An engineering model for hazard prediction of ammunition magazine doors

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Abstract

An accidental explosion in an ammunition magazine may break-up the structure and cause a significant debris hazard. Experimental and theoretical research mainly focusses on the break-up of the reinforced concrete or brick magazine walls. The behaviour of the door has usually been ignored in the derivation of Quantity Distances (QDs) and risk analysis. The study reported in this paper shows that although the door represents only one or just a few large “fragments”, the size, impact distance, and consequences of a hit, make it a relevant object to take into account.

Within the Klotz Group (KG), available experimental data on slab and door launch velocities has been collected, as well as information about the ballistic behaviour and impact distance. Data from small and full scale magazine tests, with and without earth cover, have been used to validate an engineering model for the prediction of the launch velocity, and an analytical door trajectory model. The results show that observed launch velocities can be well understood with the semi-empirical DLV equation, and observed impact distances can be reproduced with realistic assumptions about ballistic behaviour. Uncertainties remain with respect to the deformation of a door and ricochet.

For the storage of small quantities the door hazard is typically dominant compared to other explosion effects. A parametric study showed that in many cases door impact takes place outside the established Inhabited Building Distance (IBD). Whether QDs need to be adjusted to account for the door hazard depends on a number of aspects, including the size of the door and stochastic variation of the door launch direction in the horizontal plane. The results of this study stress the importance of preventing the launch of a door, such as by a door barricade.

The results of this study can be used for further development of the KG Engineering Tool (KG-ET), by implementing the presented model for the prediction of door impact. The results can also be used for risk analysis and to support possible future updates to QDs within NATO AC/326.

Keywords: accidental explosion, ammunition magazine, door, hazard, risk

1. Introduction

An accidental explosion in an ammunition magazine may break-up the structure and cause a significant debris hazard. Experimental and theoretical research focusses mainly on the break-up of the reinforced concrete or brick walls. The Klotz Group (KG) has developed the KG Engineering Tool (KG-ET) to quantify this phenomenon (Van der Voort, et al., [1], [2]).

The behaviour of the door has usually been ignored in the derivation of Quantity Distances (QDs) and risk analysis. The reason for this is that concrete debris pieces are usually far more numerous than the door which often remains a single “fragment”, or breaks up in just a few pieces. As a result, the consequences and risks are usually dominated by the debris. Nevertheless, the large size and impact distance of the door make it a relevant object to take into account.

The Klotz Group (KG) is a cooperation of 8 nations (Norway, The Netherlands, USA, UK, Singapore, Germany, Switzerland and Sweden) with the aim to improve the safety of storage and transportation of explosives. Within the KG, available experimental data on slab and door launch velocities have been collected, as well as information about the ballistic behaviour and impact distance (Van der Voort, et al., [3]). The current paper gives a summary of the results, and addresses the following research questions:

- What information on doors is available from tests?
- Is it possible to model the door launch velocity and door impact distance?
- How do door impact distances compare to established IBD?

Only from some tests quantitative information about doors is available. In other cases the door was left out of the magazine during the test, barricades caught the door, or from anecdotal evidence it is known that the door flew over the fence and could not be retrieved afterwards.

To answer the above questions we revisit slab launch tests which led to the DLV formula in Section 2. An analytical door trajectory model is presented in Section 3. The model is compared to scaled Earth Covered Magazine (ECM) trials in Section 4. A comparison with small quantities of explosives in full scale ECM tests is made in Section 5. In Section 6 we compare the model to tests with the Kasun structure (a small reinforced concrete cubicle). Section 7 deals with a comparison between QDs and door distances.

2. Slab launch velocity

In order to obtain information on the launch velocity of ammunition magazine doors, we revisit the slab launch tests (Dörr, et al. [4]) which led to the DLV formula. High explosive charges were initiated centrally in a 1 m^3 cubicle detonation chamber, and the launch velocity of a steel slab placed on top of the chamber was measured with high speed camera. The areal mass of the slab was varied between 120 and 480 kg/m^2 (15 to 60 mm thick steel) while the loading density was varied between 0.0156 and 16 kg/m^3. The results showed that the gas pressure developed in the chamber is the main reason for the slab acceleration, while the shock impulse is only of secondary importance. Analysis of the test results led to the DLV formula:

$$\mathrm{DLV} = 525 \cdot \sqrt{\frac{\gamma \cdot L_c}{m}} \qquad \text{(m/s)} \qquad (1)$$

Loading density	$\gamma = Q/V$	(kg/m^3)
Charge mass	Q	(kg)
Internal volume	V	(m^3)
Areal mass	m	(kg/m^2)
Characteristic length	$L_c = V^{1/3}$	(m)

A number of variations to the initial test set up were carried out. Changing the position of the explosive charge in the chamber only led to small either positive or negative deviations in launch velocity. This observation once more confirmed that the gas pressure is more important than the shock impulse, at least for the loading densities tested. Clamped tests were carried out with concrete slabs mounted to the detonation chamber to simulate the attachment of building walls at the connecting corners. This resulted in a significant increase in launch velocity of about 30%. It was hypothesized that this could either be caused by delayed venting (during the initial acceleration venting is prohibited by connecting walls) or a prolonged gas pressure loading phase (larger pressure built up before the slab fails). The first option was tested by performing tests with a free slab but with a frame placed around it in order to prevent direct venting. It appeared that the 30% velocity increase could be fully explained by delayed venting.

A next variation was made by testing rectangular detonation chambers instead of cubicle ones. Van Doormaal, et al. [5] performed numerical simulations that supported a correction factor to the DLV formula to make it applicable to rectangular detonation chambers:

$$DLV = 525 \cdot \sqrt{\frac{\gamma \cdot L_c}{m}} \cdot \sqrt{\frac{\Pi_{cube}}{\Pi_{rect}}} \qquad (m/s) \qquad (2)$$

Perimeter of a slab for a cubicle (reference) detonation chamber Π_{cube} (m)

Perimeter of a slab for a rectangular detonation chamber Π_{rect} (m)

The background for this correction is that the area through which detonation products vent during slab acceleration is directly related to the slab perimeter. This is illustrated in Figure 1 for a cubicle and a rectangular chamber. The smaller side of a rectangular chamber will have a relatively small perimeter compared to the sides of a cube with the same volume. As a result there will be less venting and a slab on the smaller side will reach a larger velocity than given by Eq. 1.

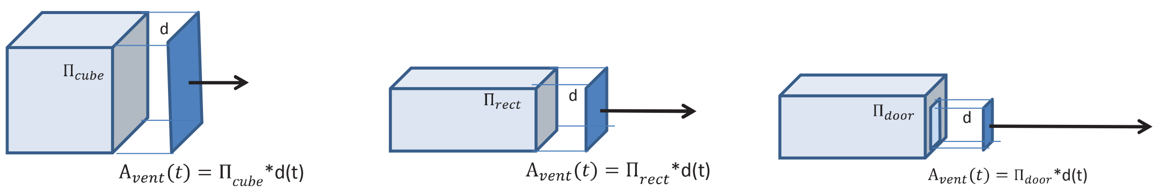

Figure 1. Illustration of the vent area for slab launch from a cubical chamber (left), rectangular chamber (middle), and the launch of a door (right). The vent area A_{vent} is equal to the slab perimeter times the displacement d(t). Note that the launched slab is shown on the side of the chamber, whereas the slab in the DLV tests was at the top.

At the bottom of Figure 1 a further generalization is shown. When the slab covers only part of a wall (e.g. a door in a wall), the DLV can be written as:

$$DLV = 525 \cdot \sqrt{\frac{\gamma \cdot L_c}{m}} \cdot \sqrt{\frac{\Pi_{cube}}{\Pi_{door}}} \qquad (m/s) \qquad (3)$$

In a next phase, five slabs (four on the sides and one on the top) were launched from a cubical arrangement, instead of just the top slab. Loading densities varied between 1 and 8 kg/m^3. These multiple slab launch tests showed that due to the increased venting the launch velocity was about 15 % lower than given by Eq.1. As part of the multiple slab launch tests, mixed mass arrangements where used. It appeared that if one of the slabs was twice lighter than the other slabs (15 versus 30 mm steel plates), this slab would obtain a launch velocity almost identical to a single slab launch, i.e. Eq. 1. The velocity of the heavier slabs was clearly smaller.

Forsén, et al. [6] performed tests with two of the aforementioned variations conducted at the same time. In this test series multiple slabs were launched not only from cubical but also from rectangular arrangements (Figure 2).

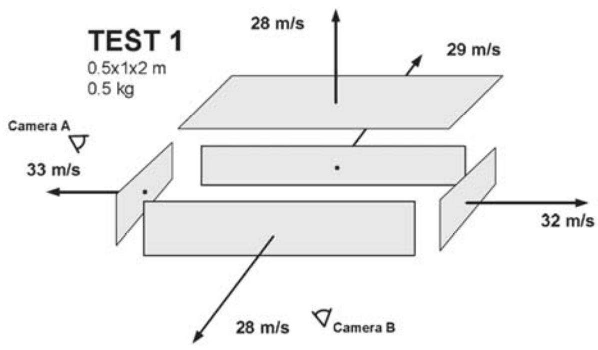

Figure 2 Multiple slab launch test with rectangular arrangement (Forsén, et al. [6])

In Figure 3 the launch velocities measured by Forsén, et al. [6] are shown together with launch velocities from a cubical arrangement by Dörr, et al. [4]. The rectangular arrangement had dimensions of 2*1*0.5 m. The launch velocities observed for the cubical arrangement (red data points) are clearly smaller than the DLV formula (Eq.1, black curve), but correspond reasonably well when the multiple slab launch correction (-15%) is applied (red curve). It should be noted that data points for the cubical arrangement from Forsén, et al. [6] are not visible because they are under the data points from Dörr, et al. [4]. For the walls of the rectangular arrangement, an additional correction was applied as given in Eq. 2. For the long walls (green curve and green data points) this means a reduction, while for the short walls (orange curve and orange data points) this means an increase. By coincidence, the increase for the short walls brings the velocity back to about the same value as given by Eq.1 (black curve).

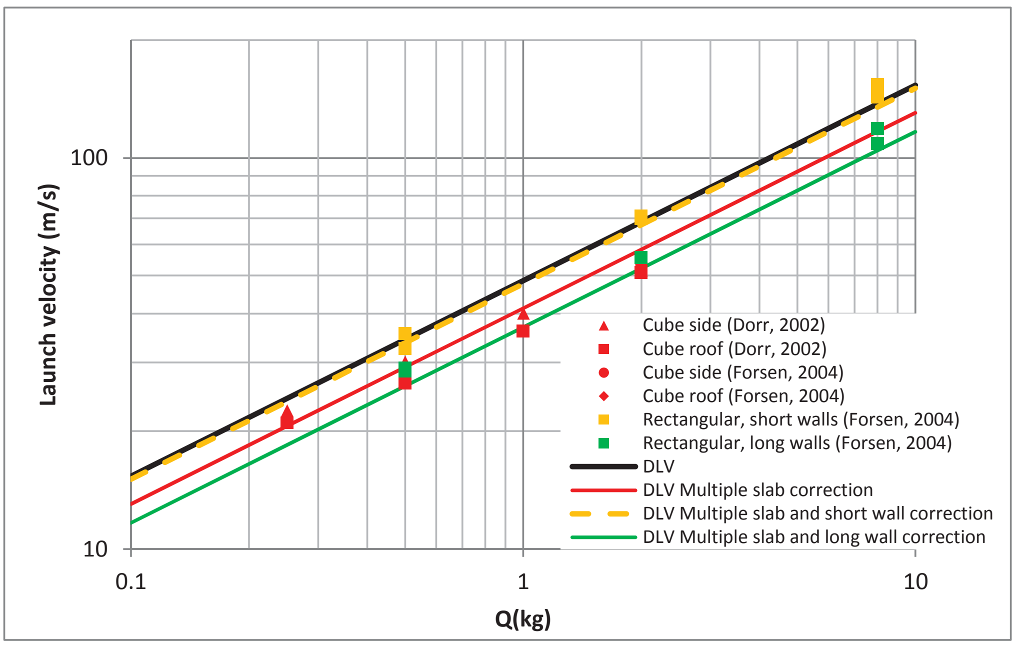

Figure 3 Slab launch velocities from multiple slab launch tests with cubical and rectangular arrangements together with model predictions and correction factors discussed in the text.

These results show that the correction factors for multiple slab launch and rectangular arrangements can reasonably well be applied simultaneously.

3. Door trajectory

The initial launch conditions of a door are formed by the launch velocity (discussed in the previous paragraph), launch angle and orientation. The orientation of the door during the launch is obviously face-on. During flight we may distinguish between three extreme cases; the door remains in its face-on orientation until impact, the door starts tumbling, or it turns to an edge-on orientation and remains in that orientation until impact. These three modes of flight are illustrated in Figure 4 which determine the ballistic behaviour of the door. Furthermore it is important to know if the door, which typically consists of one or more steel plates, will stay intact, deform or even fragment into smaller pieces. Information about these aspects may be obtained from experiments with high speed camera and pick-up data.

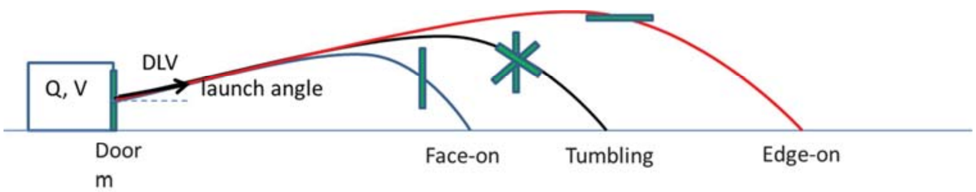

Figure 4 Three possibilities for the ballistic behavior of the door.

In all of the three cases presented above a massive object is moving through air in a relatively shallow trajectory. For this situation the horizontal drag approximation is valid, and the impact distance can be predicted with the following equation (Van der Voort, et al. [1]):

$$R = \frac{1}{\kappa} \cdot \ln\left(1 + \frac{2 \cdot \kappa \cdot U^2 \cdot \cos(\alpha) \cdot \sin(\alpha)}{g}\right) \tag{4}$$

R	impact distance	(m)
g	gravitational acceleration	(9.81 m/s^2)
α	launch angle	(°)
κ	ballistic coefficient	(1/m)
U	launch velocity	(m/s)

This equation assumes a launch from zero height, and only deals with first impact, i.e. no ricochet effects are considered. The ballistic coefficient can be formulated as:

$$\kappa = \frac{f \cdot \rho_a \cdot C_D}{2 \cdot m} \tag{5}$$

Density of air	ρ_a	1.225 kg/m^3
Drag coefficient	C_D	1 (-)
Areal mass	m	(kg/m^2)
Fraction of average presented area to the total door area		f (0-1)

More information about the drag coefficient of plate-like objects is reported by Chai, et al. [7], Chrostowski, et al. [8], and Hoerner, et al. [9], and an overview is given by van der Voort, et al. [3]. The high door launch velocities, possible deformation of the door, and complex tumbling motion, fall outside the range of performed tests. A general value of 1 for the drag coefficient was therefore employed in the current study.The factor f gives the fraction of the average presented area to the total door area. For face-on motion it is equal to 1, for tumbling motion or cases where the door deforms it will have a smaller value.

4. Comparison with small scale ECM trials

In a cooperation between Singapore and Norway two series of small scale ECM trials were conducted in 2012 (Wei, et al. [15]) and 2014 (Wei, et al. [16]). The shape of the test structure was almost cubical; in the tests at 1/5th scale the dimensions were 1 by 1 by 0.8 m, in the tests at 2/5th scale they were 2 by 2 by 1.6 m. An impression of the construction of the 1/5th scale test structure is given in Figure 5. The properties of the test structures and the test matrix are shown in Table 1 and 2.

Figure 5 Construction of the 1/5th scale test structure.

Table 1 Properties of the test structures in the 1/5th and 2/5th scaled ECM trials.

Test series	Internal dimensions				Door properties			
	Length (m)	Width (m)	Height (m)	Volume (m3)	Width (m)	Height (m)	Steel thickness (mm)	Areal mass (kg/m2)
1/5th	1	1	0.8	0.8	0.8	0.6	10	77
2/5th	2	2	1.6	6.4	1.6	1.2	20	156

Table 2 Test matrix including results from the 1/5th and 2/5th scaled ECM trials.

Test series	Test no.	Earth cover (m)	Q (kg)	γ (kg/m3)	Mode of flight	Door launch angle (°)	Door launch velocity (m/s)	Door distance (m)	Ricochet
1/5th	1	0	8	10	-	-	-	240	-
1/5th	2	0.12	8	10	-	-	-	341	-
1/5th	3	0.24	8	10	-	-	-	365	-
1/5th	4	0	16	20	-	-	-	-	-
1/5th	5	0.24	16	20	-	-	-	437	-

1/5th	6	0.12	2	2.5	-	-	-	162	-
2/5th	1	0.96	128	20	Tumbling	8	285	886	No, impact in swamp
2/5th	2	0.48	128	20	Tumbling	6	260	936-986	No, impact in swamp, 50-100 meters beyond first door

For the 1/5th scaled tests the door impact distances were registered, and a qualitative impression of the deformation of the doors is shown in Figure 6.

Figure 6 Deformation of the doors in the 1/5th scale test for test 1 (no earth cover), and test 2 and 5 (with an earth cover).

Due to the increase in interest in the behaviour of the door, high speed camera recordings of the door were made in the 2/5th scale tests (Figure 7).

Figure 7 High speed video recordings of the door launch in the 2/5th scale test.

Analysis of these recordings resulted in the launch velocity and angle. The recordings showed that the door was launched at a much higher velocity than the remaining part of the structure's front wall. Also it was observed that the door was deformed, and tumbling during its entire trajectory. In the 2/5th scale tests the doors landed in a swamp and remained about 1.5 m below ground level (Figure 8, left). This ensured that the crater and the resulting door distance was due to first impact. It is not known if and how much ricochet contributed to the door distance in the 1/5th scale tests.

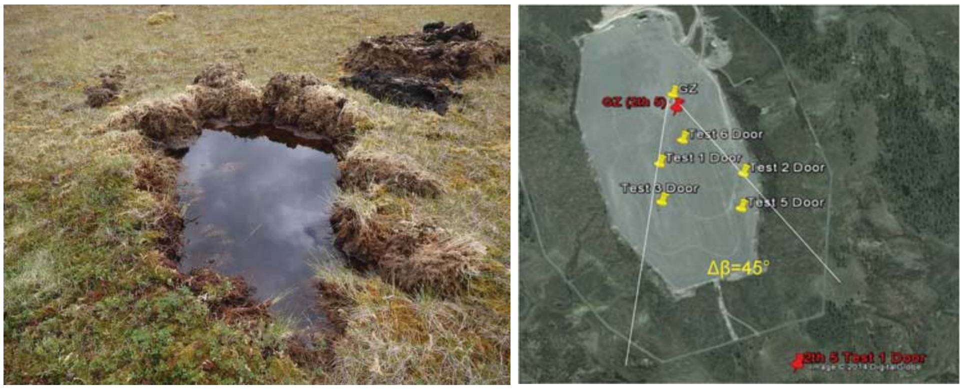

Figure 8 Impact crater in swamp in the 2/5th scale test (left). Door impact distances in 1/5th and 2/5th scaled test (right).

Figure 8 (right) gives an overview of the GPS marked impact locations in both test series. From this figure both the door distances and the azimuthal spread can be obtained. It appeared that all doors were distributed within a 45° zone. Moderate wind speeds suggest that the spread is caused mostly by stochastic variation and not by weather influences.

Figure 9 shows a comparison between the observed launch velocities in the 2/5th scale tests and the DLV formula (with and without a correction for the door perimeter). As the launch velocity of the door is much higher than that of the remaining part of the front wall, the venting will primarily take place along the door perimeter. As a result it is important to take into account the correction factor given in Eq. 3. A striking feature is that the observed velocities fall right in between the predictions with and without the correction.

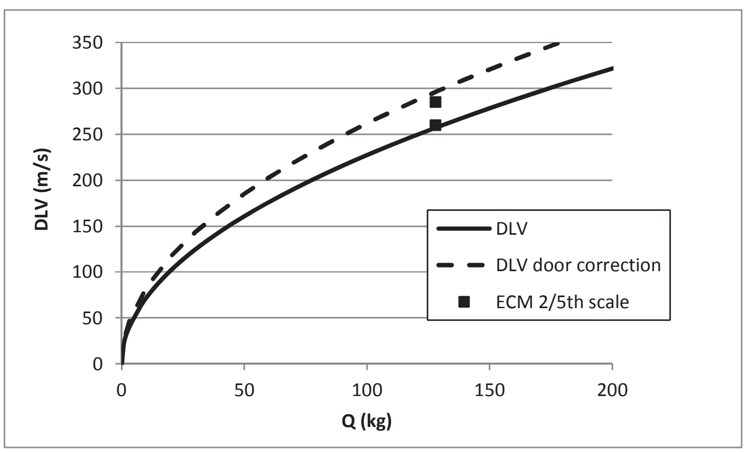

Figure 9 Door launch velocities from 2/5th scale tests together with model predictions (DLV with and without a correction for the perimeter of the door).

Taking the DLV (with door correction) as the launch velocity, the impact distance has been plotted in Figure 10. Curves are shown for face-on motion, and tumbling. The observed impact distances correspond to presented areas of f = 35 to 50% of the door area. These presented areas are realistic when compared to Figure 6 and Figure 7

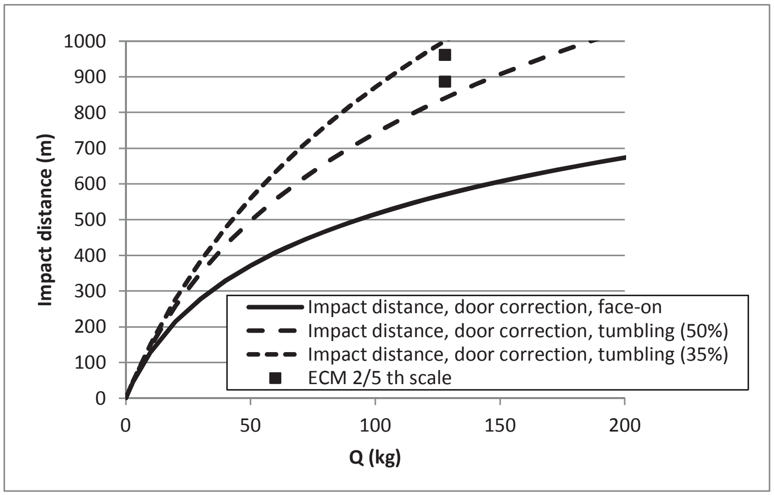

Figure 10 Door impact distance from 2/5th scale tests together with model predictions for face-on and tumbling motion (based on an average presented area of f = 35 and 50% of the door area) and launch angle of 7°.

For the 1/5th scale test, velocities were not registered and therefore only the impact distances could be compared with model prediction. The result is shown in Figure 11. As before, a correction for the door perimeter was taken into account. An average presented area between f = 60 and 80% of the door area was required to reproduce the observed distances. These are still realistic presented areas, but they are significantly larger than for the 2/5th scale test. The difference may be caused by a different break-up of the structure at the smaller scale leading to a different launch angle and/or launch velocity. Also a different deformation and ballistic behavior could be part of the explanation.

Two of the 1/5th scaled tests were done without an earth cover. The impact distance (determined for only one of these two tests) is significantly smaller compared to the tests with a cover (red data point). The reason is obviously that in the case without earth cover multiple slab launch takes place. The prediction for this case was therefore done separately with an additional multiple slab correction (red curve). The impact distance for this case could be reproduced when assuming a face-on motion.

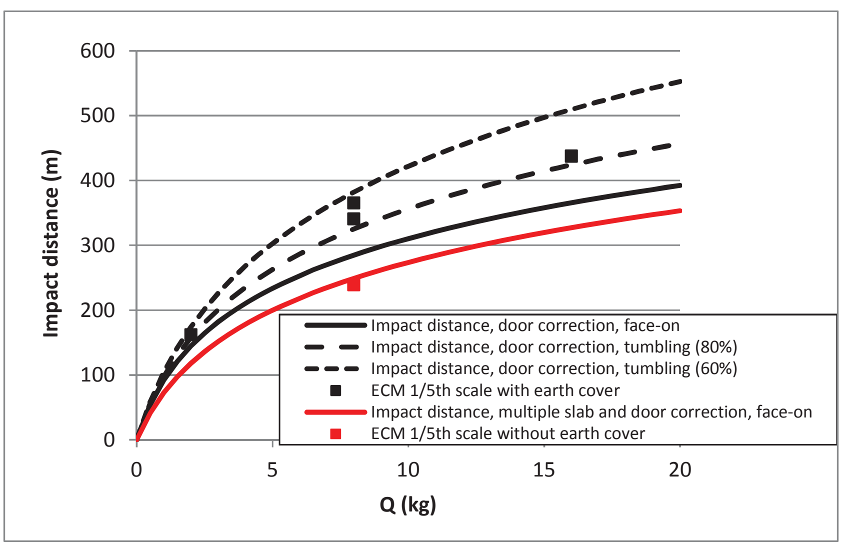

Figure 11 Door impact distance from 1/5th scale tests together with model predictions for face-on and tumbling motion (based on an average presented area of f = 60 and 80% of the door area) and launch angle of 7°.

5. Comparison with Hastings tests

Reeves, et al. [10] report on the Hastings igloo tests. Small high explosive charges where detonated in 12 excess navy 1940's concrete arch magazines with a wooden door that was covered with steel paneling (Figure 12).

Figure 12 Hastings igloos with barricade.

The internal dimensions were 24.4 m length, 8.08 m wide and 3.66 m high. Due to the arch shape the internal volume is about 80% of the volume of a rectangular box with the aforementioned dimensions. The earth cover was at least 0.6 m. The door had dimensions 1.2 m* 3 m, and an estimated areal mass of 98 kg/m2. The magazine headwalls faced an earth-backed concrete blast shield at about 4.5 m.

The test matrix is shown in Table 3. The first eight tests were conducted to investigate at which charge mass the explosion would produce limited external effects. Small charge masses ranging from 5.4 kg to 18 kg, applied at various placements inside the igloo, only resulted in the launch of the door and damage or failure to the headwall without any significant debris throw. The final four tests consisted of explosive charge masses from 27 kg to 68 kg placed in the center of the igloo, and resulted in concrete debris being projected over the barricade, which was documented in the report in terms of distribution and maximum distance out of the front of the magazine. No data were presented in the report for debris out of the sides and rear of the magazines.

Table 3 Test matrix

Test no.	Q (kg)	Charge location	Global damage description
1	18	4 m from headwall	Launch of door Damage or failure of headwall but no significant concrete debris
2	11	4 m from headwall	
3	5.4	4 m from headwall	
4	5.4	4 m from headwall	
5	5.4	4 m from headwall	
6	5.4	20.4 m from headwall (4 m from rear wall)	
7	7.3	4 m from headwall	

8	5.4	20.4 m from headwall (4 m from rear wall)	
9	45.4	Center of Igloo	Launch of door
10	68	Center of Igloo	Concrete debris projected over the barricade
11	36	Center of Igloo	
12	27	Center of Igloo	

In between the head wall and the blast shield the launch velocity of doors was determined with high speed camera. Measured velocities are shown in Table 4. Besides a dependency on the charge mass, the results also exhibit a dependency on charge placement. A charge placed near the rear wall results in a higher velocity compared to a charge placed near the headwall.

Table 4 Velocity measurements.

Test no.*	Q (kg)	γ (kg/m3)	Door launch velocity (m/s)
3, 4 or 5	5.4	0.0094	28
6 or 8	5.4	0.0094	41
7	7.3	0.0126	29
2	10.9	0.0189	50
9	45.4	0.0786	91

*in some cases the match with the exact test was not clear, but the charge mass was known.

Due to the large volume of the ECM (about 577 m^3) and the relatively small door area, the door correction factor for the DLV is large (about 2). Figure 13 shows that this correction factor is important to obtain a good match with the experimental values.

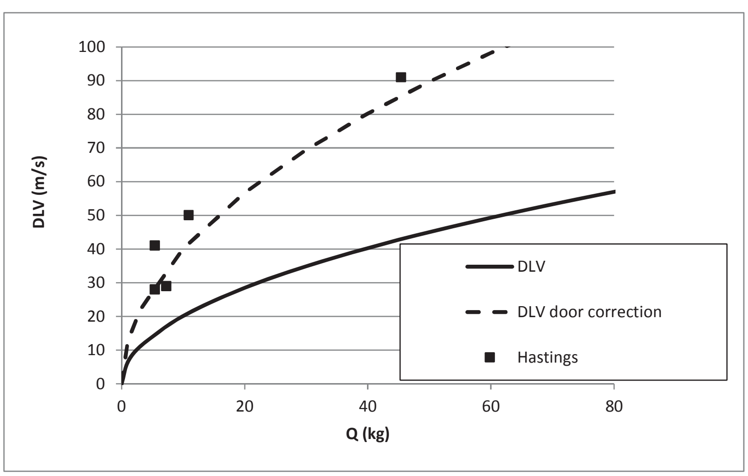

Figure 13 Door launch velocity (Reeves, 1984) together with model predictions (DLV with and without a door correction).

6. Comparison with Kasun tests

The Kasun structure is a heavily reinforced concrete cubicle structure with dimensions given in Table 5. An impression of the heavy door is given in Figure 14.

Table 5 Properties of the Kasun test structure.

Internal dimensions					Door properties			
Length (m)	Width (m)	Height (m)	Volume (m3)	Wall thickness (mm)	Width (m)	Height (m)	Door mass (kg)	Areal mass (kg/m2)
2	2	2	8	150	0.9	1.7	800	523

Figure 14 The Kasun structure with its heavy door.

Three test series were conducted by Langberg, et al. [11], Berglund, et al. [12], and Grønsten, et al. [13], with explosive charges in the Kasun structure. Only in the first series (with relatively small charge masses), both door impact distances and launch velocities were registered. The door is given as an 800 kg piece of debris in the pick-up data by Langberg, et al. [11]. In the second and third series the door landed in the woods and was not recovered.

Figure 15 and Figure 16 show the remains of the structures after detonation of 0.6, 1, 2 and 5 kg. For charge masses below 2 kg only the front of the structures breaks up and is launched. Beyond 5 kg the structure completely fails.

Figure 15 Kasun trials for 0.6 kg (left) and 1 kg (right) with closed door.

Figure 16 Kasun trials for 2 kg (left) and 5 kg (right) with closed door.

Figure 17 shows a comparison between the observed launch velocities in the Kasun tests and the DLV formula (with and without a correction for the door and multiple slab launch). The observed velocities are close to the three curves. The results for the small charge masses agree best to the DLV equation with the door correction, but without the multiple slab correction. For the 50 kg test the multiple slab correction is clearly necessary, which is in agreement with the break-up behavior described above.

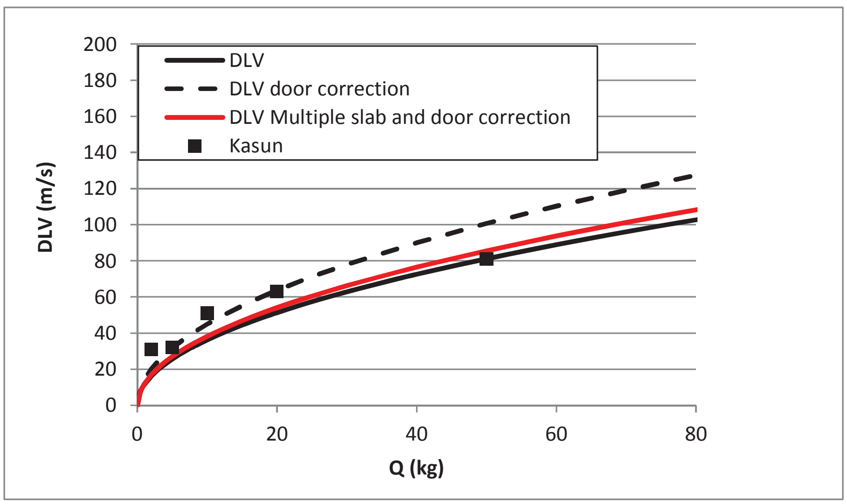

Figure 17 Door launch velocities from Kasun I tests together with model predictions (DLV with and without a correction for the perimeter of the door and multiple slab launch).

7. Comparison between QDs and door distances

Swisdak, et al. [14] developed an empirical model for the debris IBD for above ground reinforced concrete and brick structures (Figure 18). This model is based on the pick-up of debris pieces and does not take the door into account). The debris IBD is defined as the distance where the hazardous debris density (number of debris per m^2) drops below 1 per 56 m^2. A hazardous debris piece has an energy larger than 79J. The above suggests that at the IBD the probability of a serious injury or lethality is in the order of 1%, because 0.56 m^2 is about the area of an average person. The maximum curve is given by the following equation:

$$IBD = 64.995 + 7.249 \cdot \ln(NEQ) + 6.693 \cdot \left[\ln(NEQ)\right]^2 \quad (6)$$

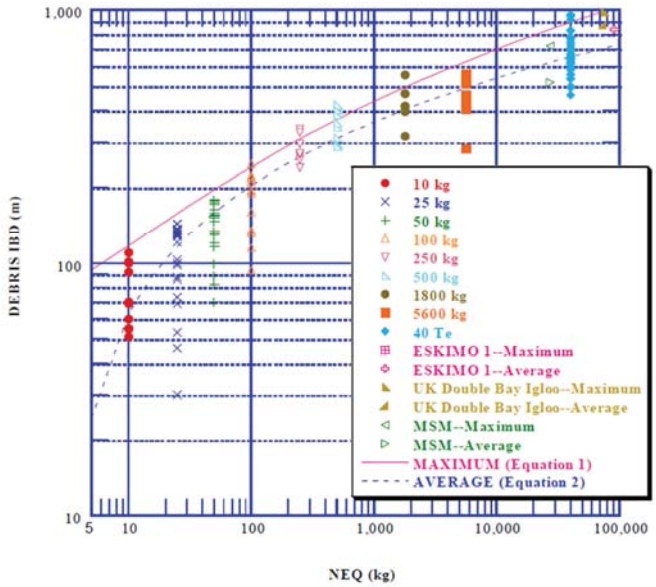

Figure 18 Empirical model for debris IBD for aboveground reinforced concrete and brick structures (Swisdak, et al. [14]).

Figure 19 compares Swisdak's model (maximum curve) with door distances predicted with the presented model for magazines of two internal volumes (10 and 50 m^3), and three door areal masses (100, 300 and 500 kg/m^3). The DLV without corrections was used as initial velocity.

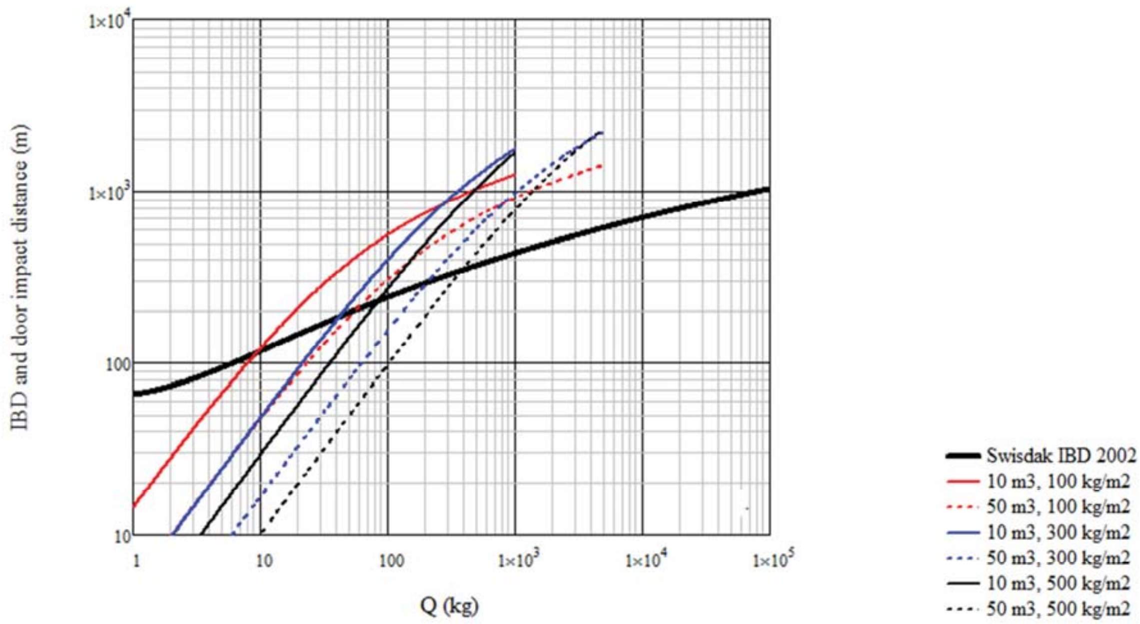

Figure 19 Comparison of IBD for above ground magazines given by Swisdak, et al. [14] and predicted door impact distances for various internal volumes and door areal mass. The loading density varies between 0.01 kg/m^3 and 100 kg/m^3 for each curve, and the assumed project area was 50% of the door area.

This parameter study shows that in many cases door impact takes place outside the established IBD. In a particular test or accident this means that a high lethality exists in regions outside IBD. However, when we repeat the “experiment” multiple times, the launch direction in the horizontal plane will differ due to stochastic variation. Whether QDs need to be adjusted to account for the door hazard depends on the hit probability, which is determined by the size of the door and the stochastic variation of the door launch direction.

8. Conclusions

In the current study available experimental data on slab and door launch velocities has been collected, as well as information about the ballistic behaviour and impact distance. Data from small and full scale magazine tests, with and without earth cover, have been used to validate an engineering model for the prediction of the launch velocity, and an analytical door trajectory model. The results show that observed launch velocities can be well understood with the semi-empirical DLV equation, and observed impact distances can be reproduced with realistic assumptions about ballistic behaviour. Uncertainties remain with respect to the deformation of a door, and the importance of ricochet.

For the storage of small quantities the door hazard is typically dominant compared to other explosion effects. A parametric study showed that in many cases door impact takes place outside the established Inhabited Building Distance (IBD). These door fragments have large consequences at impact and require special consideration. Whether QDs need to be adjusted to account for the door hazard depends on a number of aspects, including the size of the door and stochastic variation of the door launch direction in the horizontal plane. The results of this study stress the importance of preventing the launch of a door, such as by a door barricade.

The results of this study can be used for further development of the KG-ET, by implementing the presented model for the prediction of door impact. The results can also be used for risk analysis and to support possible future updates to QDs within NATO AC/326. A relevant question is what influence the door hazard has on risk measures such as the individual and collective risk.

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