Blast Injuries to People in Buildings

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Abstract

A study has been performed to estimate primary blast injuries to humans inside buildings that are exposed to blast waves. The blast wave propagating into the building through openings can cause injuries similar to blast injuries in free-field. 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. The simulations include the building damage that creates the openings. The simulations are verified by experimental data.

From the pressure the velocity of the human chest wall and the corresponding lethality is found by methods based on the Axelsson model, which takes account of the complete time history of the pressure.

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

Introduction

When the blast wave from an explosion damages a building, people inside can get injured from impact by building parts. In addition the blast wave propagating into the building through openings can cause injuries similar to primary blast injury in free-field.

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 reflections will lead to a blast wave with a complex shape.

The injuries caused by complex blast waves can be estimated from the pressure-time history. Numerical simulations can give the pressure-time history at any position in a building. The dynamic response of the building can also be included. A series of such simulations is described in this paper. The simulation model is verified by comparing the results with experiments.

This study is a part of the development of the Norwegian-Swedish computer tool for quantitative risk analysis, AMRISK[1]. The work is made by the support of the Norwegian Defence Materiel Agency.

Blast Injury Model

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. Indirect effects are not considered here, but some results indicate that they are of less importance than the direct effects.[3]

For the estimation of direct blast effects from simple shock waves the modified Bowen's model[4, 5] is generally accepted. Inside a building the pressure wave may have a complicated shape and be without a sharp shock front, in which case this 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. The model of Axelsson and Yelverton[6], which is the most prevalent, describes the movement of the chest or the chest wall in a single degree of freedom model.

The damage indicator of the model is the calculated chest wall velocity, v_c. This is the average of the chest wall velocities calculated from pressure values registered at four positions around a Blast Test Device (BTD)[7]. When pressure registrations from a BTD are not available, values of the incident pressure wave can be used to estimate v_c. Teland et al[8] 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[9-11]. The normalised irreversible work, W, made by the pressure on the lungs, is calculated from the movement of the front and the two sides of the human chest. 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

$$z = b_0 + b_1 \ln W \qquad (1)$$

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

$$P = \frac{1}{1+e^{-z}} \qquad (2)$$

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

In [11] 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

$$v_c = 50.62 \text{ m/s} \cdot W^{0.4786} \qquad (3)$$

is in good agreement with the results. Then W can be found from v_c, and the lethality is given by equations (1) and (2). This modified version of the Axelsson's model is employed in the lethality calculations presented in this paper.

Development of the Simulation Model

The model for simulating the propagation of blast waves into buildings was developed stepwise, making it possible to evaluate different parts of the numerical calculations.

The simulations are made by ANSYS Autodyn 15.0.[12] The formation of the shock wave after detonation of an explosive charge and the subsequent propagation of the shock wave towards the house is simulated by a 1D-model. The further propagation through openings into the house is simulated in three dimensions.

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, see Figure 1. Dimensions of the house are given in the Appendix. The Lykkebo house was a test subject in three trials where charges of 40, 27 and 5 metric tons were detonated at different distances from the house.[13, 14]

Figure 1 The Lykkebo house[13]

Later a number of experiments were performed with a model of Lykkebo made of rigid plastic components in scale 1:25.[15] The tests were made both with and without plates in the window openings.

These tests were simulated accordingly using a rigid and fixed house. The window plates were modelled as rigid plates without interaction with the rest of the house. The simulations gave results in good correspondence with the experiments, especially without window plates.[3] This shows that the simulation model is able to reproduce the pressure propagation into a rigid building with openings, also when there are plates in the openings.

Next it was assumed that also real windows could be modelled as unconstrained rigid plates. Then only the mass resists the acceleration by the blast load, and the structural resistance is ignored. This approach was investigated by simulating a test where 400 kg TNT was detonated 25 m from a chamber with a window in the front wall facing the charge.[16] The 1 m x 1 m window of 6 mm annealed glass was fastened in a frame attached to the wall. 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. So also in this case the building structure could be modelled as rigid and unmoveable. Figure 2 shows a picture of the front side.

Figure 2 Test structure with chamber and concrete walls[16]

The result of the simulation was pressure values inside the building in good correspondence with test results, see Figure 3

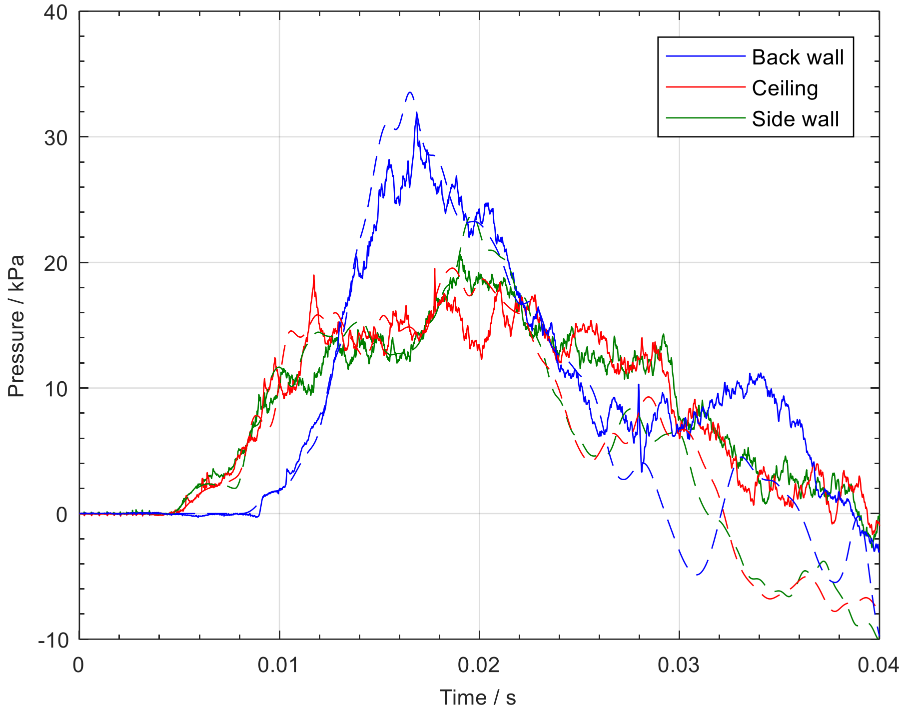

Figure 3 *Pressure values in a chamber from experiment[16] (solid lines) and simulation[3] (dashed lines) with 400 kg TNT detonated 25 m from the chamber*

The breach limits for a window of this type is estimated to 46 Pa·s for impulsive loads and 37 kPa for quasi-static loads.[17] In the test the maximum 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.

In the final development step of the simulation model damage to the building was included. The building damage is described by dividing the front wall into several, rigid and movable parts, see Figure 4. 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 of 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. The windows are still modelled as rigid bodies without any constraints.

The three rooms considered in the simulations are the bedroom, the kitchen and the living-room. The details in the rest of the house are left out of the model.

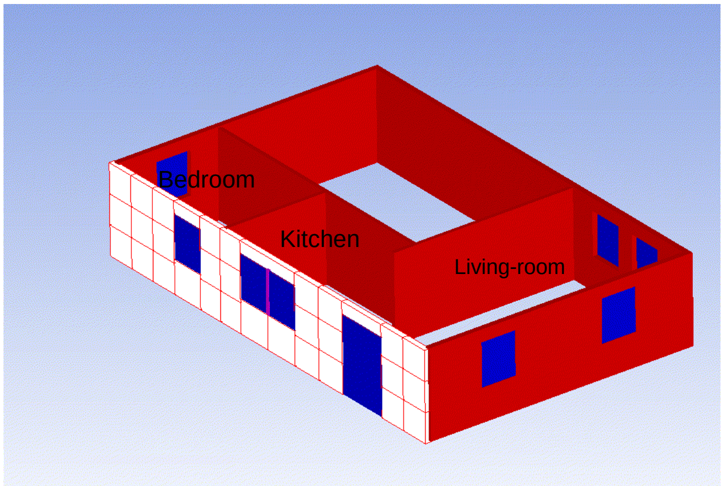

Figure 4 Drawing of ground floor of the Lykkebo model with front wall elements

A verification of the model was made by simulating a blast test against a replica of Lykkebo in scale 1:5.[15] The house was constructed similar to the full-scale house using downscaled building parts including wood elements, tiles and windows. The window panes were single and 2.15 mm thick.

In the test 350 kg of the slurry explosive Texit 40[18] vas detonated at a distance of 35 m from the house. The building damage from the blast was extensive, as shown in Figure 5 and Figure 6. 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.

Figure 5 Gable walls of Lykkebo in scale 1:5 after detonation of 350 kg Texit 40 35 m from the house[15]

Figure 6 Front wall and back wall of Lykkebo in scale 1:5 after detonation of 350 kg Texit 40 35 m from the house[15]

Because the properties of Texit 40 were unknown the simulation of the detonation was performed with 400 kg TNT. This produced free-field pressures in good agreement with test recordings[3].

Figure 7 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.

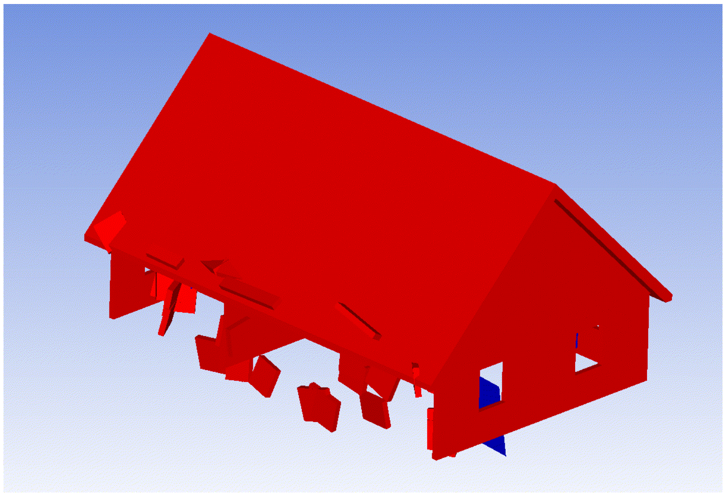

Figure 7 *Image captured from the end of the simulation with 350 kg Texit detonated 35 m from the Lykkebo house in scale 1:5*

The registered pressures in the test and the simulation are shown in Figure 8. The pressure was measured on the front wall, in the middle of the kitchen back wall and on the left side of the living-room in line with the kitchen back wall. The incident pressure was 48 kPa in the simulation, and the impulse 390 Pa·s, which corresponds to 1950 Pa·s in full scale.

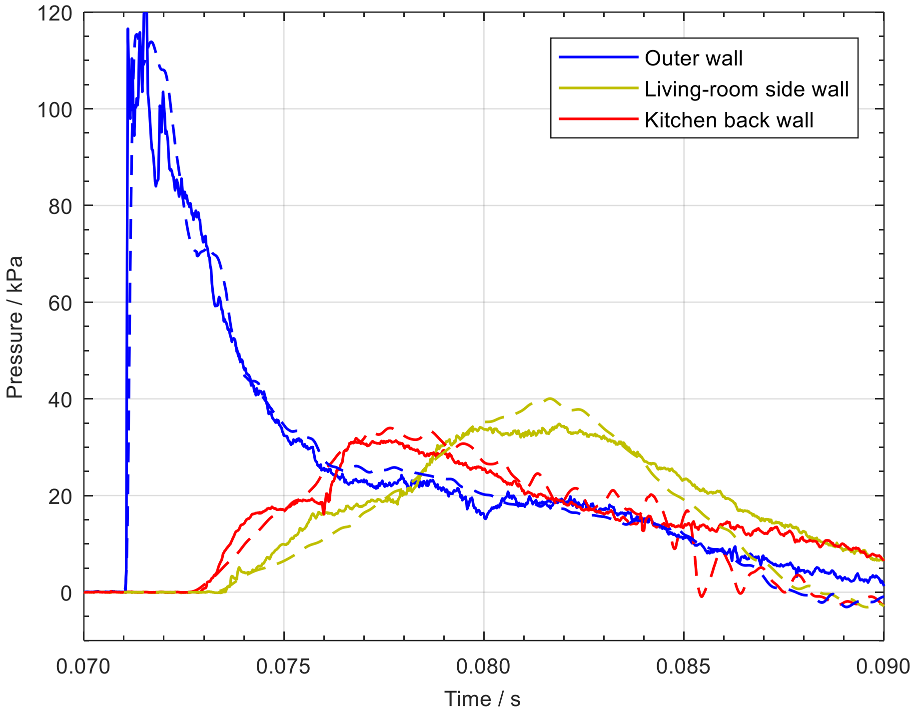

Figure 8 *Pressure values from test (solid lines) and simulation (dashed lines) with 350 kg Texit detonated 35 m from the Lykkebo house in scale 1:5*

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 very good.

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 8 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[5] 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. In the test 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.

General Calculations

The results presented above show that numerical simulations can reproduce experimental pressure values inside a building that is exposed to a blast wave.

General calculations are made with a model of the full-scale Lykkebo house. This model is an upscaled version of the model used for Lykkebo in scale 1:5 with rigid and movable front wall elements and windows. The windows of Lykkebo are double-paned 2 x 4 mm windows. In the model they consist of 8 mm single glass panes. The thickness of the walls is 16 cm, and the area density is 65 kg/m^2.[13]

During the simulations inside pressure values are collected from 316 gauge points distributed across the living-room, kitchen and bedroom, 1.2 m above the floor. The resulting lethality is calculated by the modified Axelsson's model and averaged over the room areas.

The simulation method is not verified against experiments with larger blast loads than in the Lykkebo 1:5 test. Simulations show that also then there will be small differences between the pressures with a rigid and a moveable front wall. 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.

Simulations are also made with a model of a concrete structure, which is a much stronger building type than the wooden house. 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.

The concrete model is so far not verified by experiments, but a calculation example may show that the modelling approach is reasonable. A 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.

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 injury. A simulation shows that this is the case for the concrete structure.

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. We have estimated the lethality from building damage by the *PI*-curves for different building types developed by ACTA.[19] The building type most similar to Lykkebo is the small wood structure. The considered concrete structure is the small reinforced concrete building with a wall thickness of 20 cm and about the same building area as the wood structure (230 m^2).

Results

The calculations of the average lethality are made for a series of different pressure loads. The resulting average lethality values in the wood structure exposed to different pressure loads are depicted in the *PI*-diagram in Figure 9. The figure also shows contours that are fitted to the lethality values.

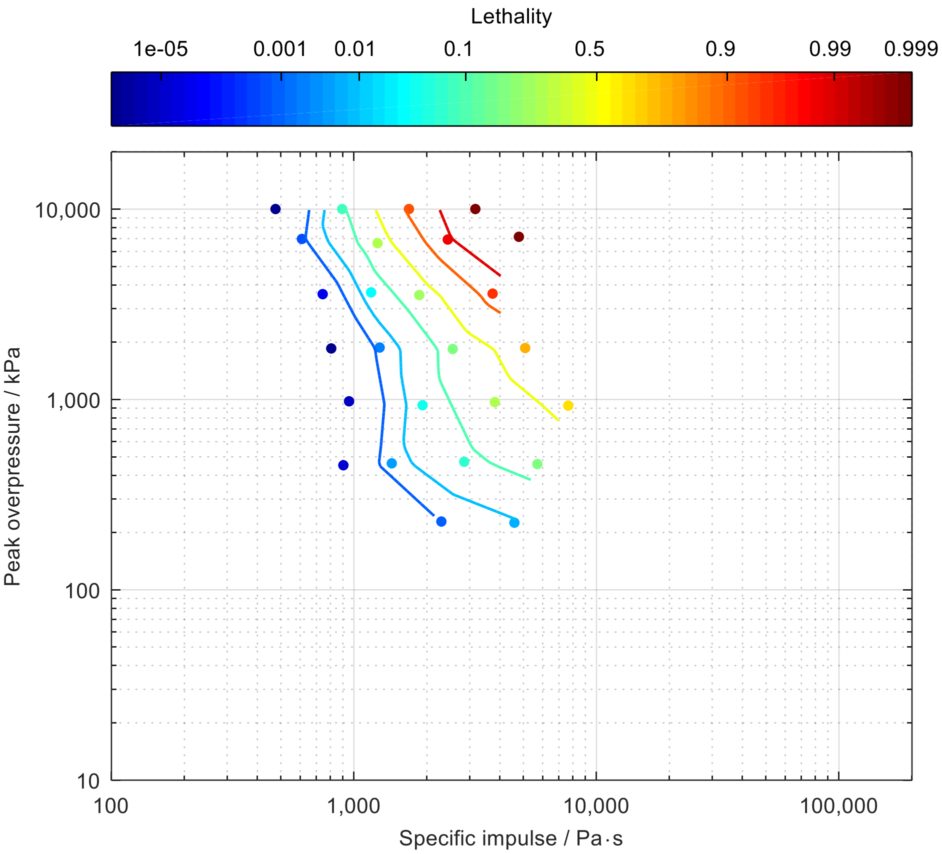

Figure 9 Lethality from blast injuries in wood structures found from simulations and fitted contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality

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 is only $8{\cdot}10^{-10}$.

The lethality from blast injuries and from building part injuries in a small wood structure can now be compared. Figure 10 shows the effect of the two injury mechanisms and the cumulative effect when the two damage mechanisms are considered independent. The curves for the total lethality are not defined outside the area containing blast injury values.

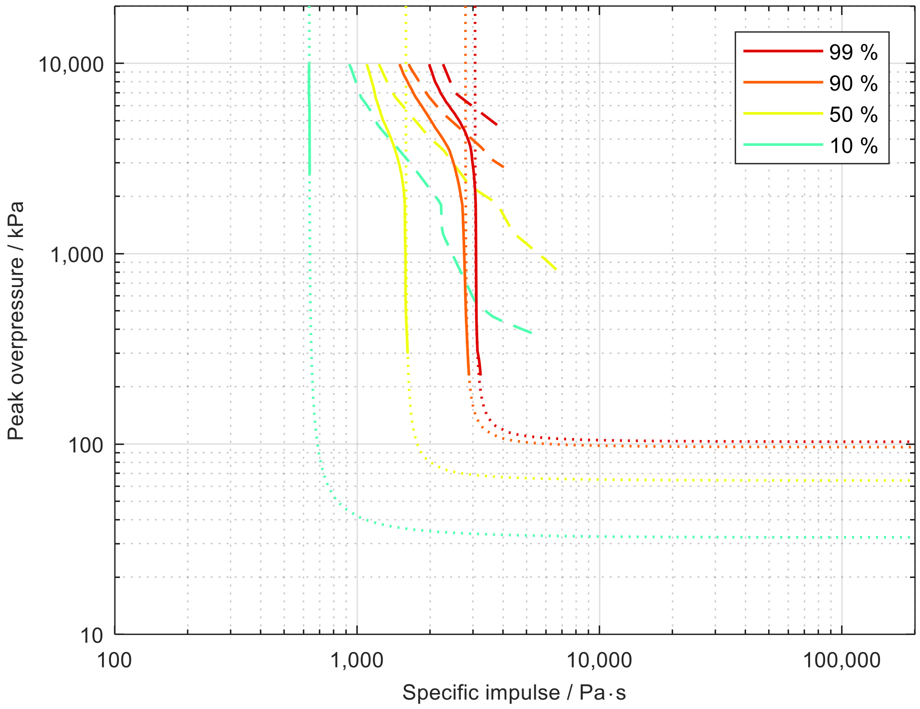

Figure 10 Contours for 10 %, 50 %, 90 % and 99 % lethality from blast injuries (dashed lines), building damage[19] *(dotted lines) and both of the injury types (solid lines) in wood structures*

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. At other values this injury mechanism can be neglected.

The extent of blast injuries inside concrete structures is not very different from wood structures, as shown by the lethality contours in Figure 11. Note that the simulations with concrete structures cover a larger range of pressure and impulse values than the simulations with wood structures.

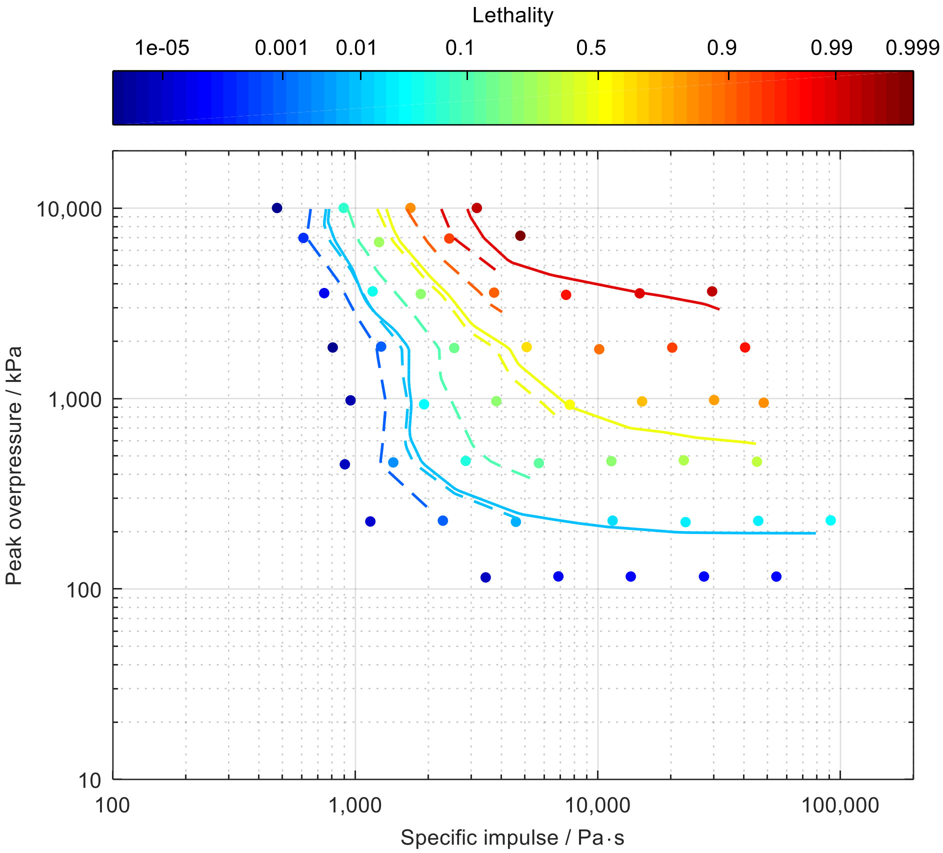

Figure 11 *Lethality from blast injuries in concrete structures found from simulations and fitted contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality (solid lines) together with contours for wood structures (dashed lines)*

In concrete structures the lethality becomes a bit smaller than in wood structures, especially at the highest impulse values. This is of course due to the difference in wall mass, which gives the concrete wall a slower acceleration.

In contrast to the small differences shown in Figure 11 there are considerable differences between constructions of wood and concrete when it comes to the lethality from moving building parts. Figure 12 shows the effect of the two injury mechanisms in concrete structures and the cumulative effect.

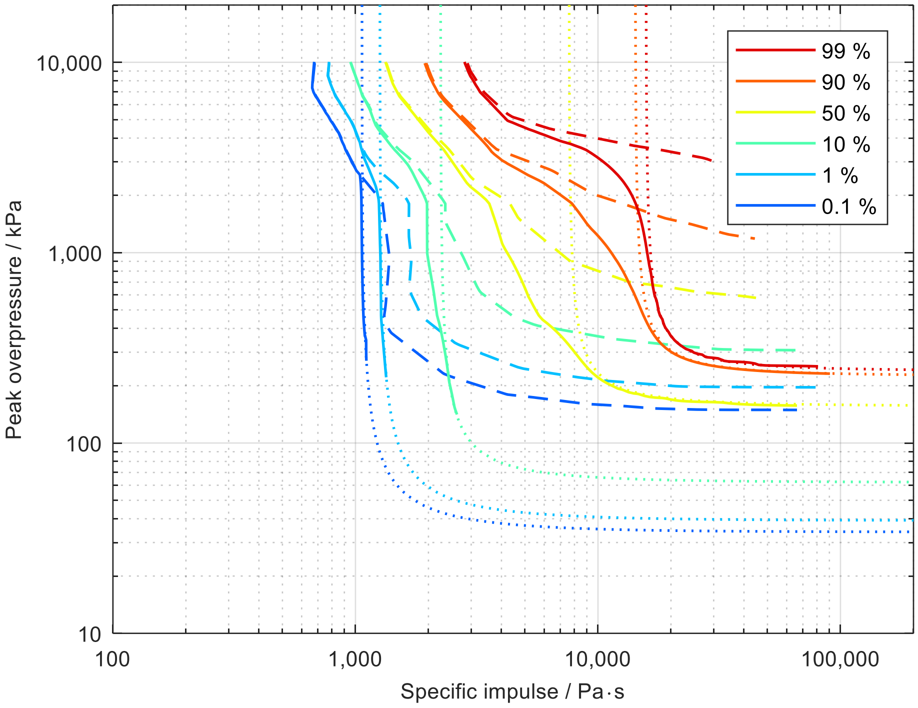

Figure 12 *Contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality from blast injuries (dashed lines), building damage*[19] *(dotted lines) and both of the injury types (solid lines) in concrete structures*

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.

The shape of the iso-contours cannot be described by simple equations, nor can the lethality as a function of pressure and impulse. However we have fitted curves defined by the equation

$$(p-A)(i-B)=C \tag{4}$$

to the lethality contours for concrete structures. The curves can at least 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 1 give the curves shown in Figure 13.

Table 1 *Parameters for PI-curves for lethality from blast injuries in concrete structures*

Lethality	*A* / kPa	*B* / Pa·s	*C* / kPa^2·s
0.1 %	143	640	180
1 %	194	750	250
10 %	300	900	600
50 %	551	1,060	2,500
90 %	1,150	1,350	4,900
99 %	2,720	1,660	8,145

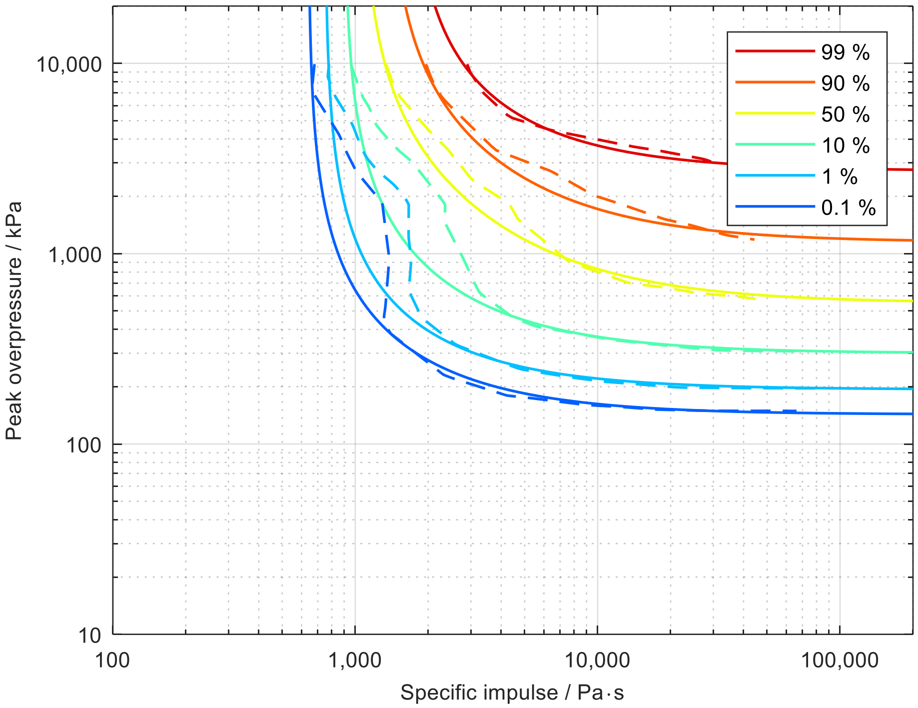

Figure 13 Contours for 0.1 %, 1 %, 10 %, 50 %, 90 % and 99 % lethality from blast injuries in concrete structures and fitted PI-curves

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 14.

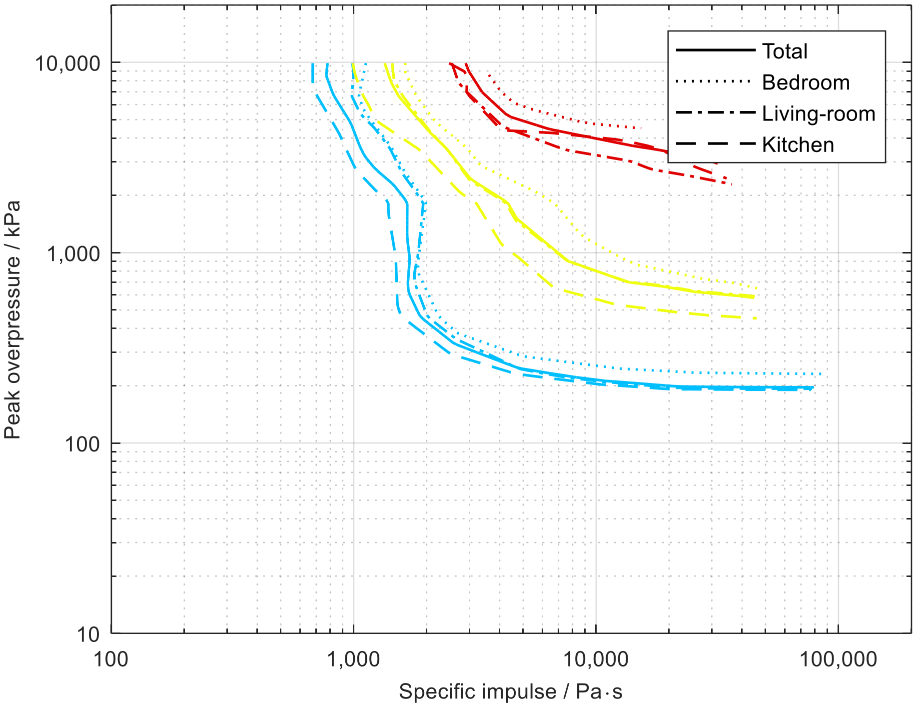

Figure 14 Contours for 1 %, 50 % and 99 % lethality from blast injuries in bedroom, living-room and kitchen and in all the three rooms of the concrete structure

There are clear, but quite small 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 %.

Conclusions

To estimate blast injuries to people in buildings the propagation of external blast waves into buildings has been calculated by numerical simulations. The probability of lethal injuries is found from the calculated internal blast by a modified version of Axelsson's model.

The simulations give pressure values in good accordance with experiments. Ignoring the strength of the walls and windows seems to be of little importance to the results.

The results show that for strong structures like reinforced concrete structures, hazards to the occupants from the pressure inside may be significant, compared to the injury from building debris, when the pressure outside the building is about 500 kPa or higher. The lethality from blast injury can be estimated by constructed iso-contours 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.

The difference between the 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 – Dimensions of the Lykkebo house

Figure 15 shows a plan view of the ground floor of Lykkebo.

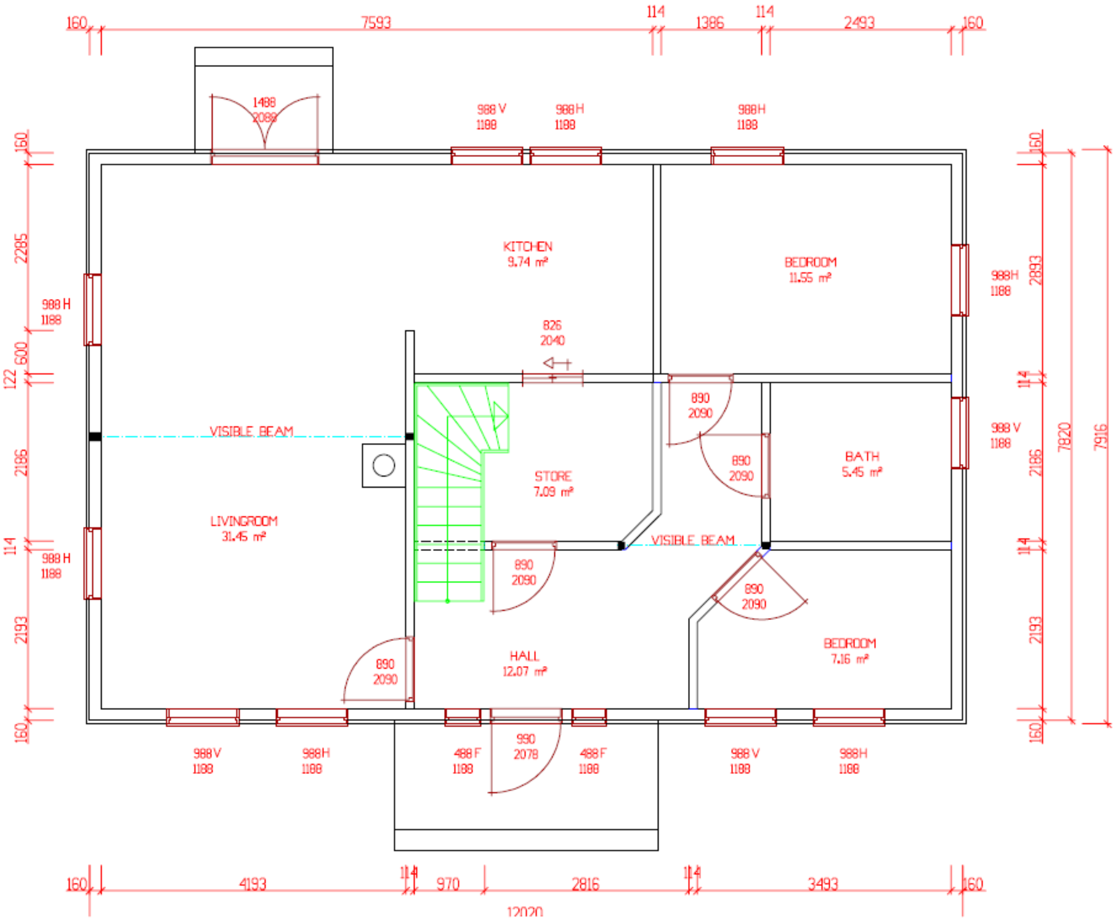

Figure 15 Ground floor plan of Lykkebo with dimensions in mm[13]

The size of the windows is 1 m x 1.2 m. The lower edge of the window openings is 0.9 m above the ground, whereas the door into the living-room is at ground level. The floor-to-ceiling height is 2.4 m.

When only the openings in the front wall are considered, the ratios of the windows areas and the room area are 0.099, 0.24 and 0.10 for the bedroom, the kitchen and the living-room, respectively. The total opening area of the windows and the external door in the three rooms is 12.5 m^2, giving a ratio of 0.237 to the floor area of 52.7 m^2.

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