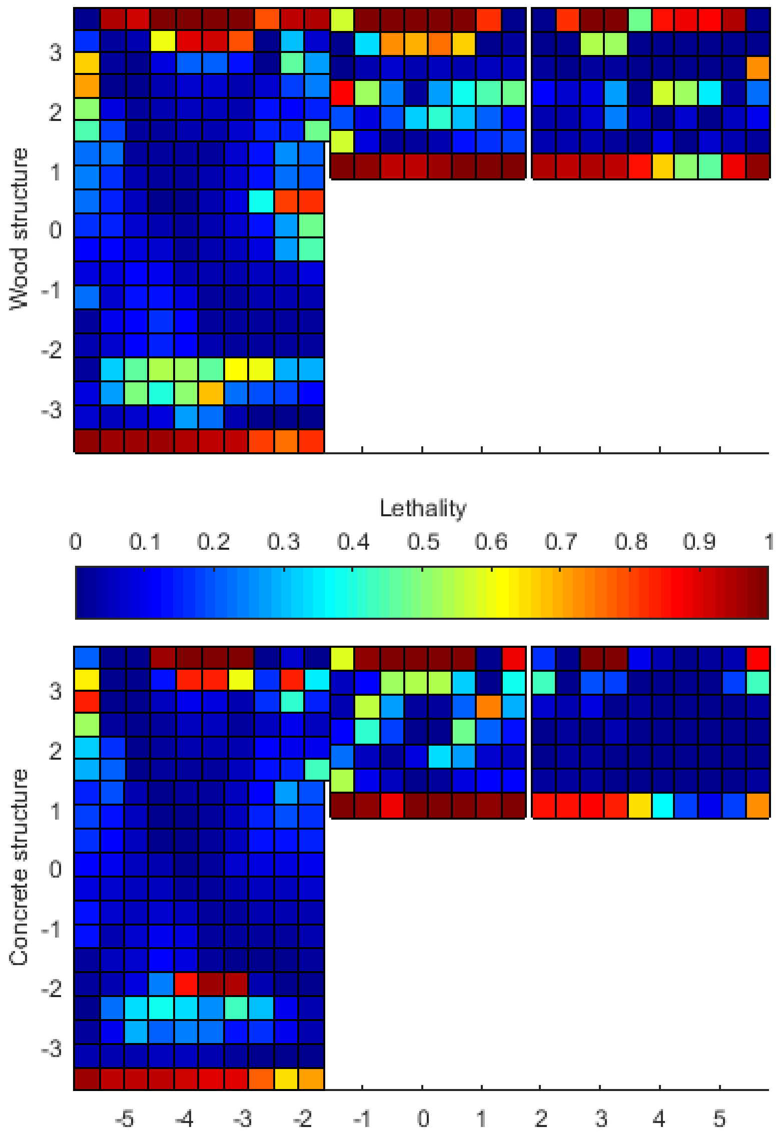


Figure 6.2 Lethality from blast injury in the Lykkebo model with wooden walls and concrete walls from an incident pressure wave of 960 kPa peak pressure and 3,800 Pa·s impulse

The figure shows that the lethality is largest behind the front windows and the door and close to the back walls. We also see an increased lethality behind the left window close to the front.

In a risk analysis the overall lethality for the persons in a house is employed. We assume that the inhabitants of the house will be randomly located. Then the lethality for a person is the average across the floor, which is the average of the lethality values shown in Figure 6.2.

The resulting lethality becomes 29 % with wooden walls and 22 % with concrete walls. A rigid front wall gives an average lethality of 20 %. When averaged over the separate rooms in the concrete structure, the lethality becomes 15 %, 40 % and 19 % in the bedroom, kitchen and living-room respectively.

The lethality from injuries from building damage becomes 100 % inside a wooden house and 27 % inside a concrete house according to the model described in chapter 4. The cumulative or total lethality, which is the probability of lethal injury from at least one of the two injury types, becomes 43 % in the concrete structure when the two injury types are considered independent.

A comparison can also be made with the lethality caused by the incident pressure wave in free-field. The extended Axelsson's model gives a value of 98 % whereas the modified Bowen's model for standing persons [14] estimates the lethality to 100 %. The concrete building will therefore provide some protection against the blast.

6.2 Indirect blast injuries

The injuries from indirect blast effects are found by use of a model of a rigid human body (see appendix A.2.5) at different positions in Lykkebo. Simulations with the given pressure load results in average body velocities as shown in Figure 6.3.

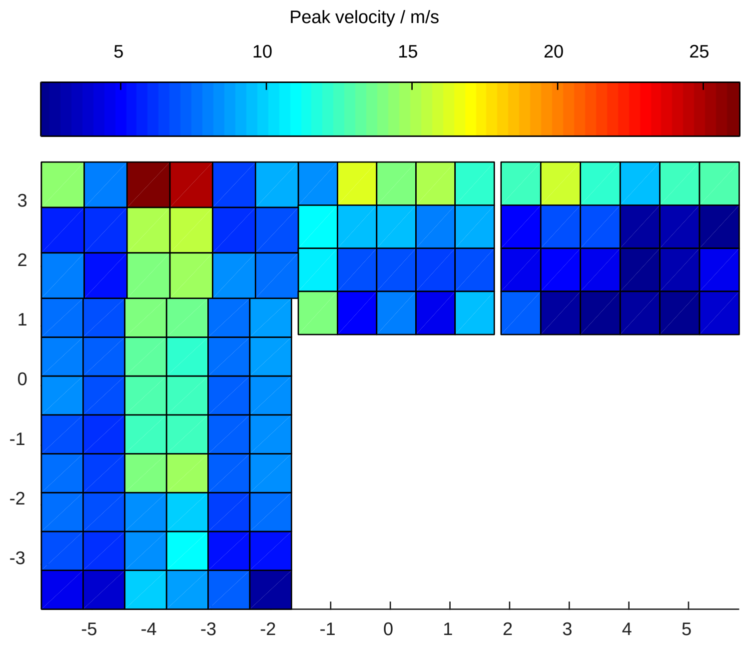


Figure 6.3 Maximum velocity of a person inside the Lykkebo model with concrete walls from an incident pressure wave of 960 kPa peak pressure and 3,800 Pa·s impulse

When the lethality is calculated by equation (2.5), the resulting values become as shown in Figure 6.4. The figure also shows lethality values from simulations with a stationary front wall.

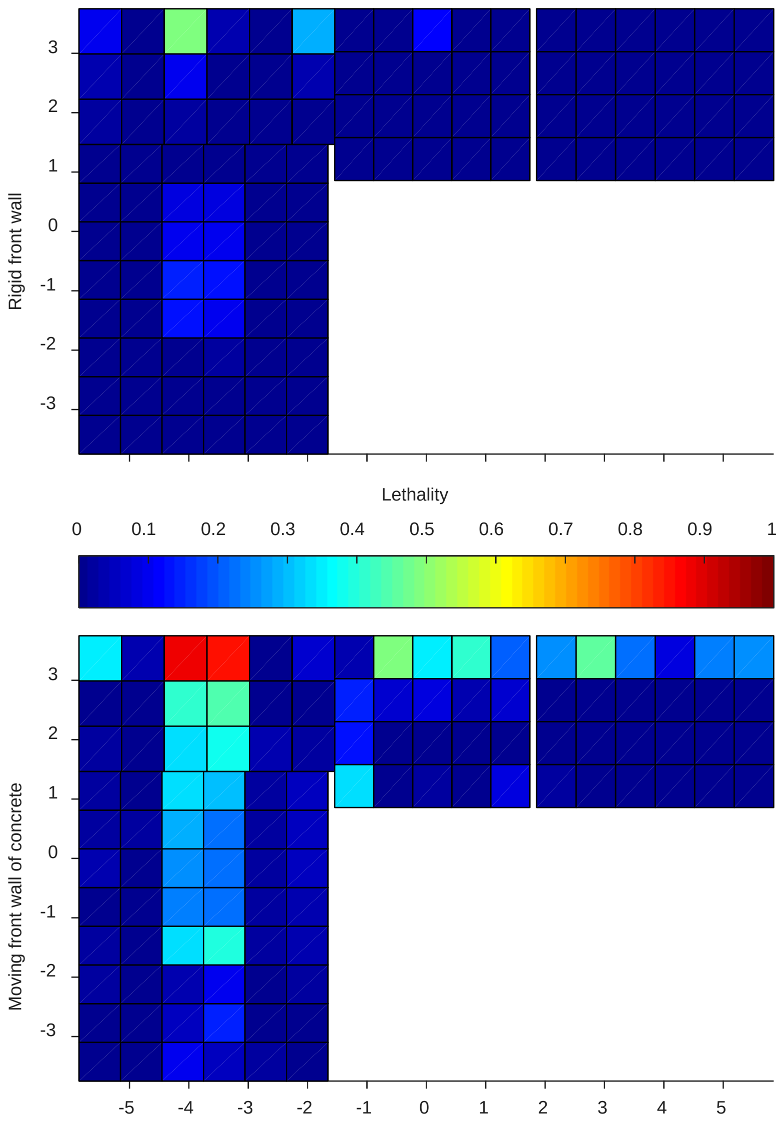


Figure 6.4 Lethality from body impact in the Lykkebo model with a rigid front wall and a front wall of concrete from an incident pressure wave of 960 kPa peak pressure and 3,800 Pa·s impulse

The mean lethality becomes 11 % with a moving front wall of concrete, hence half of the lethality caused by direct blast injury.

With stationary walls the lethality becomes 2.3 %. The difference between a moving and a rigid front wall is thus considerably larger for impact injuries than for blast injuries. The blast injuries are mainly caused by the first part of the pressure wave, which is not very much affected by the movement of the front wall. However the subsequent air stream pushing a person becomes appreciably stronger when the blast has made openings in the wall. The use of a simplified response model of the wall without structural resistance therefore brings uncertainty to the calculated lethality, assumingly on the conservative side.

For a person in free-field at the same distance from the charge as the front side of the house the blast wave gives the body a maximum velocity of 31 m/s corresponding to a lethality of 95 %.

7 Results

The calculations described above give the estimated average lethality in the Lykkebo house for one particular pressure load. In the following, results are shown for similar calculations of the direct effects of a series of incident pressure loads with different peak pressures and impulses. Both concrete structures and wood structures are considered. The results are compared with the lethality caused by building damage as described in chapter 4.

A comprehensive study of the indirect blast effects in a building has not been made because a large number of simulations are required to get results for a single pressure wave.

7.1 Wood structure

The average lethality values inside a wood structure exposed to different pressure loads are depicted in the *PI*-diagram in Figure 7.1. The example described above gives the encircled point. The figure also shows contours that are fitted to the lethality values[1].

[1] The contours are fitted by the MATLAB *contour* function to lethality values in a uniformly spaced logarithmic grid found from the values of the figure points by interpolation

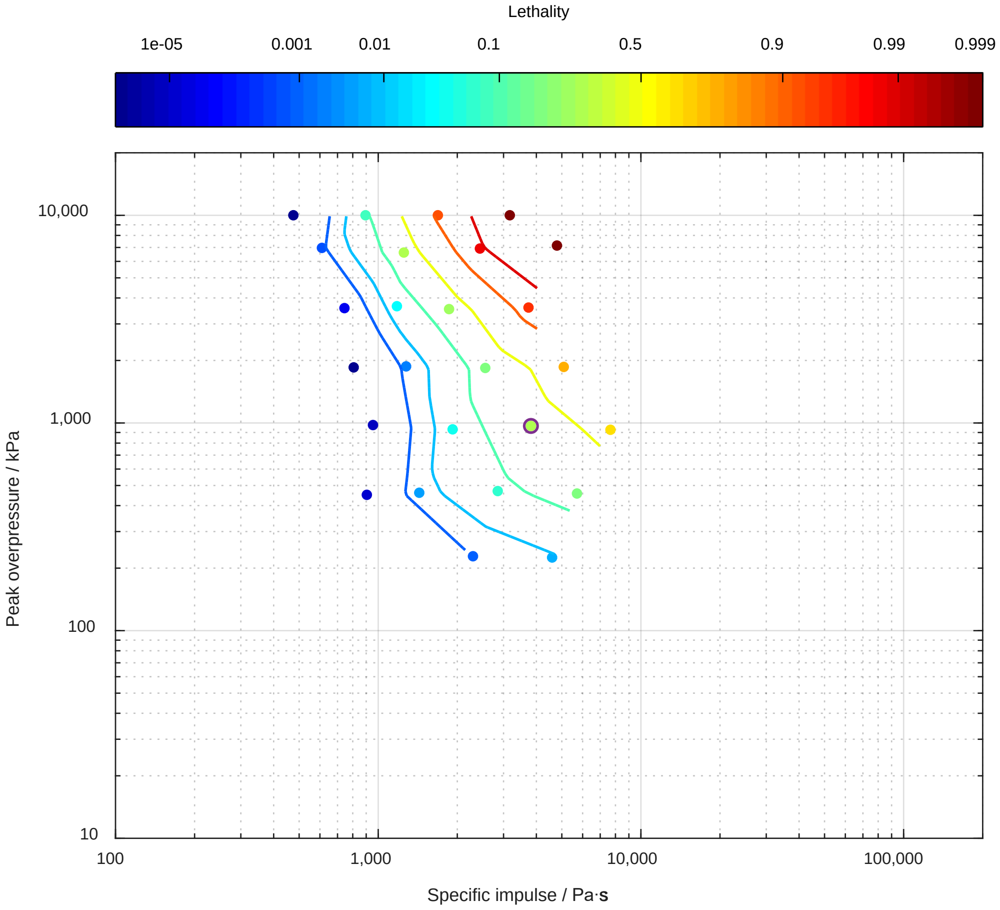


Figure 7.1 Lethality from blast injuries in wood structures found from simulations and fitted contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality

The figure shows that large pressure loads are required to give notable lethality values. The lethality estimated from the blast in the experiment with Lykkebo 1:5[2] is only $8 \cdot 10^{-10}$.

We can then compare the lethality from blast injuries and from building part injuries in a small wood structure. Figure 7.2 shows the effect of the two injury mechanisms and the cumulative effect when they are considered independent. There are no contours for lethality values below 10 % because the lowest value of the total lethality is 6 % in the area containing blast injury values.

[2] Peak overpressure 48 kPa, upscaled specific impulse 1950 Pa·s

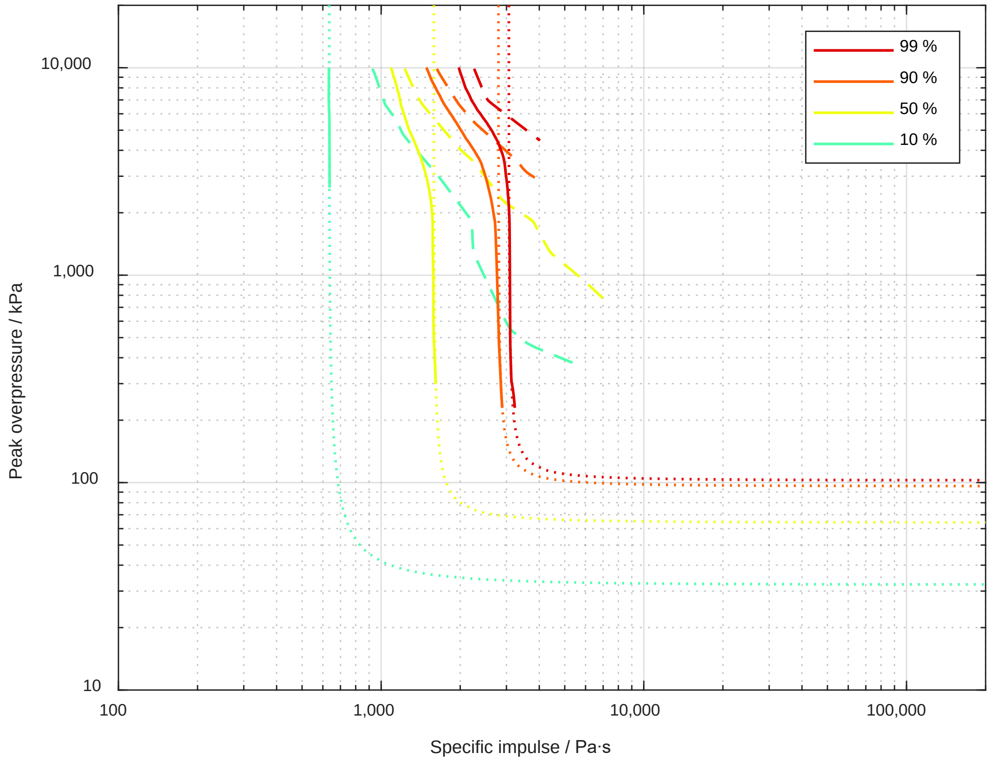


Figure 7.2 Contours for 10 %, 50 %, 90 % and 99 % lethality from blast injuries (dashed lines), building damage (dotted lines) and both of the injury types (solid lines) in wood structures

At impulse values larger than 1,000 Pa·s and pressure values larger than 2-3,000 kPa the blast injuries give a small increase in the total lethality, shown as the deviation of the curves for total damage from the curves for building damage. At other values this injury mechanism can be neglected. This includes the area not covered by the curves (below 10,000 kPa).

A further examination of the results can be made by looking at the pressure and impulse values from specific charges detonated at different distances from the building. The values are shown in Figure 7.3. The 100,000 kg charge is included here for later reference.

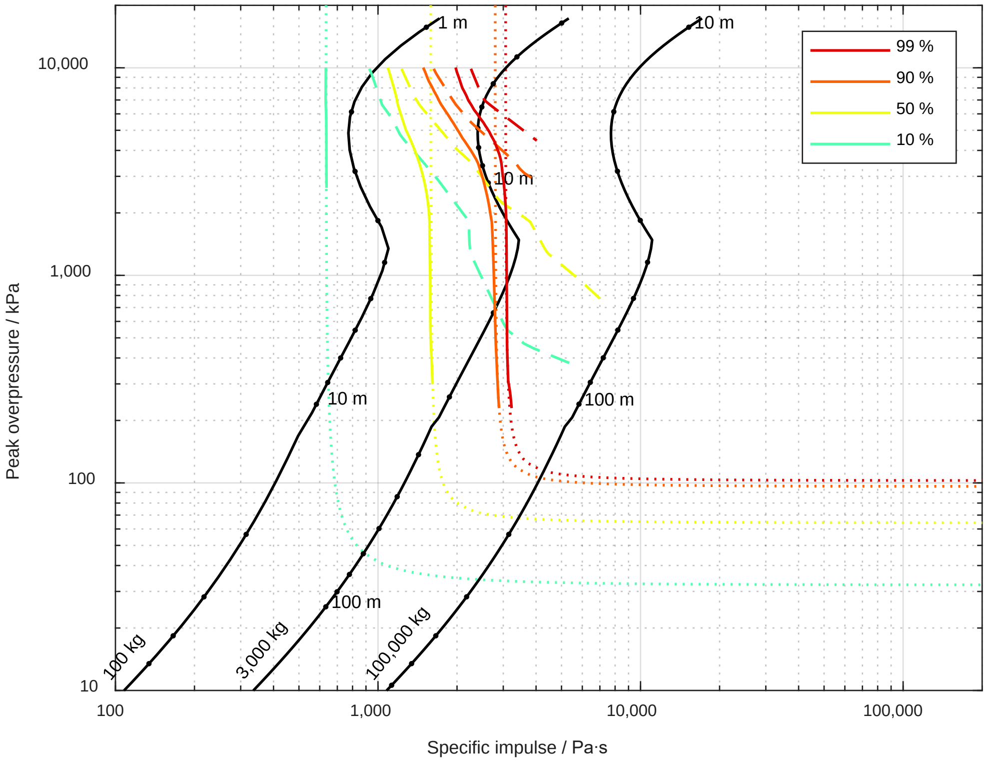


Figure 7.3 Lethality contours for wood structures and pressure and impulse values at different distances from the detonation of 100 kg, 3,000 kg and 100,000 kg TNT on the ground [20]

The lethality as a function of distance then becomes as shown in Figure 7.4.

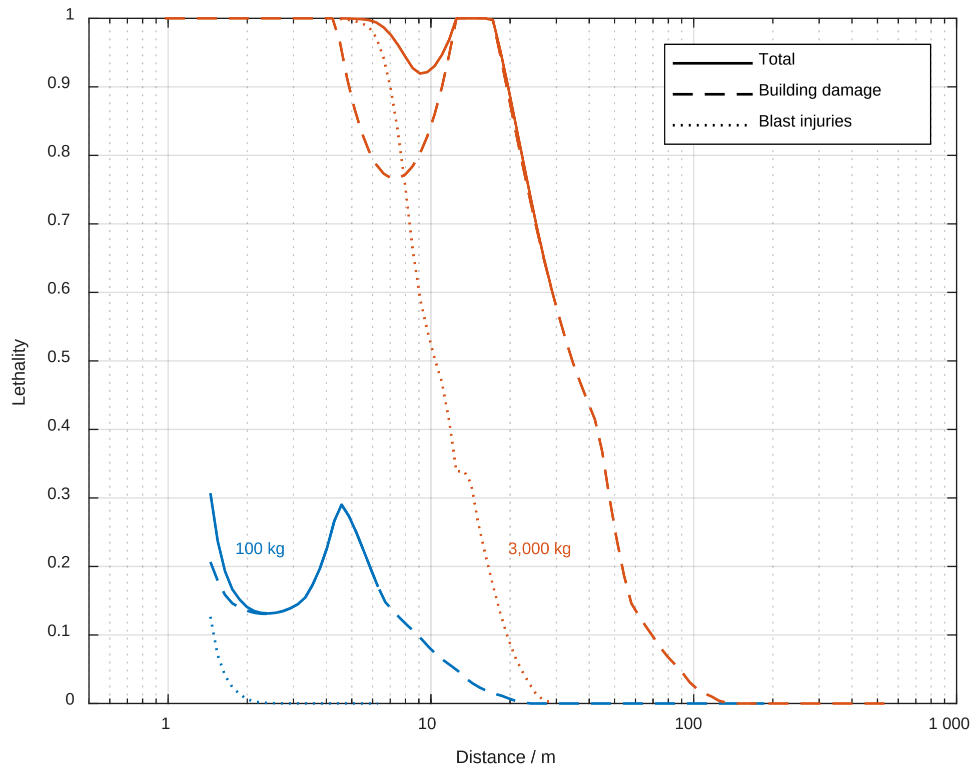


Figure 7.4 Lethality to people in a wood structure caused by blast injuries, building damage and both of the injury types when charges of 100 kg and 3,000 kg TNT are detonated on the ground

It is apparent that the blast injuries only give small contributions to the total lethality at the shortest distances.

7.2 Concrete structure

The walls of a concrete structure are heavier than the walls of a wood structure and will not as easily be damaged and displaced by the incident pressure wave. Thus the pressure inside the building gets lower. Still the difference between a wood structure and a concrete structure is not very large, as shown by the lethality contours in Figure 7.5 . The simulations with concrete structures cover a larger range of pressure and impulse values than the simulations with wood structures. Also here the point from the calculation example is marked.

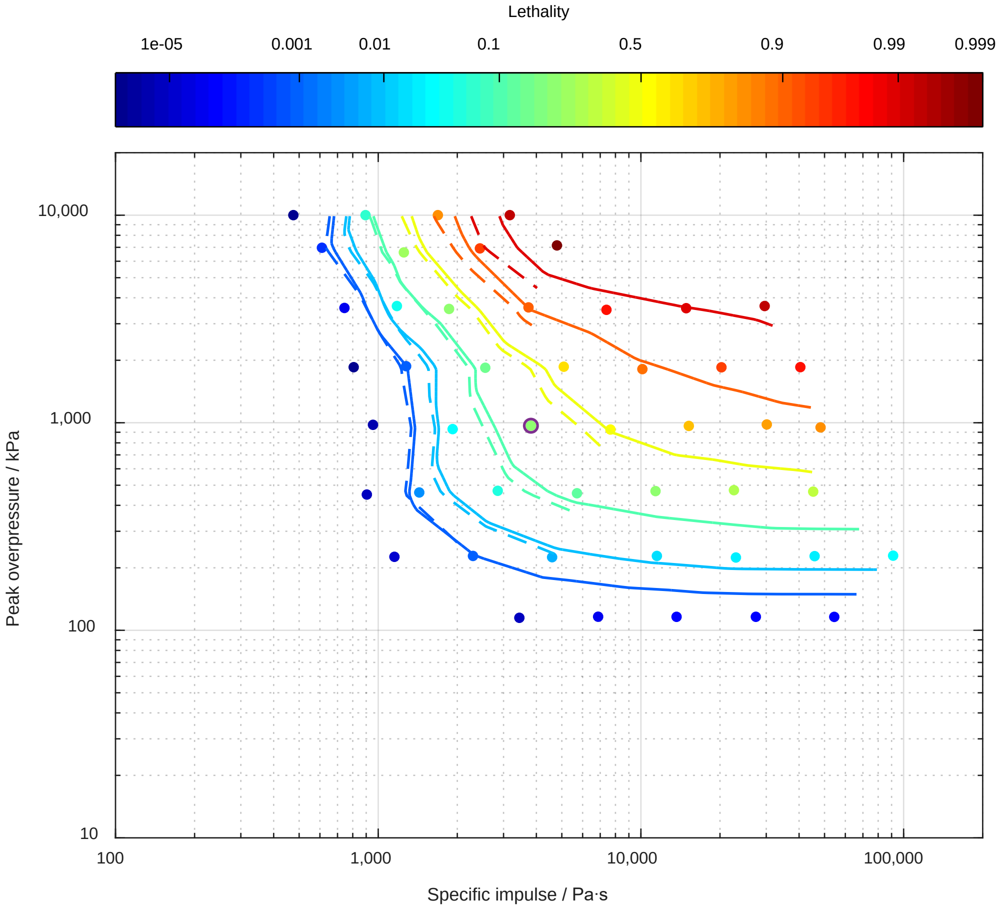


Figure 7.5 Lethality from blast injuries in concrete structures found from simulations and fitted contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality (solid lines) together with contours for wood structures (dashed lines)

In contrast to the small differences shown in this figure there are considerable differences between constructions of wood and concrete when it comes to the lethality from building parts. Figure 7.6 shows the effect of the two injury mechanisms in concrete structures and the cumulative effect.

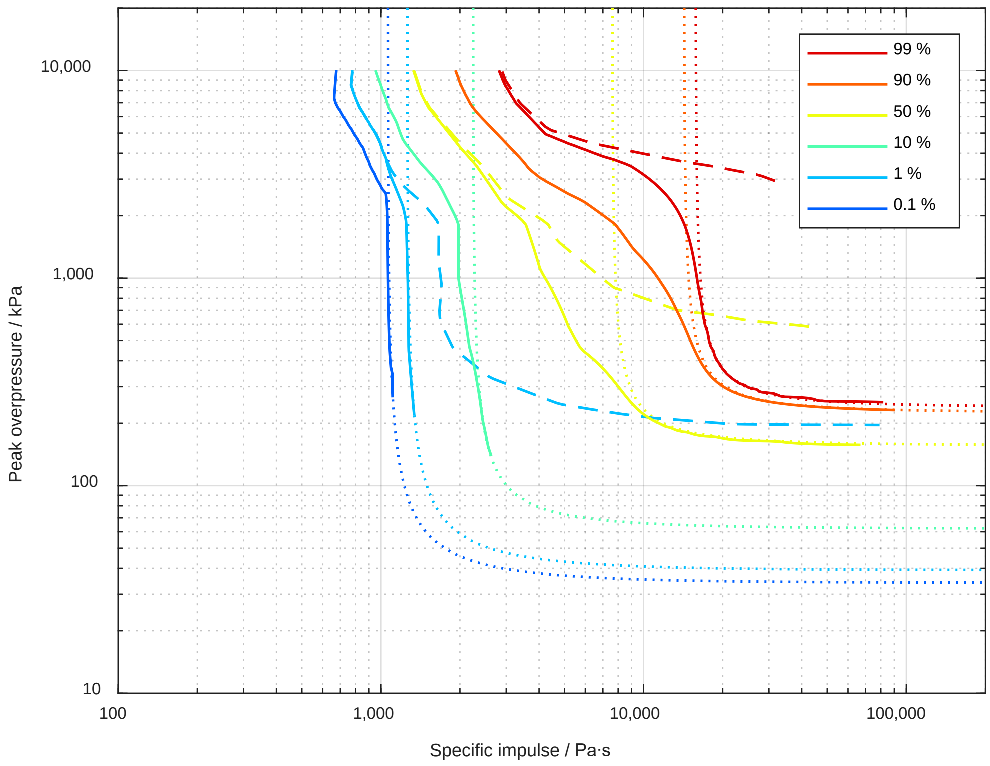


Figure 7.6 Contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality in concrete structures from blast injuries (dotted lines), building damage [25] (dashed lines) and both of the injury types (solid lines)

The curves for the total lethality follow the curves for building damage up to a pressure of about 500 kPa. For lower pressures the blast injuries only give a minor contribution to the total lethality. However for higher pressures the blast injuries should be taken into account.

If we employ the pressure and impulse values from the three charges shown in Figure 7.3, the relation between lethality and distance from the charge becomes as shown in Figure 7.7.

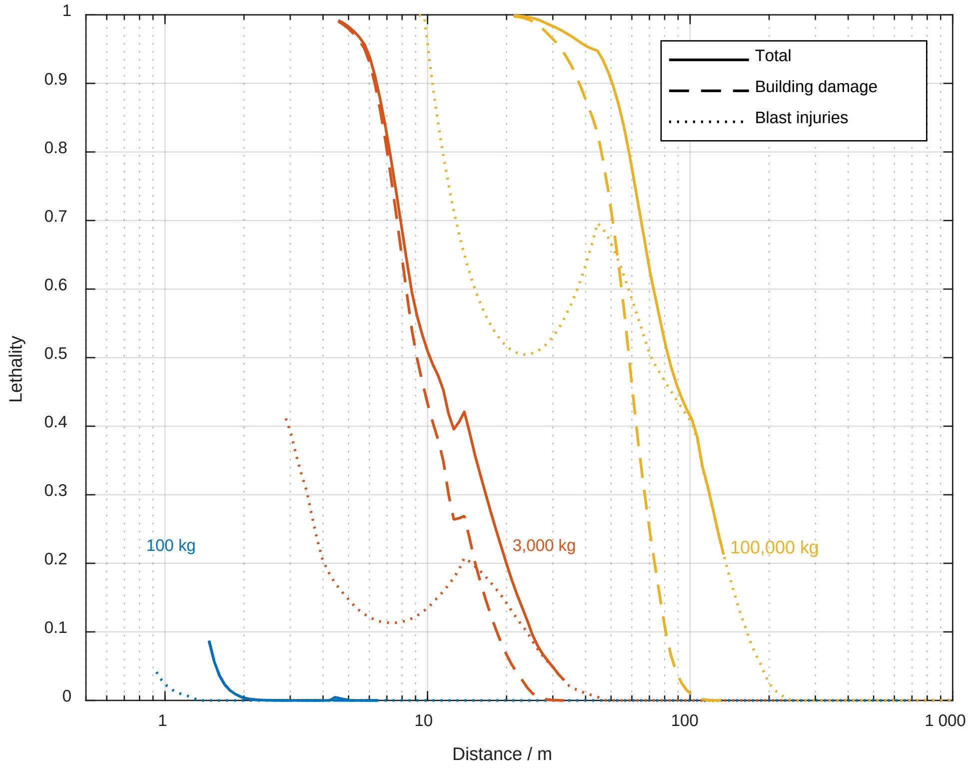


Figure 7.7 Lethality to people in a concrete structure caused by blast injuries, building damage and both of the injury types when charges of 100 kg, 3,000 kg and 100,000 kg TNT are detonated on the ground

The figure shows that the lethality is mainly determined by blast injuries at short distances.

The shape of the iso-contours for blast injuries cannot be described by simple equations, nor can the lethality as a function of pressure and impulse. However we have fitted curves described by equation (4.1) to the contours. The curves can give a rough estimate of the injury inside a concrete building for a blast wave with a given initial pressure and impulse.

The fitted parameters in Table 7.1 give the curves shown in Figure 7.8.

Table 7.1 Parameters for PI-curves for lethality from blast injuries in concrete structures

	A / kPa	*B* / Pa·s	*C* / kPa²·s
0.1 %	143	640	180
1 %	194	750	250
10 %	300	900	600
50 %	551	1060	2500
90 %	1150	1350	4900
99 %	2720	1660	8145

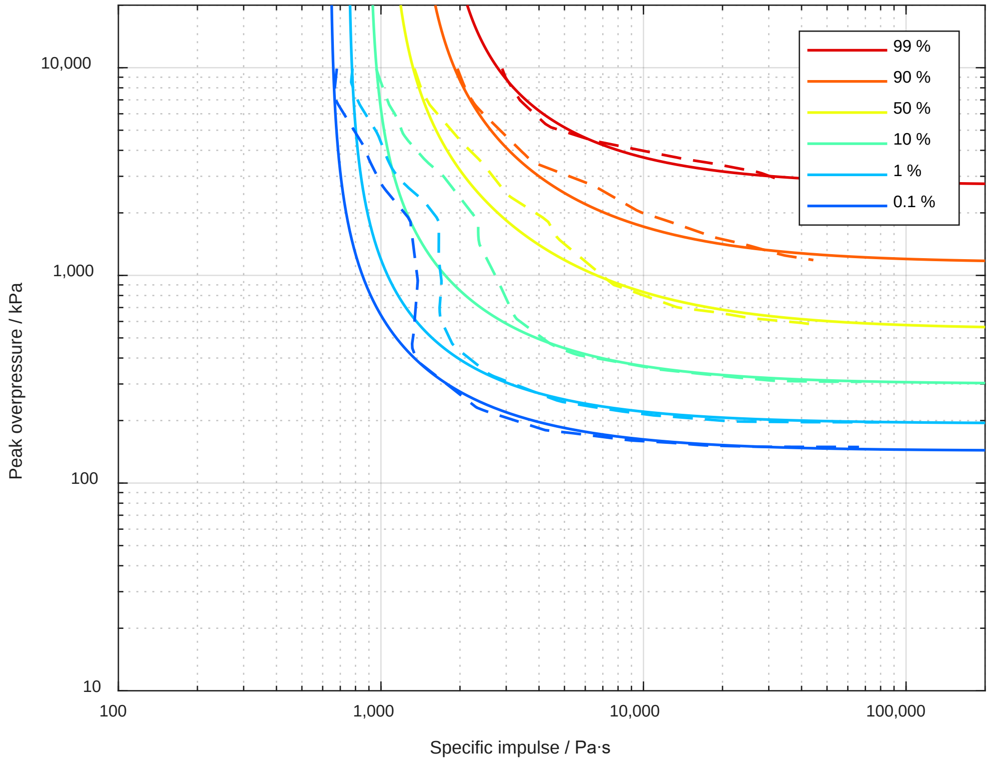


Figure 7.8 Contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality from blast injuries in concrete structures and fitted PI-curves

The shape of the fitted curves does not take account of the shape of the contours at the lowest impulse values, and there the lethality values given by the curves become too large.

The pressure that propagates into a room through an opening depends on the size of the opening and the size of the room. This is apparent when comparing iso-contours for the lethality in the three rooms that are investigated, see Figure 7.9.

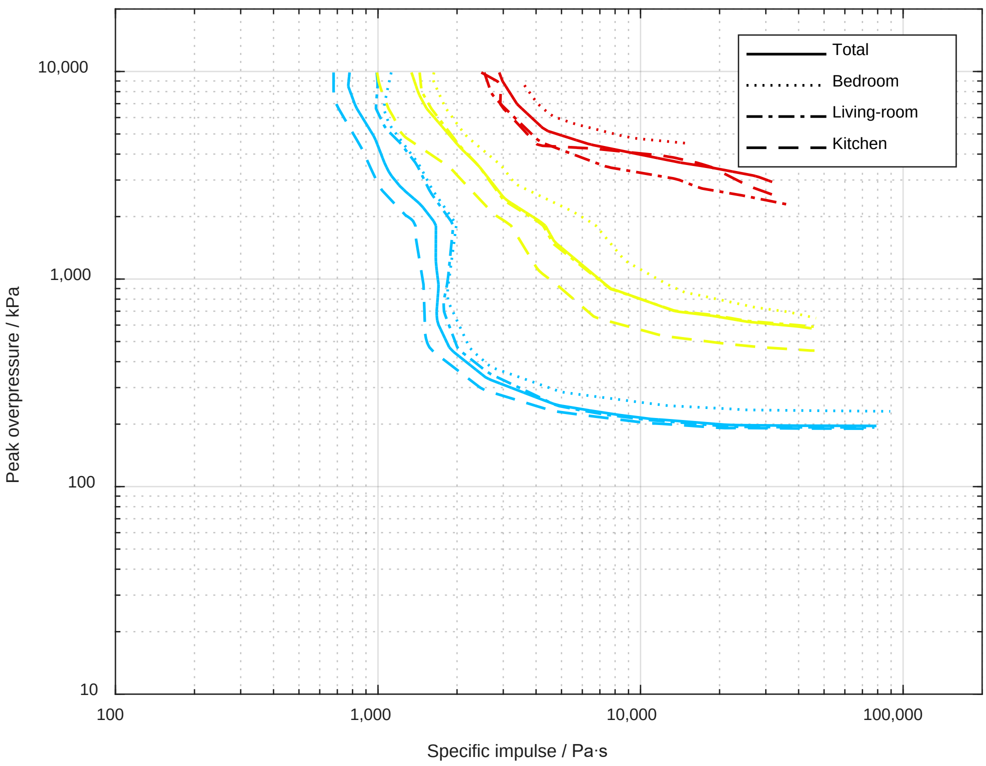


Figure 7.9 Contours for 1 %, 50 % and 99 % lethality from blast injuries in bedroom, living-room and kitchen and in all the three rooms of the concrete structure

There are clear, but not very large differences between the results for the different rooms. The lethality is lowest in the bedroom and highest in the kitchen except at the largest pressure and impulse values. In the living-room the lethality is roughly less than or equal to the total lethality at lethality values less than 50 %.

8 Discussion

The simulation method is not verified against experiments with larger blast loads than in the Lykkebo 1:5 test. Simulations show that also then the differences between the pressures with a rigid and a moveable front wall will be small. The energy of the blast wave will be larger, so the work spent on deformation and breakage will be comparatively smaller. Disregarding the structural resistance should therefore have less effect when the pressure gets higher.

Very large pressure loads may also damage the side walls and the back wall. The simulations do not take that into account. Usually the blast injury is determined by the first peak of the internal blast wave. If the blast wave reflects against the walls before they fail, any subsequent wall damage will be of minor importance to the first peak. A simulation with an incident pressure of 7,000 kPa and an impulse of 4800 Pa·s where also the side walls and back wall can move freely gives the same average lethality as when only the front wall can move.

The concrete model is so far not verified by experiments, but the calculation example in chapter 6 suggests that the modelling approach is reasonable. The pressure load of 960 kPa peak pressure and an impulse of 3,800 Pa·s gives an average lethality of 0.22 in the concrete version of Lykkebo. A similar simulation with a stationary and rigid front wall gives a lethality of 0.20. The small difference shows that the major part of the inside pressure has entered the building through the window openings. The corresponding lethality of 0.29 for a wood structure confirms this. The mass of the concrete wall only allows a small pressure intrusion through the wall. Including resistance to deformation will therefore not influence the results significantly.

When the cumulative lethality from blast injuries and injuries from building damage is calculated, the two injury types are considered independent. However the outcome of both of them depends on the extent of building damage. These events are in that respect not independent. However, for a given incident pressure wave with corresponding building damage, the two injury mechanisms may be considered independent, and the cumulative lethality can be calculated accordingly.

9 Conclusions

Existing methods for estimating injury to people inside a building that is exposed to a blast wave mainly deal with the injury from building debris. However, when the blast wave enters the building through openings it can also cause direct or indirect blast injuries. Such openings can be formed when the blast wave damages the windows and the rest of the building.

In a series of numerical simulations the propagation of external blast waves into buildings has been calculated. The blast injury is then estimated from Axelsson's model of the chest and correlating injury measures.

The results show that for strong structures like reinforced concrete structures, hazards to the occupants from the pressure inside is significant compared to the injury from building debris, when the incident pressure exceeds 500 kPa. The lethality from blast injury can be estimated by constructed isocontours in a *PI*-diagram.

The pressure injury to people inside light buildings is not much larger than inside R/C structures when the windows are similar. However the injury from building parts can become much larger in light buildings. In wooden structures the pressure injury can therefore be neglected when the incident pressure is below 3 MPa. At higher pressures the blast injuries give a small contribution to the total lethality inside the building.

Modelling windows as rigid bodies, without interaction with the rest of the house, gives simulation results in good accordance with experiments. The similar modelling approach used for the front wall by dividing it in rigid elements, also gives results that agree with experimental data.

The difference between lethality values calculated for different rooms is moderate. The results of this study are therefore good indications of the extent of blast injuries in rooms of somewhat different designs.

Appendix

A Numerical simulations

The numerical simulations described in this report are carried out by ANSYS Autodyn. ANSYS Autodyn is an explicit analysis tool for modelling non-linear dynamics of solids and fluids, and their interaction [26]. Different solvers can be integrated in a model. Examples of this are the simulations described in this report, in which calculation of blast wave propagation is combined with calculation of building response and blast effects on humans. Furthermore, user subroutines can be linked to the code, such as routines for calculating injuries to people by the Axelsson model [15].

Bendik A. Sagsveen, Jan Rune Nilssen and Odd Halsnes at FFI have provided the geometry and the meshing of the Lykkebo house used in the numerical simulations. Jan Arild Teland, also at FFI, has given professional guidance and support on the numerical tool ANSYS Autodyn.

A.1 Methods

The detonation of a charge and the propagation of the resulting shock wave is a spherical-symmetrical process, or hemispherical if the charge is on the ground. It can therefore be modelled in one dimension, and we have employed Autodyn's wedge geometry. This corresponds to a spherical charge, so for detonations on the ground the charge mass is set to twice the real mass to account for reflection on the ground. These calculations are made with the Euler-Godunov processor, which can deal with more than one material type.

The detonation itself is not modelled, but a constant detonation velocity is assumed. The expansion of the detonation gas is described by the Jones-Wilkins-Lee (JWK) equation of state for pressures down to 1 kbar. The equation is written as

$$p = A\left(1-\frac{\omega\eta}{R_1}\right)e^{-\frac{R_1}{\eta}} + B\left(1-\frac{\omega\eta}{R_2}\right)e^{-\frac{R_2}{\eta}} + \omega\rho e \qquad \text{(A.1)}$$

where p is pressure, η is the ratio of the density ρ and the reference density ρ_0, e is internal energy, and A, B, ω, R_1 and R_2 are empirically determined parameters. The parameters used for C4 and TNT are shown below. They are collected from the material library included with Autodyn.

Table A.1 Parameters in the equation of state for C4 and TNT (JWL)

	C4	TNT
ρ_0	1 601 kg/m^3	1 630 kg/m^3
A	$6.0977 \cdot 10^{11}$ Pa	$3.7377 \cdot 10^{11}$ Pa
B	$1.295 \cdot 10^{10}$ Pa	$3.7471 \cdot 10^{9}$ Pa
R_1	4.5	4.15
R_2	1.4	0.9
ω	0.25	0.35
u_{CJ}	8,193 m/s	6,930 m/s
e_{CJ}	$9.0 \cdot 10^{9}$ J/m^3	$6.0 \cdot 10^{9}$ J/m^3
p_{CJ}	$2.8 \cdot 10^{10}$ Pa	$2.1 \cdot 10^{10}$ Pa

When the density ratio becomes small the two first terms in the equation above can be neglected, and the equation of state becomes as for an ideal gas with the adiabatic coefficient equal to ω+1. In Autodyn this transition is made automatically at pressures below 1 kbar.

For air the equation of state for an ideal gas is used,

$$p = (\gamma - 1)\rho e \qquad \text{(A.2)}$$

with pressure p, adiabatic exponent $\gamma = 1.4$, density ρ and specific internal energy e. In undisturbed air at standard conditions the internal energy is set to $2.068 \cdot 10^5$ J/kg and the density to 1.225 kg/m^3.

The size of the Euler cells in the 1D simulations varies with different charge sizes, but is always less than 1 mm. The model is scaled, and between 20 and 99 cells are filled with explosives.

When the blast wave has reached the house the further propagation is modelled in three dimensions. The initial condition of the air in front of the house is derived from the 1D simulation by the remapping routine of Autodyn. The remapping may include cells containing the detonation gas. These cells are assumed to be filled by air with values of the state variables collected from the detonation gas. The 3D calculations are made by use of Autodyn's Euler-FCT solver for ideal gases.

Zeigler et al [35] included Axelsson's model (chapter 2.1) as a subroutine in Autodyn. By the routine the chest wall velocity that the pressure at a position would inflict on a person can be collected from the simulations.

When a part from the building covers an Euler cell, the pressure in the cell becomes zero. Then after the part has passed, the pressure in the cell increases fast. This may lead to unrealistically high chest wall velocities. In these cases the solution of Axelsson's model is made without the time points with zero pressure. Another issue in this context is that the time steps in the Autodyn simulations may be too large for the Axelsson's model at very rapid pressure changes. We have therefore made most of the calculations with the Axelsson's model with a differential equation solver in MATLAB.

The Euler grid extends so far out from the side and the back of the house that boundary effects only have a minor influence on the pressure propagation. A routine available in Autodyn is used as boundary condition. The routine (Euler Flow Out) adds a cell on the outside of the boundary, where the state of the gas is set to the same as in the cell inside.

Towards the charge the grid reaches as far as necessary to include cells that influences the pressure flow in the house significantly. The length of the cells increases with the distance from the house according to the relation

$$l_i = l_0 e^{ki} \qquad \text{(A.3)}$$

where l_i is the length of cell i, l_0 is the initial length and k is a growth constant.

The calculations with the windows are made with a rigid material and Autodyn's shell solver. Shell parts do not have a geometric thickness. When interacting with an Euler grid, the parts are given an artificial thickness so that they fully cover the cells they initially reside in. Still the mass of the shell parts are defined by a density and a thickness.

The walls are rigid volume parts.

A.2 Models

A.2.1 Lykkebo tests in scale 1:25

Inside the house the size of the Euler cells is 4 mm. Outside, the length increases as described by equation (A.3) with k = 0.0235. The grid reaches 0.53 m out from each side and 0.38 m from the back side of the house, and 1.7-2.0 m from the front side in the direction of the charge. The height of the grid is 0.63 m.

Pressure values are registered at the same positions as in the tests.

Initially interaction between the window plates and the construction was included, by use of Autodyn's trajectory model with a penalty force. Later investigations found that the interaction between the window plates and the construction reduced the velocity of the plates when they reached the interior edge of the window openings. A simulation of one of the tests was then made without contact forces. In Figure A.1 the results are compared with the results from the original simulation.

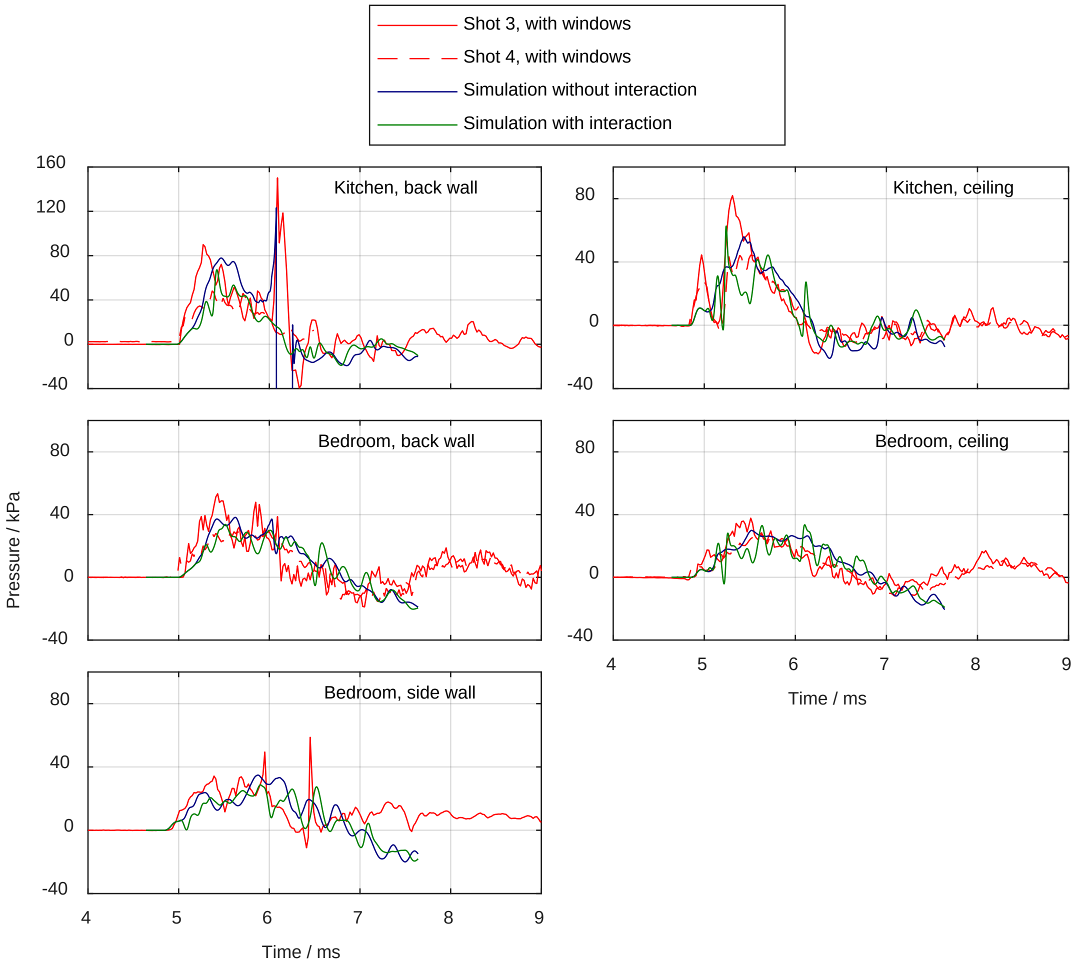


Figure A.1 Pressure values in kitchen and bedroom in the 1:25 model of Lykkebo from test and simulations with and without interaction between windows and construction when 0.32 kg C4 is detonated 2.2 m from the house

The simulation results are clearly influenced by the contact forces against the windows. The peak pressures are somewhat reduced when the forces are included. However the simulations without interaction seem to give results in as good accordance with the test results as the simulations with the interaction. It was therefore decided not to include the interaction in the further simulations.

A.2.2 Lykkebo in full scale

The Euler grid extends 5-15 m out from the side walls, depending on the length of the blast wave, and out to 3.6 m from the back wall. The grid is 9.9 m high. In a 13 m wide, 9 m long and 3 m high inner volume the cells of the grid are cubic with 5 cm side length. Further out the cells are stretched in the direction of the charge as described by (A.3) with $k = 0.095$. The extent of the grid in this direction is different for the various pressure loads.

The windows in the house are modelled as rigid bodies with an area thickness of 20 kg/m^2. Contact forces between the windows and other parts of the house are not taken into account.

Except for the front wall the house is regarded as a rigid, stationary body. The interaction between the front wall elements and the adjacent walls is calculated by Autodyn's trajectory model with a penalty force. In the simulation of the five tonne trial also the front wall is completely rigid.

Similar to the model in scale 1:25 the calculations includes the living-room, kitchen and bedroom.

At the five tonne trial explosives with an equivalent TNT charge weight of 5,011 kg were detonated in an ISO container [29]. The simulation of the detonation is made assuming a TNT charge of 5,000 kg detonated on the ground.

A.2.3 Lykkebo test in scale 1:5

The Lykkebo model used in the simulation of the third test against Lykkebo in scale 1:5 is a downscaled version of the model for Lykkebo in full scale, but with a window thickness of 2.15 mm.

The experiment was performed at an altitude of 855 meters above sea level. According to measurements from the Norwegian Meteorological Institute the ambient pressure at the time of the test was 92.2 kPa, and the temperature was 16° C. These conditions were employed in the simulation.

The side length of the Euler grid is 2 cm in the rooms on the ground floor and out to a small distance from the house (2.62 m x 1.96 m x 0.6 m). Further out the side length increases by a factor 1.1 per cell ($k = 0.0953$), and the total grid size is 15 m x 27.8 m x 4.5 m.

A.2.4 Experiment with a chamber with window

The Euler grid used in the simulation of the chamber test fills the chamber with 5 cm cells. Outside the chamber the grid extends from 20 m behind to 24.5 m before the front wall, and it is 40 m wide and 39.4 m high. The cell size is 5 cm in a 3 m wide, 2 m deep and 3 m high volume around the chamber. Outside this volume the cell size increases in each direction by the factor $k = 0.093$ (equation (A.3)). The part of the grid outside the chamber is connected to the part inside only in the window opening.

The chamber and the concrete wall are modelled as rigid and stationary bodies. The window is rigid with an area density of 15.6 kg/m^2, similar to the annealed glass pane used in the test.

The experiment was performed at the same test site as the Lykkebo test in scale 1:5. In the simulation of the chamber test the ambient pressure was estimated by the barometric formula [12] to 91.4 kPa, and the corresponding air density is 1.105 kg/m^3.

Table A.2 shows values of pressure, impulse and duration measured in the test and in the simulation.

Table A.2 Pressure wave parameters from test [33] and simulation when 400 kg TNT is detonated 25 m from the chamber

	Pressure / kPa		Impulse / Pas		Duration / ms	
	Test	Simulation	Test	Simulation	Test	Simulation
Free-field	93 101	90	655 704		30.6 30.6	16.8
Front wall, left	214	232	1150	1230	16.7	15.2
Inside, left wall	20.4	23.8	334	281	28.8	26.9
Inside, ceiling	19.0	19.5	331	282	32.9	27.5
Inside, back wall	31.7	33.5	363	309	29.6	21.2

A.2.5 Man

To calculate the acceleration of a person by the pressure wave simulations were made with a dummy model [36]. The mass of the body is 75.5 kg and the height 1.76 m, see Figure A.2. The surface area is 2.01 m^2.

The material of the body is rigid and with a uniform density. In the coordinate system shown in the figure the centre of gravity is at (0.000, 0.976 m, 0.058 m), and the components of the inertia tensor relative to the centre of gravity is I_{xx} = 13.95 kg·m^2, I_{xy} = 0.00, I_{xz} = 0.00, I_{yy} = 1.14 kg·m^2, I_{yz} = -0.18 kg·m^2, I_{zz} = 14.62 kg·m^2. By comparison an investigation of a representative selection of soldiers in U.S. Air Force in 1963 [37] found average values of the moment of inertia about the axes through the centroid of I_x = 11.64 kg·m^2, I_y = 1.28 kg·m^2 and I_z = 13.00 kg·m^2.

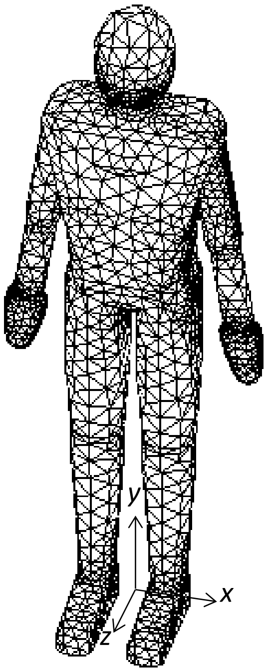


Figure A.2 Drawing of human model [36]

To avoid that the pressure wave hitting a body is disturbed by other bodies nearby, the number of bodies in a simulation is limited to two per room.

A.3 Results

A.3.1 Lykkebo tests in scale 1:25

In Figures A.3-A.9 results from the simulations of tests with Lykkebo in scale 1:25 are drawn up together with the experimental results. The times from the simulations are shifted to fit the arrival times of the tests. Figure 5.3 shows the similar comparison for the tests with 0.32 kg C4 at 2.2 m.

In a few of the simulations the pressure measured at the kitchen back wall drops to zero, giving an overpressure of -1 atm (Figure A.3, Figure A.6 and Figure A.7). The cell containing the pressure gauge is then covered by a window, as described in chapter A.1.

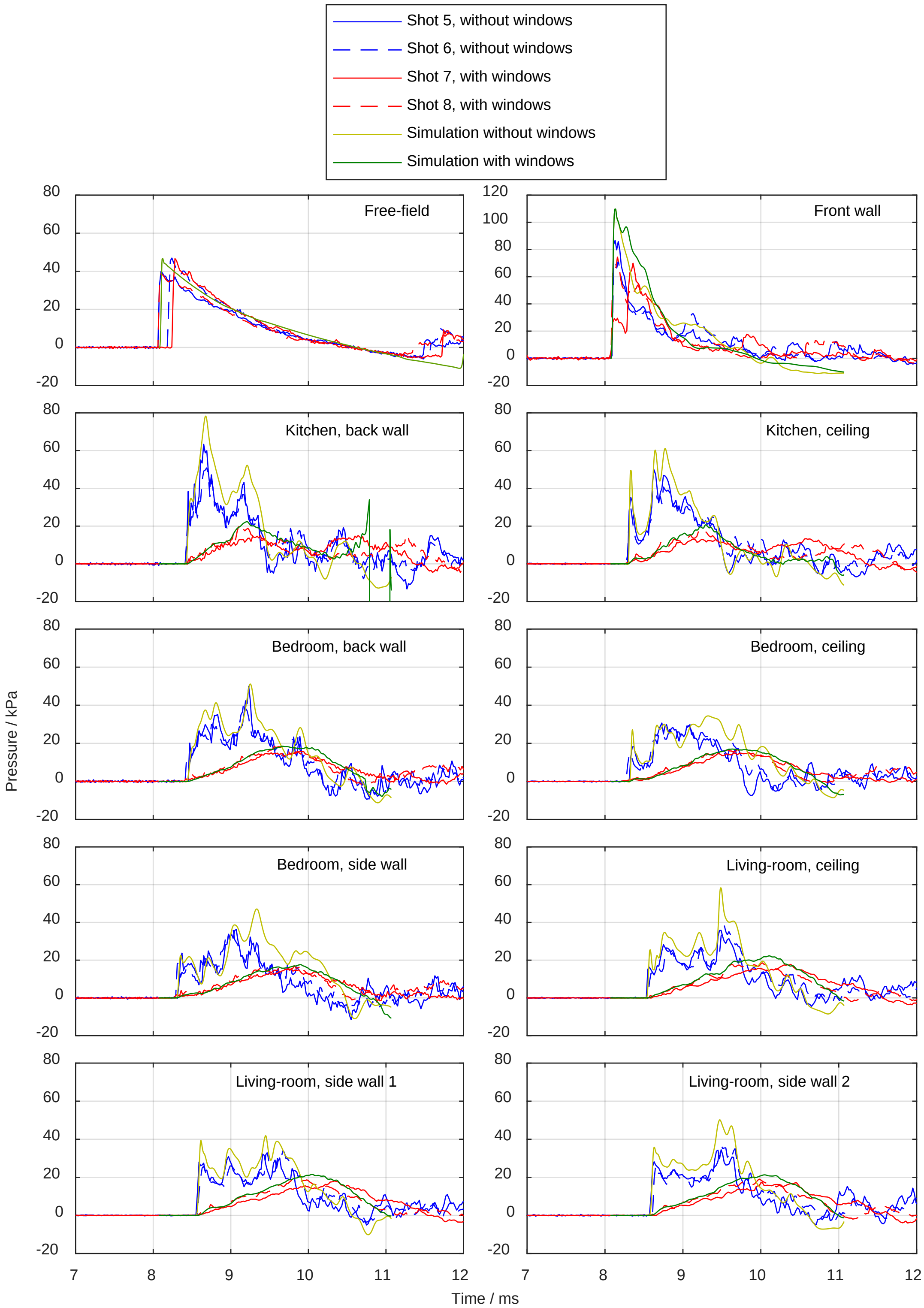


Figure A.3 Test and simulation results from detonation of 0.32 kg C4 3.76 m from Lykkebo 1:25

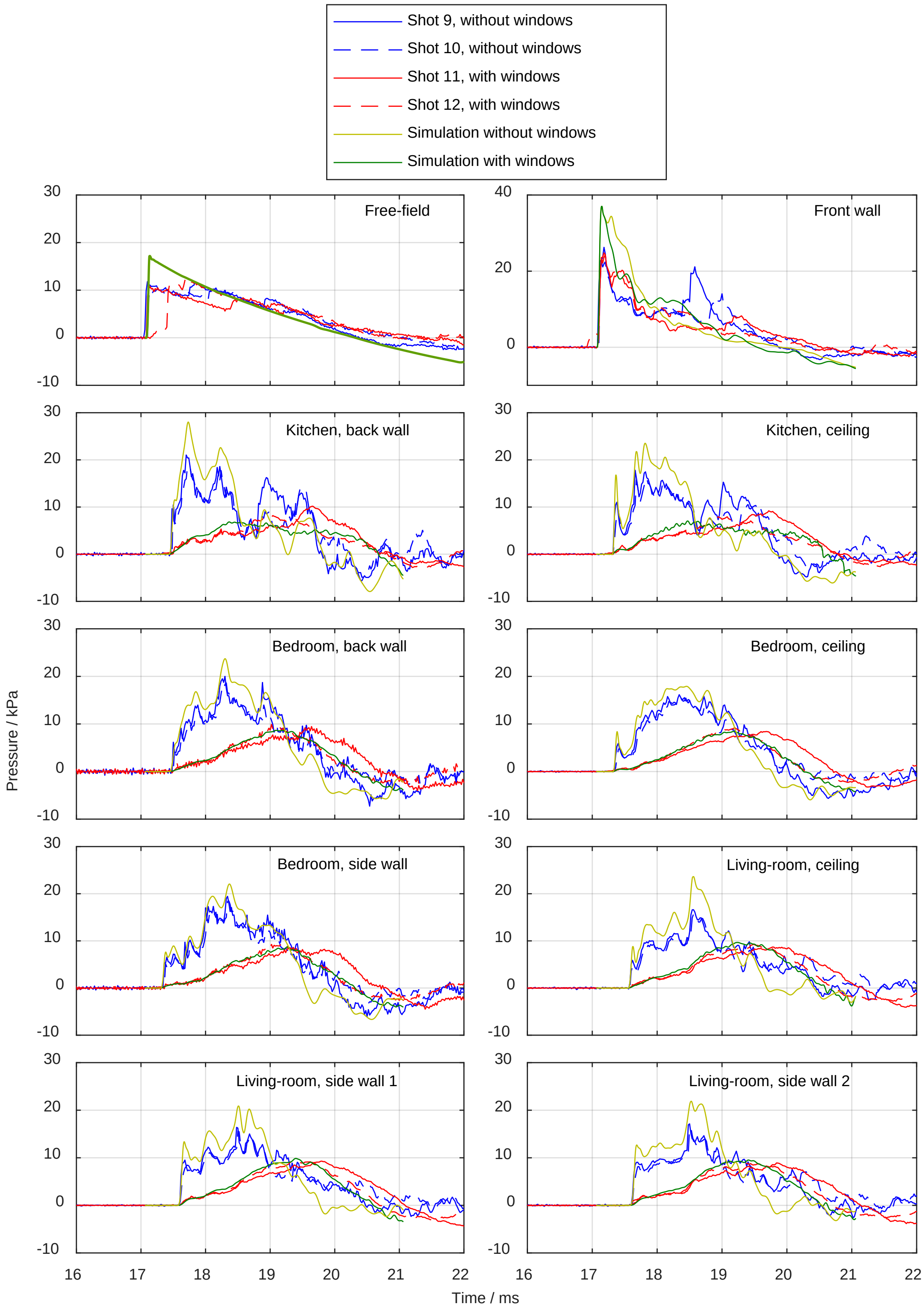


Figure A.4 Test and simulation results from detonation of 0.32 kg C4 7.0 m from Lykkebo 1:25

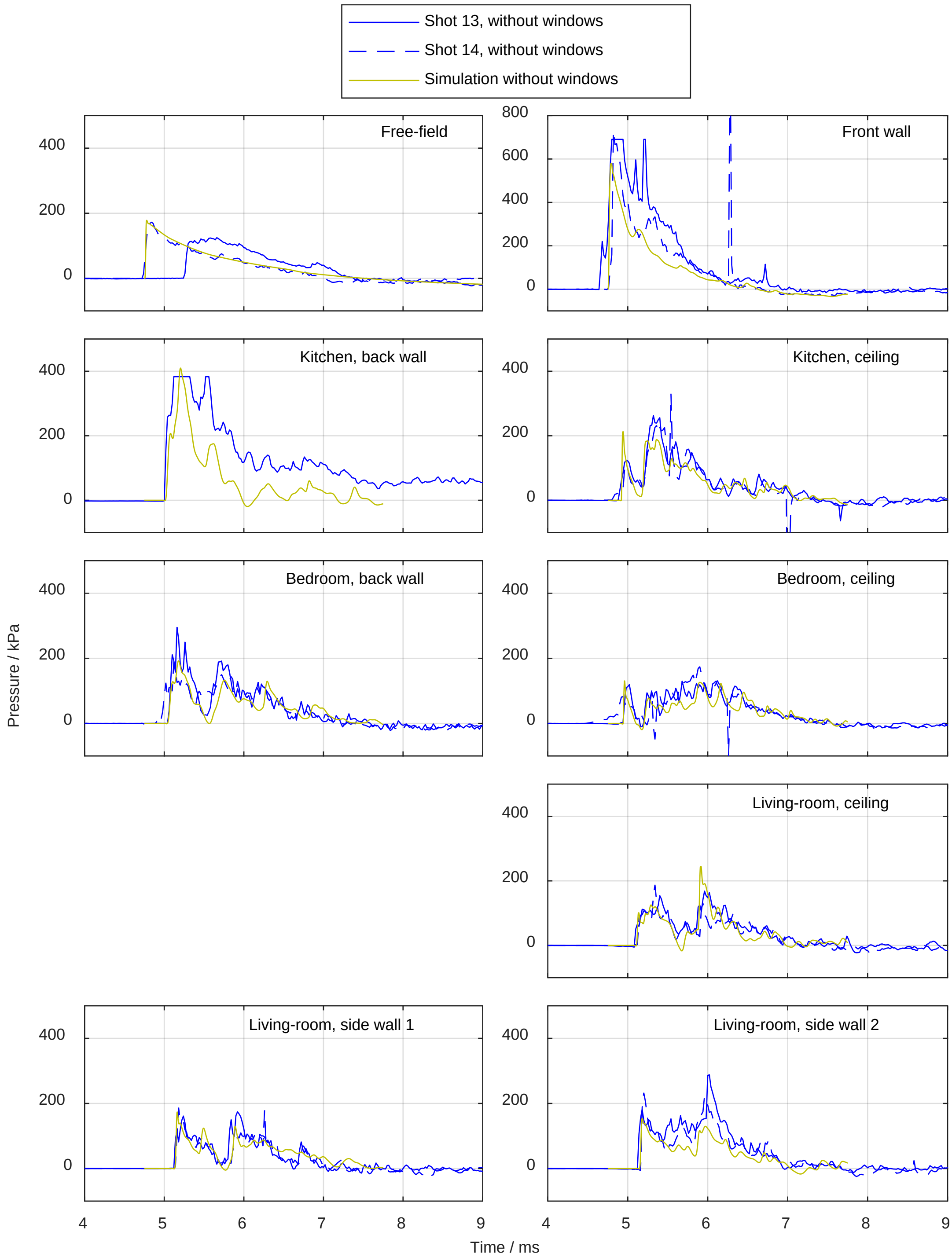


Figure A.5 Test and simulation results from detonation of 2.0 kg C4 3.5 m from Lykkebo 1:25

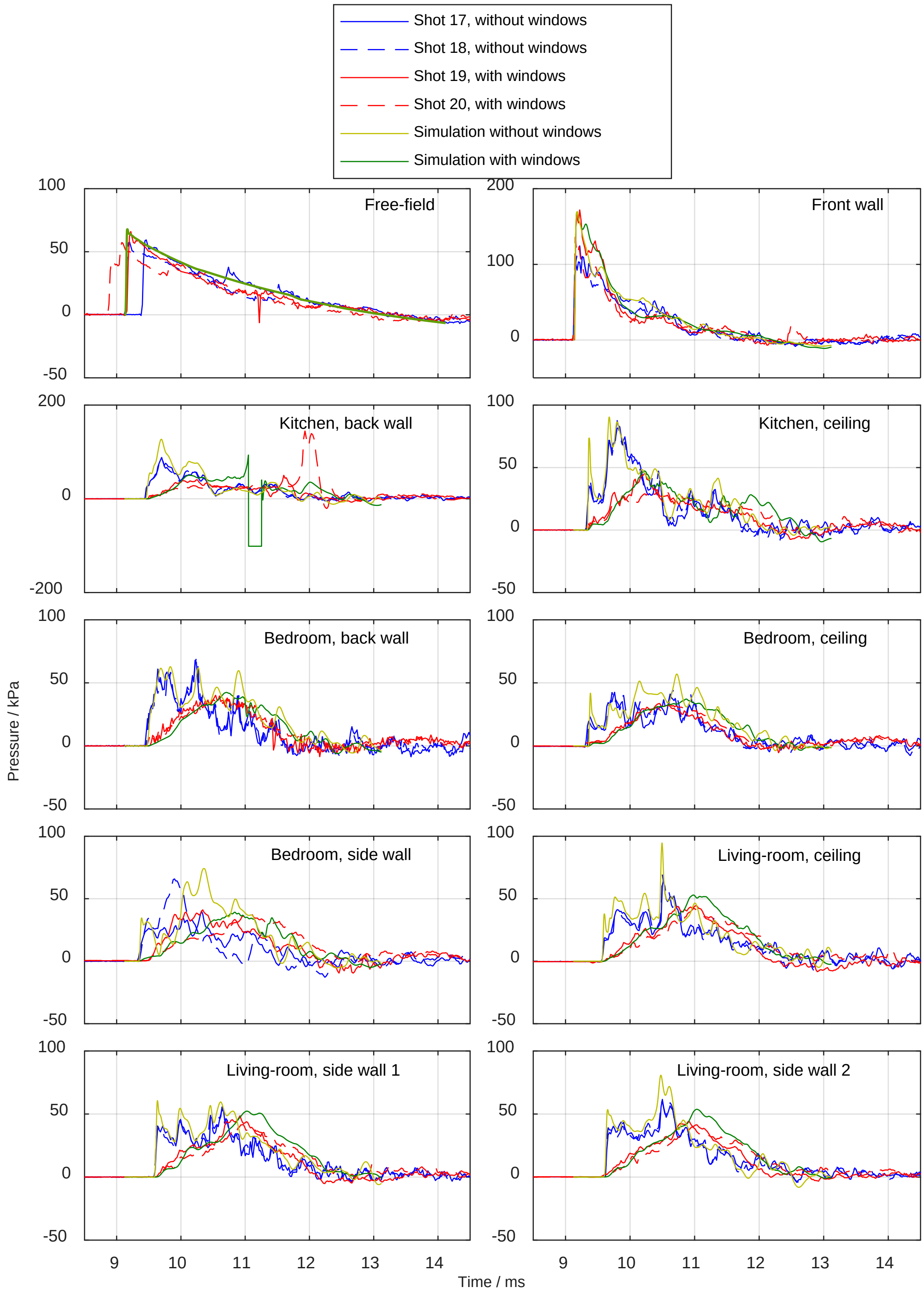


Figure A.6 Test and simulation results from detonation of 2.0 kg C4 5.67 m from Lykkebo 1:25

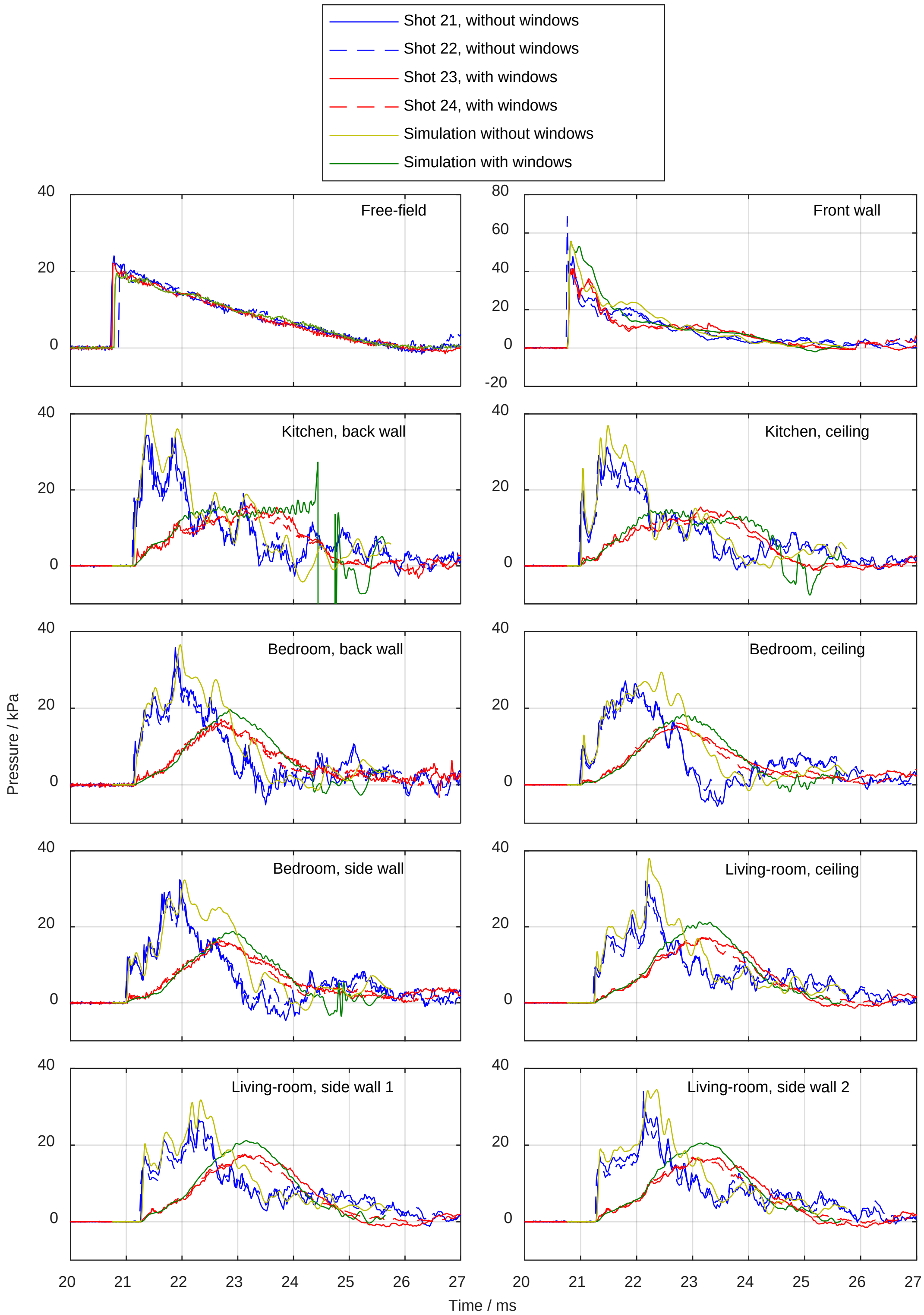


Figure A.7 Test and simulation results from detonation of 2.0 kg C4 10.08 m from Lykkebo 1:25

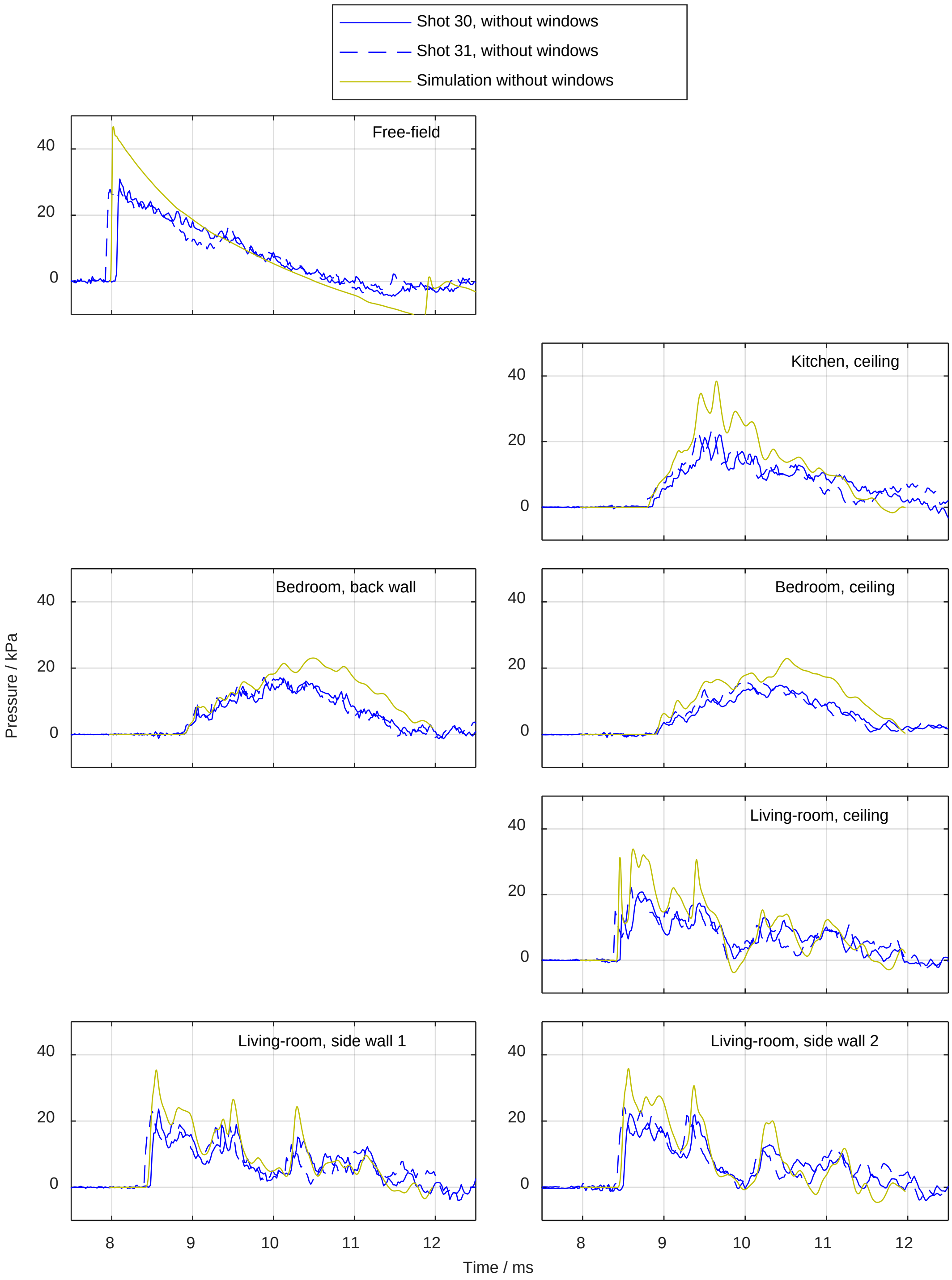


Figure A.8 Test and simulation results from detonation of 0.32 kg C4 3.76 m from the back side of Lykkebo 1:25

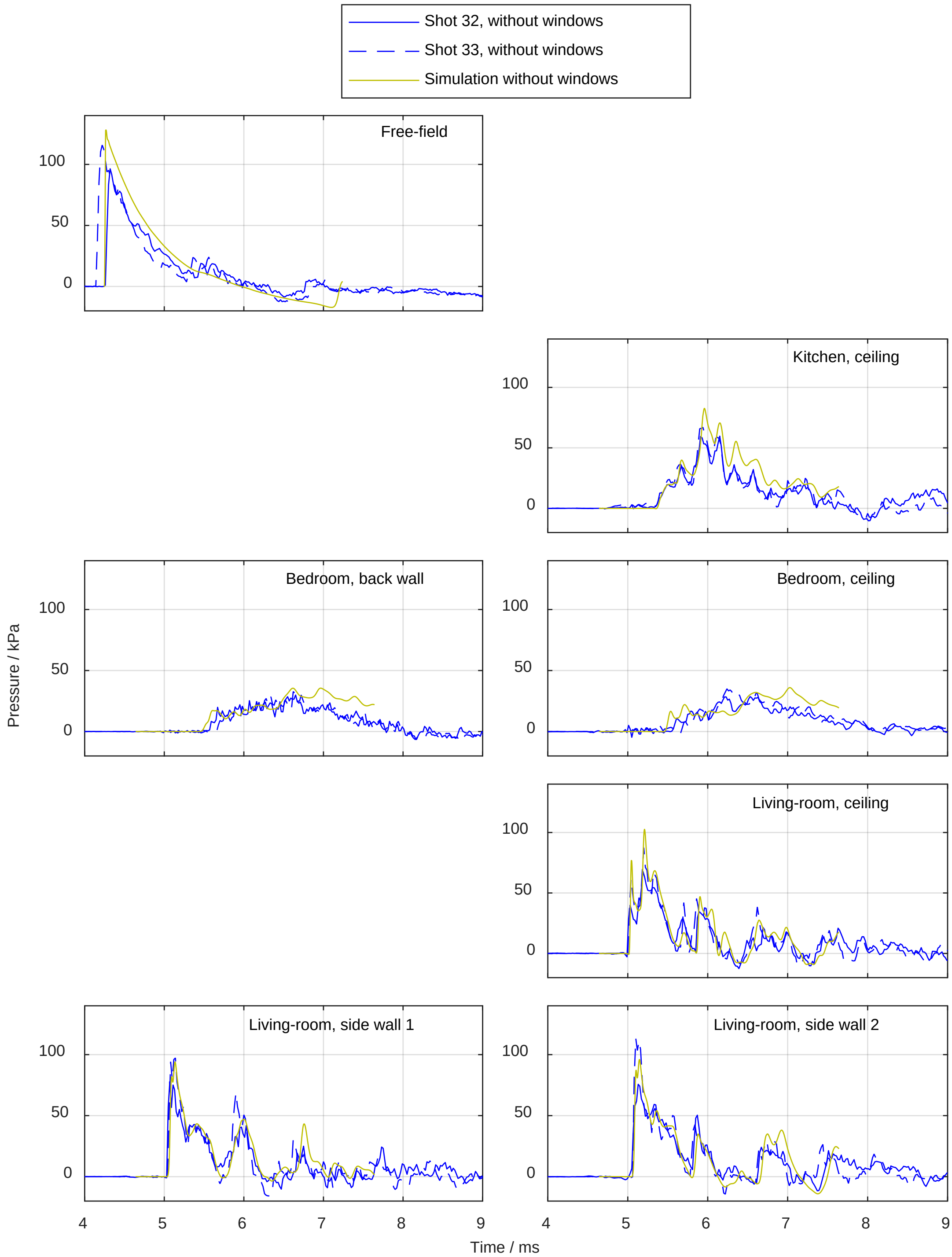


Figure A.9 Test and simulation results from detonation of 0.32 kg C4 2.2 m from the back side of Lykkebo 1:25

B Leakage pressure

The pressure build-up through small openings can be calculated by the method described by equation (3.1). We have made such calculations for the bedroom in two of the shots in the 1:25 tests with Lykkebo assuming the openings are the two window openings. The applied pressures are the registered pressure on the front wall and the side wall pressure estimated by the method of Glasstone and Dolan [38] employing the measured free-field pressure. The results are shown in Figure B.1.

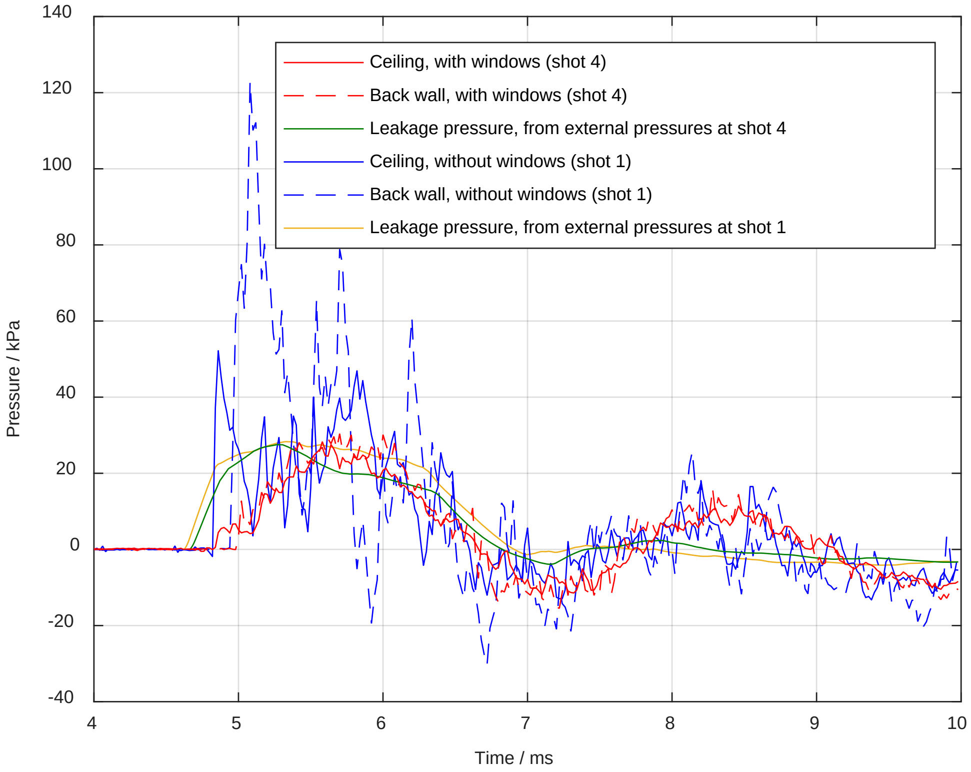


Figure B.1 Calculated leakage pressure and measured pressures in the bedroom when 0.32 kg C4 is detonated 2.2 m from Lykkebo 1:25

The difference between the two curves for calculated infill pressure is due the variation of the pressures registered at the two shots (see Figure 5.3). In the calculations it is assumed that there are no plates in the windows. Nevertheless the calculated pressures are in best accordance with the measured pressures in the test with window plates. The model for leakage pressure is intended for use when the openings are as small as vents and ducts, and windows and doors withstand the blast [10]. The results show that the model does not give a good description of the pressure propagation through the window openings.

References

[1] K. B. Holm, C. Elfving, and H. Øiom, "AMRISK version 2.0 - Reference manual," FFI/Rapport 2006/01863, Forsvarets forskningsinstitutt, 2006.

[2] K. B. Holm, "Beregning av dødelighet fra luftsjokk," FFI/Rapport 2006/01896, Forsvarets forskningsinstitutt, 2007.

[3] J. A. Teland, A. van Doormaal, M. J. van der Horst, and E. Svinsås, "Single point methods for determining blast wave injury," FFI-rapport 2011/00130, Forsvarets forskningsinstitutt, 2011.

[4] J. A. Teland and J. C. A. M. van Doormal, "Blast wave injury prediction models for complex scenarios," in *Proceedings 22nd MABS - Military Aspects of Blast and Shock*, Bourges, Frankrike, 2012.

[5] J. A. Teland, "Review of blast injury prediction models," FFI-rapport 2012/00539, Forsvarets forskningsinstitutt, 2012.

[6] J. C. A. M. van Doormaal and J. A. Teland, "Overview of injury models for complex blast waves," in *Personal Armour Systems Symposium 2012*, Nürnberg, Germany.

[7] J. A. Teland and S. Skriudalen, "Analysis of the Stuhmiller blast injury model," FFI-rapport 2013/01501, Forsvarets forskningsinstitutt, 2013.

[8] K. Kaplan and P. D. Price, "Accidental explosions and effects of blast leakage into structures," Contractor Report ARLCD-CR-79009, U.S. Army Research And Development Command, Dover, New Jersey, 1979.

[9] J. R. Rempel, "Room Filling from Air Blast," in *Slanting for Combined Weapons Effects: Examples with Estimates and Air Blast Room Filling*, H. L. Murphy and J. E. Beck, Eds. Menlo Park, California: Stanford Research Institute, 1973.

[10] "Structures to resist the effects of accidental explosions," Manual UFC-3-340-02, Department of Defense, USA, 12 May 2008.

[11] D. Bogosian and S. Fu, "Infiltration of airblast into buildings through glazed openings," in *Minutes of the 31th DoD Explosives Safety Seminar*, San Antonio, Texas, 2004.

[12] "Design and analysis of hardened structures to conventional weapons effects," TM 5-855-1/AFPAM 32-1147(I)/NAVFAC P-1080/DAHSCWEMAN-97, Joint Departments of the Army, Air Force and Navy and the Defense Special Weapons Agency, Washington D.C., 1998.

[13] I. G. Bowen, E. R. Fletcher, and D. R. Richmond, "Estimate of man's tolerance to the direct effects of air blast," Technical Progress Report DASA-2113, Defense Atomic Support Agency, Department of Defense, 1968.

[14] M. M. van der Voort, K. B. Holm, P. O. Kummer, J. A. Teland, J. C. A. M. van Doormaal, and H. P. A. Dijkers, "A new standard for predicting lung injury inflicted by Friedlander blast waves," *Journal of Loss Prevention in the Process Industries,* vol. 40, pp. 396-405, 2016.

[15] H. Axelsson and J. T. Yelverton, "Chest wall velocity as a predictor of non auditory blast injury in a complex wave environment," *Journal of Trauma: Injury, infection and critical care*, vol. 40, pp. S31-S37, 1996.

[16] J. H. Stuhmiller, K. H. Ho, M. J. van der Vorst, K. T. Dodd, T. Fitzpatrick, and M. A. Mayorga, "A model of blast overpressure injury to the lung," *Journal of Biomechanics,* vol. 29, pp. 227-234, 1996.

[17] L. N. MacFadden, P. C. Chan, and K. H. Ho, "A model for predicting primary blast lung injury," *Journal of Trauma and Acute Care Surgery*, vol. 73, pp. 1121-1129, 2012.

[18] R. K. Jones, D. R. Richmond, and E. R. Fletcher, "A reappraisal of man's tolerance to indirect (tertiary) blast injury," in *Minutes of the eleventh meeting of Panel N-2 (Blast, Shock and Thermal), Subgroup N, The Technical Cooperation Programme (TTCP)*, 1969, pp. 41-56.
[19] C. S. White, "The scope of blast and shock biology and problem areas in relating physical and biological parameters," *Annals of the New York Academy of Sciences*, vol. 152, pp. 89-102, 1968.
[20] "Explosives safety risk analysis, Part II - Technical Background," AASTP-4, Edition 1, Version 4, NATO Standardization Office, 2016.
[21] M. J. Hardwick, J. Hall, J. W. Tatom, and R. G. Baker, "Approved methods and algorithms for DoD risk-based explosives siting," Technical Paper TP 14, Revision 4, Department of Defense Explosives Safety Board, Alexandria, Virginia, 21 Aug 2009.
[22] R. T. Conway, "TP 14 Algorithm Update." AASTP-4 Custodian Group Meeting: Department of Defense Explosives Safety Board, 2014.
[23] J. Yoon and R. T. Conway, "Comparison of Internal Pressure Build-Up in TP-14 with UFC and SRI Methods." AASTP-4 Custodian Group Meeting: Naval Facilities Engineering Command, Port Hueneme, California, 2013.
[24] J. Yoon and R. T. Conway, "Proposed Equation for Calculating Interior Pressure Using UFC 3-340-02 Method and Implementing into TP-14." AASTP-4 Custodian Group Meeting: Naval Facilities Engineering Command, Port Hueneme, California, 2013.
[25] J. D. Chrostowski, P. D. Wilde, and W. Gan, "Blast Damage, Serious Injury and Fatality Models for Structures and Windows," Technical Report 00-444/16.4-03, Revision 1, ACTA, 2001.
[26] "ANSYS Autodyn Users Manual," 15.0 ed. Canonsburg, Pennsylvania: ANSYS Inc., 2013.
[27] H. Øiom, H. Langberg, and G. A. Hansen, "Lykkebo - The Norwegian part in Australian 40 tonne trial," in *Minutes of the 29th DoD Explosives Safety Seminar*, New Orleans, Lousiana, 2000.
[28] G. A. Hansen, O. Krest, H. Langberg, and H. Øiom, "Test results from the Norwegian house "Lykkebo"," Norwegian Army Material Command / Ammunition Control Centre, Norwegian Defence Construction Service, 30 March 2000.
[29] G. A. Grønsten, H. Langberg, and H. Øiom, "Woomera 5-tonne trial: The Norwegian participation," in *Minutes of the 31st DoD Explosives Safety Seminar*, San Antonio, Texas, 2004.
[30] K. B. Holm, H. Øiom, G. A. Grønsten, K. O. Hauge, D. A. Hokstad, and O. M. Bismo, "Tests of blast propagation into buildings," FFI-NOTAT 18/01372, Forsvarets forskningsinstitutt (FFI), 2018.
[31] H. Øiom and G. A. Grønsten, "Norwegian participation in the 5-tonne trial in Woomera," in *Proceedings 6th Australian Explosives Ordnance Symposium (PARARI 2003)*, Canberra, Australia, 2003.
[32] G. A. Grønsten, "Blast capacity of domestic windows," FoU rapport 13/2003, Norwegian Defence Estates Agency, Oslo, 2003.
[33] S. O. Christensen, "Blast ingress through failing facades - Experiments with laminated windows," Forsvarsbygg Futura Report: 665/2014, 2014.
[34] "Glazing hazards for explosives facilities, ESTC Standard No. 5." United Kingdom: The Explosives Storage and Transport Commitee, 2002.
[35] H. Zeigler, J. A. Teland, and E. Svinsås, "Axelssons skademodell implementert som en subrutine i hydrokoden Autodyn," FFI-Rapport 2008/06128, Forsvarets forskningsinstitutt, 2008.

[36] Model of dummy compiled by Jasmina Koric (FFI) based on a model from traceparts.com, according to ISO 15536-1 [Online]. Available: https://www.traceparts.com/en/product/iso-standing-dummy-size-176-m?CatalogPath=TRACEPARTS%3ATP02003002001001&Product=10-26092008-067883

[37] W. R. Santschi, J. DuBois, and C. Omoto, "Moments of inertia and centers of gravity of the living human body," AMRL-TDR-63-36, Behavioral Sciences Laboratory, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

[38] S. Glasstone and P. J. Dolan, *The effects of nuclear weapons*, 3. ed. Washington D.C.: United States Department of Defense and Energy Research and Development Administration, 1977.

About FFI

The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's MISSION

FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's VISION

FFI turns knowledge and ideas into an efficient defence.

FFI's CHARACTERISTICS

Creative, daring, broad-minded and responsible.

Om FFI

Forsvarets forskningsinstitutt ble etablert 11. april 1946. Instituttet er organisert som et forvaltningsorgan med særskilte fullmakter underlagt Forsvarsdepartementet.

FFIs FORMÅL

Forsvarets forskningsinstitutt er Forsvarets sentrale forskningsinstitusjon og har som formål å drive forskning og utvikling for Forsvarets behov. Videre er FFI rådgiver overfor Forsvarets strategiske ledelse. Spesielt skal instituttet følge opp trekk ved vitenskapelig og militærteknisk utvikling som kan påvirke forutsetningene for sikkerhetspolitikken eller forsvarsplanleggingen.

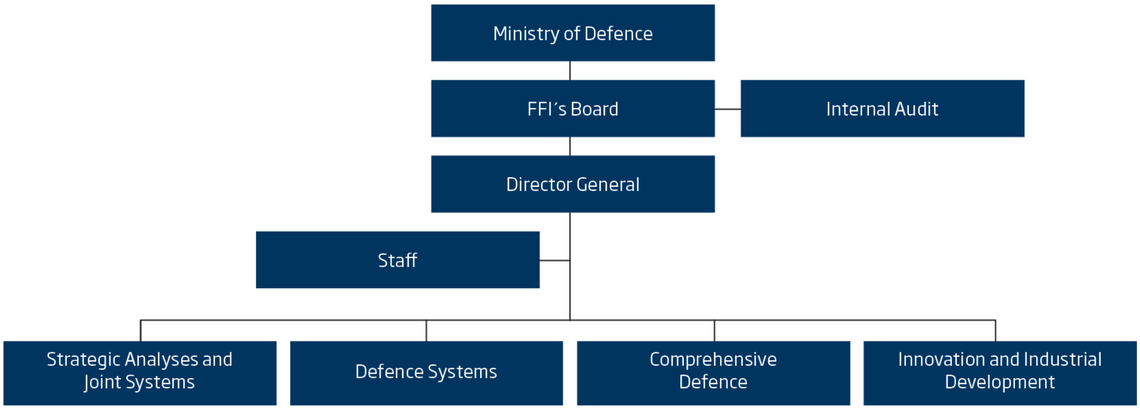
FFIs VISJON

FFI gjør kunnskap og ideer til et effektivt forsvar.

FFIs VERDIER

Skapende, drivende, vidsynt og ansvarlig.

FFI's organisation



Forsvarets forskningsinstitutt
Postboks 25
2027 Kjeller

Besøksadresse:
Instituttveien 20
2007 Kjeller

Telefon: 63 80 70 00
Telefaks: 63 80 71 15
Epost: ffi@ffi.no

Norwegian Defence Research Establishment (FFI)
P.O. Box 25
NO-2027 Kjeller

Office address:
Instituttveien 20
N-2007 Kjeller

Telephone: +47 63 80 70 00
Telefax: +47 63 80 71 15
Email: ffi@ffi.no

FFI Forsvarets forskningsinstitutt
Norwegian Defence Research Establishment