The Klotz Group Contribution to Explosives Safety

Jaap Weerheijm; TNO Defence, Safety & Security; The Netherlands

Robert Conway; NAVFAC EXWC; USA

Abstract

The Klotz Group (KG) is an international group of experts on explosives safety that collaborate based on two objectives: (i) to improve the knowledge base of explosion effects associated with the storage, processing and transport of ammunition and explosives, and (ii) to develop engineering data bases to quantify the explosion effects that enable consequence and safety assessments, and also risk analyses.

The KG meets twice a year to identify and prioritize knowledge gaps and develop a road map to bridge the gaps using KG funds, and leveraging each member country's related national research programs. The KG has been active for more than 30 years and at present its membership includes explosives safety experts from eight countries: Germany, Norway, the Netherlands, Singapore, Sweden, Switzerland, the United Kingdom, and the United States. The KG contribution to munition safety changed over the years starting mainly from large and small scale experiments dedicated to underground ammunition storage to nowadays a balanced approach of testing, engineering tools and advanced computational analyses to quantify hazards from primary and secondary debris, as well as airblast.

This paper presents a description of the KG aims and strategy, highlights of the KG contribution to explosives safety over the years and its current endeavors.

Keywords: accidental explosion, ammunition safety, external safety, international collaboration, experimental data, computational tools and guidelines.

Introduction

The Klotz Group (KG) has a long history and the establishment of its current form came about quite gradually. Its origin goes back to 1966. A group of explosives safety personnel discussed the potential solutions to reduce the blast effect caused by accidental explosions in underground ammunition magazines. It was proposed to use a large closing device, a massive block (in German: Klotz) creating a gigantic blast valve. Theoretical and experimental efforts were followed by a successful "full scale" proof test in 1973. The four participants, Norway, Sweden, Switzerland and West-Germany, decided to continue the fruitful cooperation within the field of explosives safety. In November 1975 the Klotz Club was born. The terms of reference were clearly defined stating the importance of data and knowledge exchange to achieve "a better utilization of resources". Three areas of mutual interest were identified:

- Explosives Quantity Distance data and prescriptions as applied to manufacture and storage of ammunition;
- Structural response to both internal and external explosions
- Risk Analyses

It is interesting to note, that the original motivation still applies for the Klotz Group today. Over the years, the number of participating countries increased, and the focus shifted from underground to above ground magazines. But as of 2018 the key drivers for the international cooperation are still: (i) better utilization of national research resources, (ii) data exchange, (iii) understanding the explosion phenomena, (iv) quantify the explosion effects and (v) enable Risk Analysis. Because the effort of the group has always been on technical topics, political issues could be avoided. Knowledge and data were provided to the NATO panels dealing with guidelines and regulations, thus any discussion of what is an acceptable level of risk or consequence are not a part of discussions within the Klotz Group.

The Klotz Club changed its name to the Klotz Group in 1998. Today, the Klotz Group consists of the member nations Germany, Norway, the Netherlands, Singapore, Sweden, Switzerland, the United Kingdom, and the United States.

In the next two sections the current strategy of the Klotz Group and a historical overview of the main trends in the KG-research program are given. Next some highlights are presented illustrating the developments and contributions of the KG to the explosive safety community. The paper is concluded with a sketch of the aims and planned efforts for the near future.

KG Strategy 2018

In the most recent Terms of Reference (ToR) the aim of the KG is formulated as: *"to improve the knowledge and modeling of explosive effects, and to understand the consequences of such effects, in order to reduce risks associated with the storage, processing, and transport of ammunition and explosives for the military and the civilian community".*

To achieve this objective, experts from the member nations meet twice a year to define and update the KG research program and discuss the progress. They have considerable expertise in examining results of accidental explosions, experimental data, and analyses to upgrade the general knowledge of explosion effects and consequences. This internationally clustered knowledge is used to enable risk assessments of potential accidental explosions associated in particular with the storage of ammunition.

To structure the meetings and the KG research program the following tasks were defined:

- *Share information from accidents, tests, and studies to upgrade the general knowledge of explosion effects, and to understand the requirements of consequence modeling, in order to improve explosives safety;*
- *<u>Discuss, plan, and execute projects of common explosives safety interest</u>*
- *Study methods to improve safety and to enhance knowledge about the probabilities of accidents during the storage of ammunition*
- *<u>Develop tools</u> to aid in explosives risk analyses by improving the accuracy and reliability of hazard effects predictions*

- *Identify gaps in the knowledge of explosion effects, associated consequences, and application of explosives safety*
- *Serve as an international platform to coordinate national R&D programs within areas of common interest and to provide national and international organizations with information necessary for regulations*

Besides the common interest, the important mechanism to achieve the objectives is the KG research program which is funded by a yearly contribution of all member countries. In the task list given above, some task phrases are underlined which provide the main input for the KG research program. The projects in the program are the missing links between the national research programs and/or can act as a catalyzer for national research.

Initially the projects were mainly experimental (e.g., the debris launch velocity (DLV) tests), but over the years, projects were defined to study mechanisms (e.g., break up and modelling of reinforced concrete (RC) magazines) and to develop tools in which the common and shared knowledge of the group is integrated and can be maintained. The resulting tool of these extensive efforts is the KG-Engineering Tool.

These developments over the years are presented and illustrated in the next sections.

Historical Overview of KG Research

The initial work focused on definition (1966 – 1971) and then development and testing (1971 – 1975) of the Klotz design. After the Klotz design was in production, the Klotz Club was officially established. The scope of the group enlarged afterwards, but the primary focus was still on safety of underground ammunition storage. In 1985 it was agreed on to have a Klotz Club test facility in Älvdalen, Sweden. In 1986 a joint test was performed to investigate debris throw, airblast and ground shock from explosions in underground ammunition storage. It was followed in 1987 with a 2nd test at the Klotz Club facility in Älvdalen. In the following year, the scope of the effort was expanded to shallow underground storage conditions, an explosives storage facility somewhat between the definitions of underground storage and earth covered magazines, and a test was performed at NAWC China Lake, USA.

In their annual meeting in 1988, where the results of the tests and future plans were discussed, it was also decided not to establish a formal relationship with NATO/AC 258, the ammunition safety group. The rationale for this was to remove the potential for any political aspects of the work and remain independent, such as definition of an acceptable hazard or risk, and so that the focus could remain on technical discussions. As the work continued over the years, knowledge and data was gathered and evaluated. In the first decade of the Klotz Club Era, there was a strong focus on experiments and gaining reliable data. In 1989, the group expended some effort on hydrocode calculations, which was the first time the group itself pursued high fidelity, physics based modeling. Having all this new experimental and analytical data, in 1990 the group advanced the technical discussion on appropriate safety distances and pursued the development of a personal computer (PC) software program to quantify these distances for underground storage. In the years after, the prediction program remained on the Klotz Club agenda, as well as advancing the underlying methods and algorithms used to quantify the blast and debris effects, taking the charge and storage geometry conditions into account. Blast propagation within the tunnel systems was also agenda focus area of the group, and in 1991 they participated in the Camp Stanley Test in the USA by providing additional instrumentation.

During the 1990's the underground ammunition storage remained the primary focus of the group. The possibilities of using advanced computational fluid dynamics (CFD) simulations to predict the blast phenomena in tunnel systems were explored. These CFD simulations and other work resulted in new large scale tests being programmed in cooperation with Singapore to study the possibilities of water-mitigation to mitigate explosion effects in underground storage tunnel systems. Besides the primary focus area of underground storage, the safety issues related to above ground magazines were also addressed. The break-up and debris throw from reinforced concrete (RC) magazines became important issues, and were entered into the Klotz Club research program. The possibilities of using the DISPRE2 code for prediction purposes were evaluated and further developments were sponsored by the Klotz Club. DISPRE2 was originally developed by Southwest Research Institute (SwRI) under funding from the U S Department of Energy and the Department of Defense Explosives Safety Board around 1990. It addresses the failure and debris/slab launching due to internal explosion in above ground magazines and hardened aircraft shelters storing up to 5000 kg of TNT equivalent explosives material. The maximum loading density was limited to 1 kg/m^3, which was deemed too restrictive for the storage quantities and configurations that the group was investigating. Parallel to investigating the feasibility of using the DISPRE2 code, an extensive experimental program was started to gather data on the debris launch velocity for larger loading densities (up to 15 kg/m^3). The Debris Launch Velocity (DLV) program was born and resulted in the widely used empirical DLV formula. This program and resulting product is discussed in more detailing in the corresponding section on the KG highlights.

In 1998 the functioning and the research of the Klotz Club was revisited. It was decided to focus more on "transferable output" – engineering tools based on physics principles. It was also agreed that besides gaining and sharing thorough knowledge on explosion effects, the group should also focus on methods to "bundle", share, and transfer that knowledge. Furthermore, the activities of the group should be complementary and supportive to the NATO/AC 258 ammunition safety group. Additionally, the structure and organization of the group and the meetings were modified. The name was changed to Klotz Group (KG), and a permanent KG Chairman (Norway) was appointed as the official point of contact (POC) for matters involving the KG. In order to properly structure the work, which included setting both short and long term goals, it was decided to formally establish a KG research program and focus the meetings on the technical progress. The position of KG Technical Chairman was established (Netherlands). Finally, a KG liaison for the relevant NATO panels was appointed who was tasked to report the KG activities to NATO and NATO activities to the KG.

This organization and operational format is still successfully functioning today. Since 2000 the main focus of the KG has been on above ground magazines. Initially all attention was on RC magazines, the break-up process and the debris throw. To bundle the gathered data and share the knowledge it was decided to develop the KG-Engineering Tool (KG-ET) to predict the debris hazard to give input for risk analyses and quantifying safety distances. The KG-ET is discussed in more detail in the highlight section. Since the late 1990's field storage of ammunition and the related risks became paramount because of the increased number of international out of area missions. Therefore, after the KG-ET for RC magazines was sufficiently mature, it was decided to develop methodologies to be implemented into the KG-ET for other ammunition storage structure types. The first structure model to be developed after the RC model was the debris formation from ISO-container magazines. Data from US-trials were combined with KG-tests and a KG-ET version for ISO containers was developed.

Currently, the KG-research program still concentrates on the development of the KG-ET but for a variety of ammunition magazine structure types. Besides the RC and the ISO-container magazines, the open stack and the earth covered magazine are on the research agenda. Challenging tasks associated with developing advanced prediction models for debris generation are addressed by combining dedicated experiments, engineering studies, and advanced computational analysis to develop and validate the engineering models for the KG-ET. This valuable tool is intended to provide important input to the community involved in ammunition safety and risk analyses.

Highlights – Klotz Club and Klotz Group research

Development Klotz closure valve 1970 [1]:

As mentioned in the introduction, the Klotz Club (KC) started when a group of young Norwegian and Swiss engineers in 1966 discussed the possibilities to reduce the blast effects caused by accidental explosions in underground ammunition magazines. It was proposed to use a device acting as a gigantic blast valve in order to enclose the blast effect inside the magazine. Theoretical and experimental studies were carried out in Switzerland and Norway between 1967 and 1970

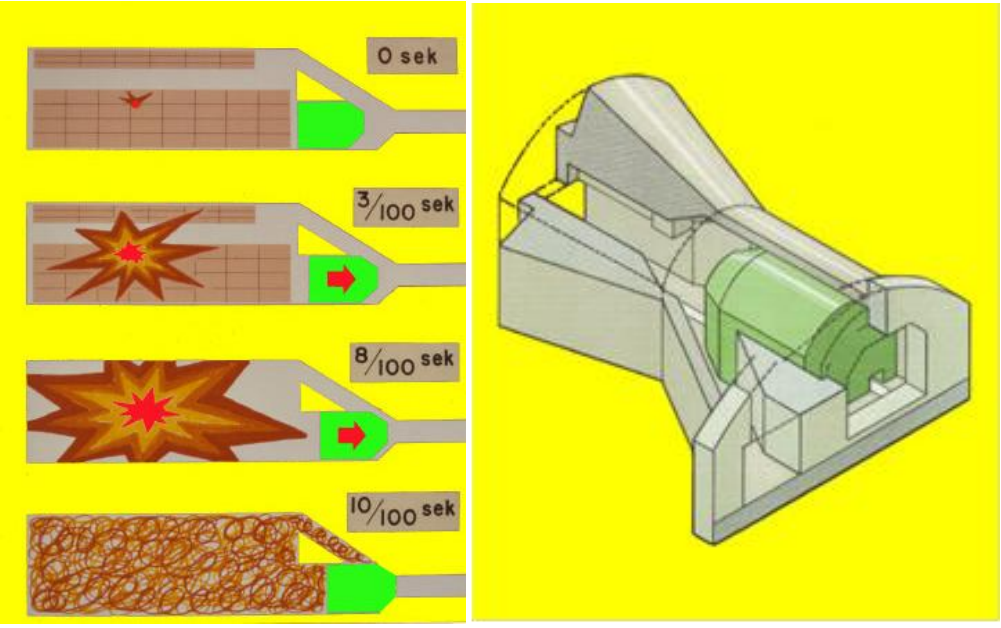


Figure 1. The main working principle of the Klotz (left) and the "Swiss" Klotz - The safety device for underground ammunition storages (right).

In May 1971, a fast acting, heavy closing device – the Klotz – was presented at an international conference in Germany. This Klotz consisted of a heavily reinforced concrete block weighing approximately 250 tonnes. In March 1972, Sweden, Norway, Germany and Switzerland decided to carry out a full scale proof test with the Klotz. This test was successfully performed in Älvdalen, Sweden, on 23 May 1973.

Figure 1 shows the main working principles of the Klotz and illustrates the Klotz placed inside an underground ammunition storage facility.

Water mitigation

Experiments had shown that explosion effects can be mitigated by water when placed close to the detonating explosives. The topic came on the KG agenda in 1993. From previous, relatively small scale experiments and only with bare charges, it was found that both maximum pressure and impulse density were reduced, as well as the fragment velocity of objects close to the charges. Interesting results, but not tested at large scale and real ammunition. Therefore, it was decided to verify the usefulness of water as a mitigation agent in ammunition magazines. In September 1996 an experiment was made with financing from the Klotz-Club and Singapore, who was not a member nation at that time. The amount of explosives and water were 1000 kg and 2000 kg, respectively. The explosive charge consisted of 180 152mm artillery shells and was detonated in the KC-tunnel in Älvdalen. The experiment was a repetition of a test previously conducted in 1989, which was originally done without water, such that the existing empirical data could be used as a baseline to assess the efficacy of water mitigation.

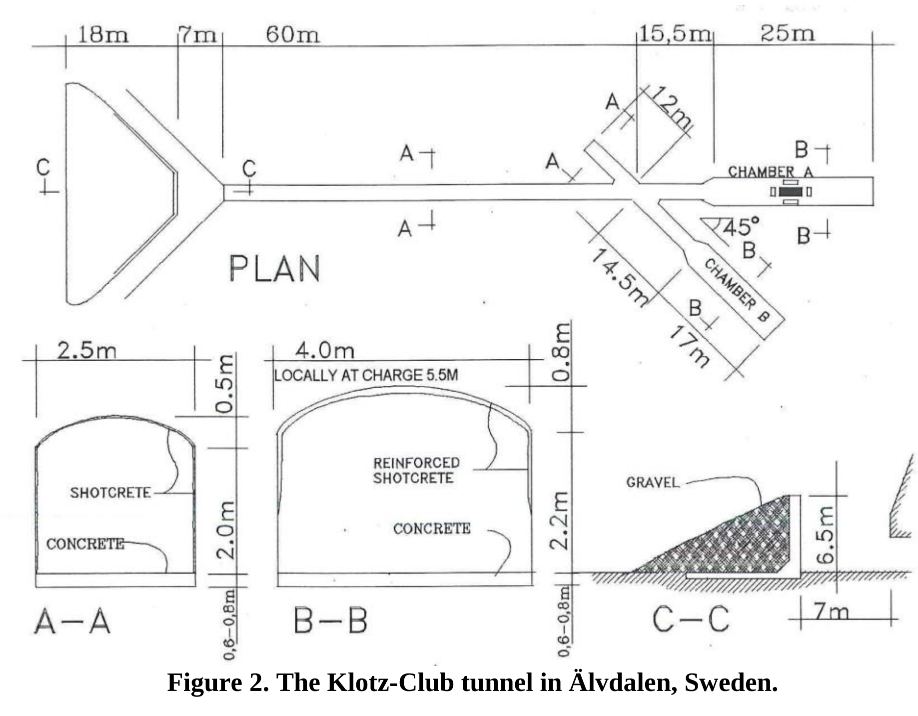


Figure 2. The Klotz-Club tunnel in Älvdalen, Sweden.

The KC-tunnel was built in 1986 and has a length of about 100 m and a cross section of about 6.3 m^2. The layout is given in Figure 2. The donor charge of 180 shells was placed on wooden pallets in the middle of chamber A. The shells were all individually primed and initiated simultaneously. Along all four sides of the charge, water filled plastic barrels were placed, as shown in Figure 3. Pressure recordings inside (3 locations) and outside the tunnel (17 locations) were made according to the lay out of the previous test in 1989. Also ground shock was measured and the steel fragments from the shells were collected along the tunnel axis. A frame with area of 1 m^2 was placed on the floor every 5 meters along the tunnel axis and all fragments inside the frame were collected and weighted.

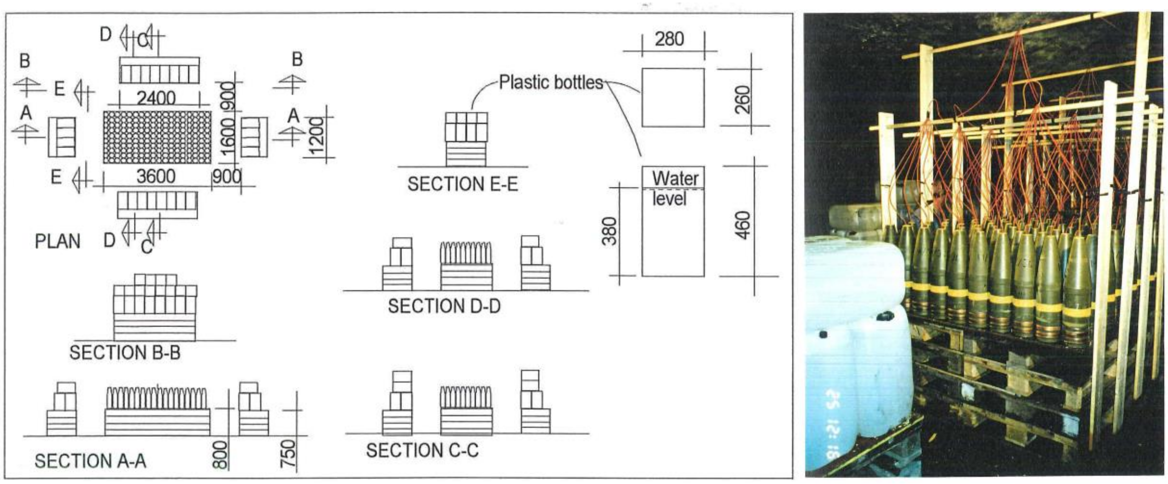


Figure 3. Layout of charge surrounded by water.

The tests results showed a reduction in pressure and impulse but not the reduction level as expected based on the small scale experiments with bare charges. Details on the data collection is given in [2] as well as the possible causes for the limited water mitigation effect in the tests. It was decided to study the mechanisms in more detail, also using advanced CFD analyses. Despite the disappointing results, the possible use of water to increase explosives safety was not entirely aborted. The KC, and especially Singapore, studied the subject in detail for a better understanding of how to best utilize the water to mitigate the explosives output. This resulted in new large scale tests in the KC-tunnel with 10 ton bare and cased charges, with and without the presence of water mitigation. These tests were funded by Singapore and performed in 2000 and 2001.

Development of Debris Launch Velocity (DLV) formula:

In order to determine debris throw distances from explosions within a structure, one of the main parameters is the debris launch velocity. In the 1990's it was decided to start a test program to investigate this parameter in more detail. The tests were planned by the Klotz Group and the Ernst Mach Institute (EMI) and carried out at test sites of the Bundeswehr in Germany. The following parameters have been studied:

- charge mass / loading density
- slab mass / mass per unit area (thickness of plate)
- slab material / steel plates and concrete plates
- structure size / length of the plate
- clamping conditions of concrete plates
- asymmetry in charge position and structure geometry
- vented / closed situations

Figure 4 and Figure 5 show various test set-ups illustrating the scope of the DLV- test campaigns.

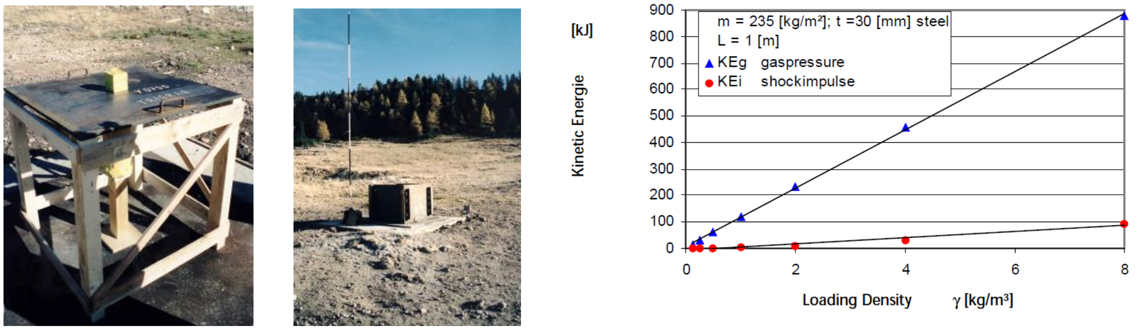


Figure 4. DLV set-up. Fully vented (left), closed test arrangement (middle) and energy contribution to DLV (right)

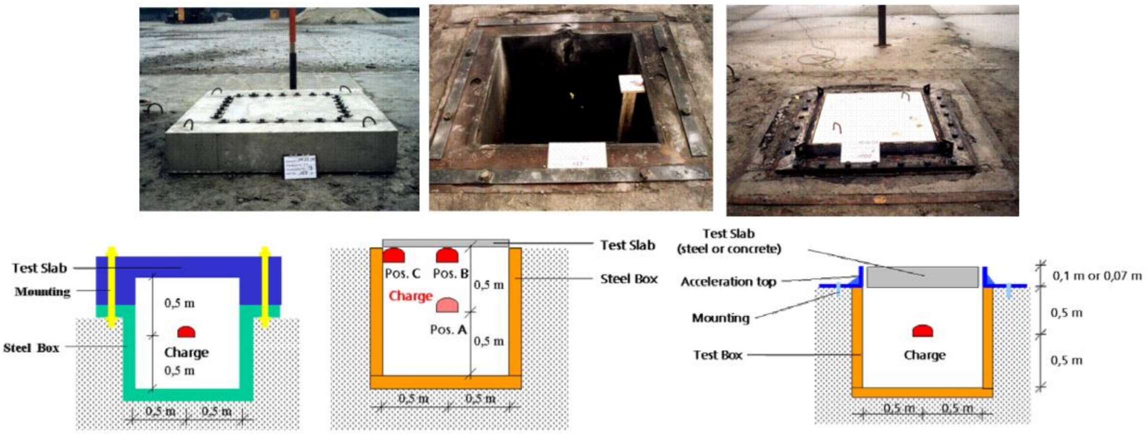


Figure 5. Test set-ups to study effect of clamping, charge position and initial venting conditions

Interesting question in the campaign was the contribution to the slab launch velocity of the shock loading versus the generated quasi static pressure. The tests with the fully vented set-up and the closed configuration showed as an overall result that the shock loading contributes 10% and the gas pressure 90% to the launch velocity. The dominance of the gas pressure is reflected in the term ($\gamma.L_{char}$) of the empirical DLV relation (eq. 1) that EMI derived.

$$v_{launch} = 525\sqrt{\frac{\gamma.L_{char}}{m}} \quad (m/s) \qquad (1)$$

With: γ = loading density. (kg TNT/m^3)
L_{char} = the characteristic length, i.e., the cube root of magazine volume. (m)
m = specific wall mass. (kg/m^2)

It has been proven over the years that the DLV gives a very good prediction of the slab launch velocity for a wide range of structures and loading conditions. Additional KG research showed that the DLV is also representative for initial debris launch velocity, as discussed in the next section. Therefore, the DLV is also used in the KG-ET which is presented as another KG highlight. For more information on the DLV tests and analyses see [2] – [7].

RC Magazines. Kasun tests: bare charge & cased charge

After the KC Era on explosives safety of underground magazines, in the 1990’s the interest broadened to above ground magazines, and especially the concrete magazines with their dominant hazard of debris throw. Reviewing the physics of explosive loading, break-up and debris throw, three loading regimes were identified (based on loading density, LD: kg TNT/m^3). These are (i) the gas pressure, (ii) the impulsive, and (iii) the shock overloading regime, see Figure 6. These regimes roughly relate to the loading density as (i) $LD < 1$, (ii) $1 \leq LD \leq 15$, and (iii) $LD > 15$ kg/m^3, respectively. Note that in the three scenarios depicted in Figure 6, the entire structure is launched as hazardous debris, but it is depicting the break-up mechanism of the structural components. In the shock overloading regime, the structural components are broken up by the shock loading prior to the gas pressure launching the debris. Conversely, the structural components are not broken apart by the shock waves in the gas pressure overloading regime, so it is the gas pressure that is breaking up the structure and launching the debris.

In the shock overloading regime local failure occurs due to a very intensive shock loading. The pressure levels in the severe shock loading are in the order of several 100 MPa exceeding the compressive strength resulting in breaching and spalling of the concrete wall or walls. The load duration is on the order of 10–100 microseconds. This failure mode occurs at $LD > 15$ kg/m^3 or at small scaled distances, Z ($Z < 0.4$ m/$kg^{1/3}$).

When the structure survives the initial shock loading, and the load duration is short in relation to the response time of the structure or structural element, the high frequency response modes are activated. Wave phenomena occur, not at a "continuum level" in the material, but at the structural level. Bending and shear waves occur. In these high frequency response modes the stress gradients are high, leading to shear failure. The largest stresses occur at discontinuities in time and/or place. This means that shear failure is most likely to occur near discontinuities in stiffness and near concentrated loads. In this failure mode the structure breaks up in large pieces with smaller debris originated from the failure zone. Due to the initial shock loading, the large debris might be "pre-fractured" and break-up in smaller pieces during the phase of debris throw. It is expected that this failure mode is dominant for the loading density range of $1 \leq LD \leq 15$ kg/m^3, while the scaled distances is on the order of $0.4 \leq Z \leq 1$ m/$kg^{1/3}$.

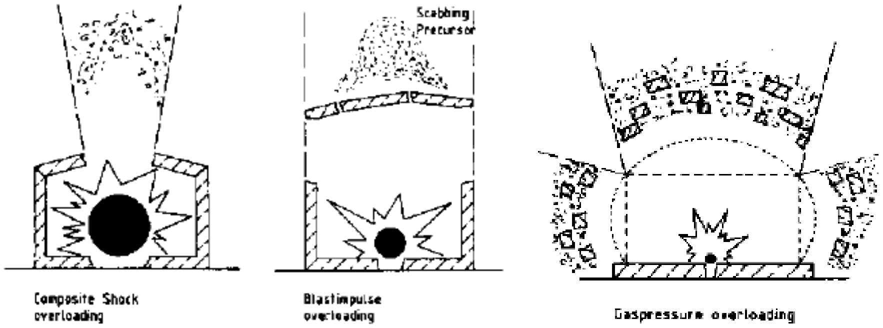


Figure 6. The three overloading regimes for RC magazines

When the composite shock loading of the explosion and also the amplitudes of the higher response modes were insufficient to cause shear failure, the gas pressure might lead to the break-up of the structure. The gas pressure is a quasi-static loading and the first eigenmode of the structure determines the response. The load amplitude is on the order of 1-10 MPa, while the load duration is on the order of 10-100 msec. In this failure mode the wave phenomena are not important anymore, as the load level is directly related to the loading density. This failure mode occurs for loading densities LD < 1 kg/m^3. Of course, at some very low loading density (LD <<< 1 kg/m^3) and structure type combination, the structure is not overwhelmed and debris is not generated. This scenario is outside the interest of this research area and thus not explicitly considered.

The main focus of the KG-research has been on the regime of 1-15 kg/m^3, as evident with the DLV test series. From the DLV concrete slab tests, unfortunately no information was obtained on the timing of complete break-up and if there is an initial velocity distribution within the debris launch velocity. To study these aspects in more detail, a laboratory test was designed testing RC slabs clamped on an explosion box while the response was recorded with high speed video, X-ray, and strain gauge recordings. The slabs had a span of 2 m, the box dimensions were 2 x 1 x 0.5 m, and the loading densities realized with single and multiple charges up to 4 kg/m^3, see [8] and Figure 7.

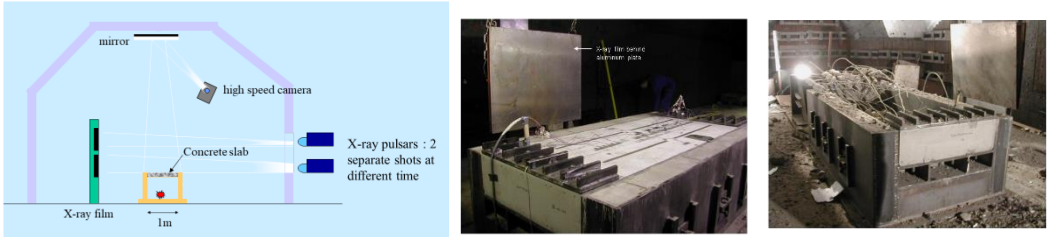


Figure 7. Instrumented break-up test

These tests clearly showed that the slab is launched as a heavily damaged slab, but break-up occurs at a later stage. In the tests this occurred at least after a launch distance of 0.5 m. Therefore, it was concluded that the DLV relation, derived for the slab launch velocity, can also be used as debris launch condition (see sections on DLV and the KG-ET).

The KG used the small, but full scale Kasun RC magazines to study the break-up and debris throw systematically at various loading densities for bare as well as cased charges. The latter is unique, because most (large scale) explosion tests are performed with bare charges and also the safety distance guidelines are mainly based on bare charge test data. In addition to the experimental work, computational studies were performed to enable extrapolation of the test results to other geometries and test conditions. The results have been used as input for the KG-ET methodology, and are also direct input and reference for Risk analyses and safety distances. Detailed information on the KG-ET methodology, validation efforts, and results of the tool are documented in numerous KG reports and publications on ISIEMS and MABS conferences. In this section just a short summary is given.

The KG selected the Kasun magazine for the break-up study [9,10,11]. It is a structure type that was in use in Norway and Sweden for storage of small amounts of ammunition. This RC-structure has a cubic shape with internal dimensions of 2x2x2 m^3 with a wall and roof thicknesses of 0.15 m and is made of concrete B35. The walls and roof are double reinforced in both directions with a concrete cover of 25 mm for the outside surfaces, and a concrete cover of 20 mm for the inner surfaces. The rebar diameter is 12 mm and the spacing is 100 mm. The reinforcement is FeB400. The structure and charge lay-out for the 2008 test series is given in Figure 8. Note that there were prior Kasun tests series to 2008, as identified in the references. The overview of the performed tested and analyses in the 1st and 2nd phase are given in Table 1.

Figure 8. Exterior (a) and interiors (b) of the Kasun structure from the tests in 2008 [11].

Table 1. Test and simulation matrix Kasun tests and analysis campaign.

Charge type	Charge weight [kg TNT]	Tested 2008	Simulated 2010	Simulated 2014/2015
1 bare	6.9	Y	Y	Y
4 bare	27.9		Y	Y
16 bare	110	Y	Y	Y
1 -155 mm	6.9	Y	Y	
4 -155 mm	27.9	Y	Y	
16-155 mm	110	Y	Y	
1-121 mm	6.5			Y
4-121 mm	26.1			Y
16-121 mm	104.5			Y

The debris data collection in the Kasun test campaigns occurred according to an internationally agreed standard [12]. A large data base on debris mass distribution and debris throw distances has been established. Besides the debris data collection, high speed (HS) recordings were also made to get information on the initial structural response and failure mode.

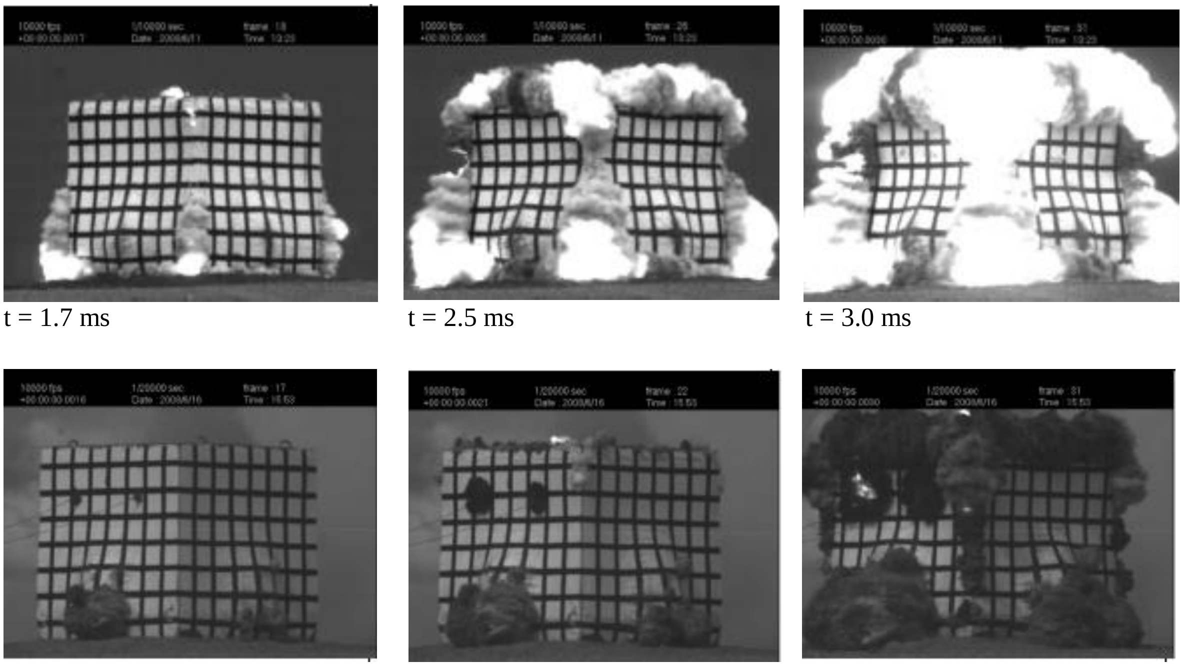

t = 1.7 ms
t = 2.5 ms
t = 3.0 ms
t = 1.6 ms
t = 2.1 ms
t = 3.0 ms

Figure 9. Frames HS recordings of Kasun tests 16 charges. (top) bare charges, (bottom) cased charges.

Figure 9 shows some initial HS frames illustrating the difference in break up for the bare and cased charges. Initial venting occurs sooner for the bare charges but the impact of the shell fragments generates a more pronounced local failure mode.

A three step procedure was developed for the numerical analysis of the sequence of events, starting from the generated blast and fragment loading up to the final break-up of the structure and launch conditions of the debris [13,14,15]. The three step approach is illustrated in Figure 10.

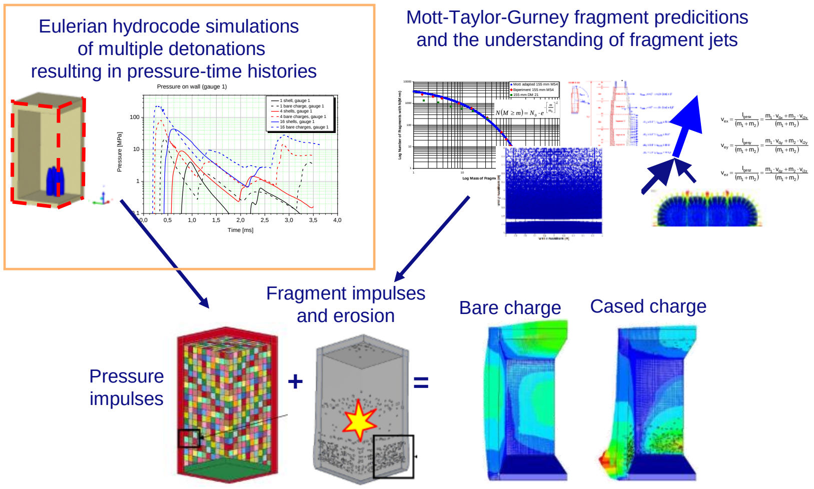


Figure 10. The three step KG modeling approach to analyze break-up RC magazines and prediction of debris launch conditions.

The first step models the detonation of the charge, the failure of the casing, and the interaction between the fragments from multiple charges/shells simultaneously detonating. These effects are explicitly modeled in order to quantify the resulting blast loading conditions on the walls and roof of the magazine. In order to predict the generated gas pressure correctly, venting due to (local) structural failure has been taken into account in the second step. A special procedure was developed to predict the temporal and spatial distribution of the fragment loading. Finally, blast and fragment loading were combined in the third step to simulate the structural response up to complete failure in order to predict the launch conditions, velocities and angles, of the wall/roof debris.

The developed procedure and the applied numerical tools enable study of the casing effect on the loading and break-up process in detail, such that they can be used to quantify the launch conditions for other geometries, ammunitions and asymmetric storing conditions. Additional computational studies revealed that besides fragment impact, also the geometry of the structure and charge lay-out dictates the launch angle, since it affects the structural failure sequence.

Summarizing the results of the KG experimental and computational research on RC magazines:

- extensive data base on debris mass distribution and throw distances, as a function of loading density;
- the gas pressure and impulsive overloading regimes were confirmed;
- the DLV prediction proved to be valid for the Kasun magazine.
- casing reduces the effective charge weight, but leads to changed debris launch angle. Consequently, the external debris throw pattern is more dependent on structure/magazine geometry and ammunition layout than the effect of casing versus bare charges.

The Klotz Group Engineering Tool (KG-ET)

The KG is developing and continually improving an engineering tool (KG-ET) for the prediction of debris throw. The tool is based on state of the art knowledge, empirical data from a number of trials, and numerical simulations of internal detonations and the resulting debris throw generated..

The KG-ET aims to capture the chain of events from (i) the internal explosive loading of the donor structure, (ii) donor break-up and debris launch, (iii) debris throw and providing the impact condition on the acceptor (structure or person). This is an incredibly challenging task which requires multiple simplifications and assumptions which require careful judgement. It is here that the broad and thorough expertise of the members of the KG is fully utilized.

The long term goal is to develop models for all common types of above ground ammunition magazines and bulk storage of bare as well as cased charges. The potential explosion sites (PES) are the (i) RC-magazine, (ii) the ISO container, (iii) open stack, primary fragments, (iv) earth covered magazine (ECM) and (v) the masonry magazine. Up to now the KG research mainly addressed the RC magazine and the ISO container. Experimental data has been shared where possible, the KG analyzed the available data and maturity of numerical models, and then the KG conducted additional tests to fill in the knowledge and data gaps.

The development of the KG-ET started about 15 years ago [16,17,18,19]. Revisiting the available data, the possibilities to quantify and capture the loading process up to the break-up process and prediction of the debris launch conditions revealed that, for an engineering model the best way forward was to derive relations for mass distribution, launch velocity and launch angle as function of the loading density and many other pre-defined and calculated parameters. Examples of these empirically derived parameters are shown in Figure 11 and Figure 12.

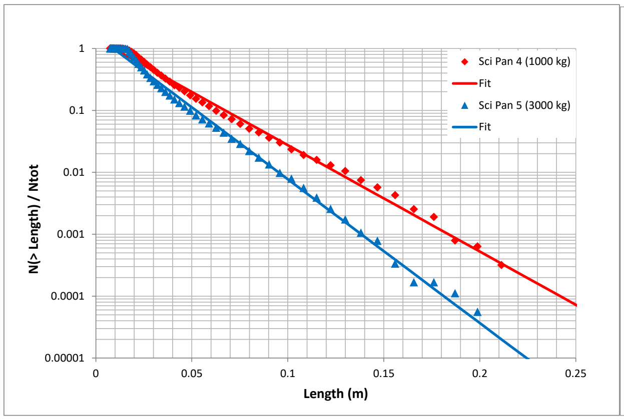


Figure 11. Empirically derived mass distribution

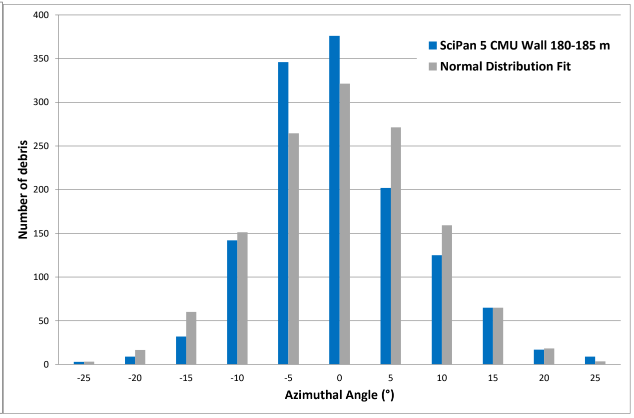


Figure 12. Empirically derived debris launch angle

In order to enable the coverage of the wide range of magazines and loading conditions, the source term theorem was adopted to describe and represent the initial debris launch conditions in the KG-ET. All the information of the initial launch conditions is presented in a "point source" as a sphere with the spatial distribution given in functions of the vertical and azimuthal angle, as shown in Figure 13.

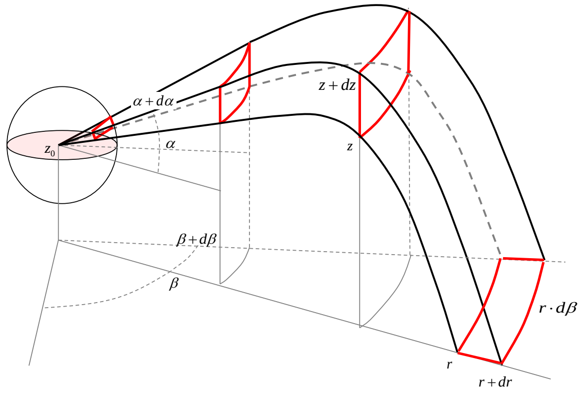


Figure 13. Illustration of source function theorem

Bin number	Bin mass [kg]	Middle mass [kg]
1	> 24.494	35*
2	9.752 - 24.494	17.1
3	4.309 - 9.752	7.03
4	1.814 - 4.309	3.06
5	0.771 - 1.814	1.29
6	0.272 - 0.771	0.52
7	0.136 - 0.272	0.20
8	0.054 - 0.136	0.10
9	0.023 - 0.054	0.039
10	0.011 - 0.023	0.017
G	< 0.011	Not relevant

* Value assumed in absence of top value

Table 2. Mass classes of SciPan.

The debris mass distribution is represented in so called mass bins. For RC magazines the SciPan mass bin distribution was adopted, see Table 2. Each mass bin can have its own spatial distribution (α,β) and initial launch velocity (v_o). With this information the debris trajectory calculations are performed to predict the trajectory and the impact conditions (velocity, angle) at the final throw distance or on a defined target (ES, exposed site). The calculation and data processing procedures are combined with a user interface. The structure of the KG-ET v 3.0 (2018) is depicted in Figure 14 and Figure 15.

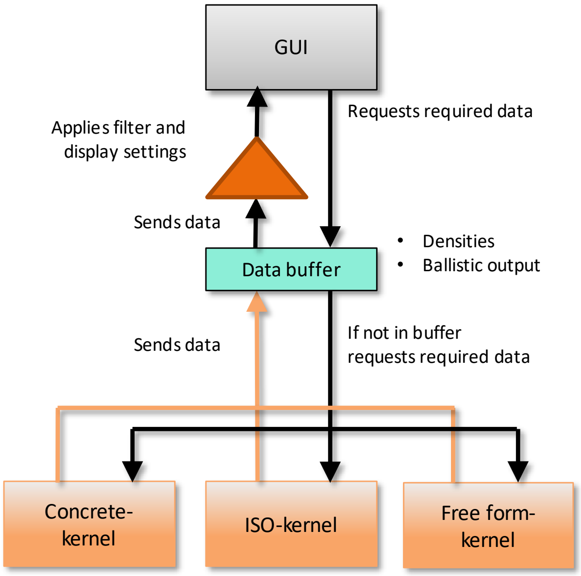


Figure 14. Organization scheme KG-ET 3.0.

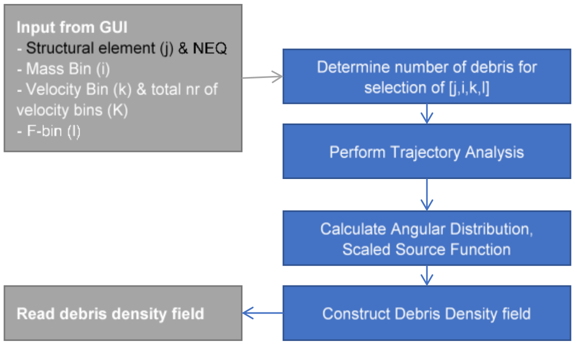
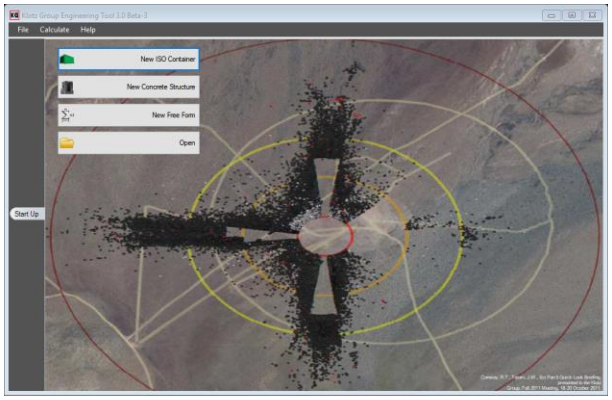
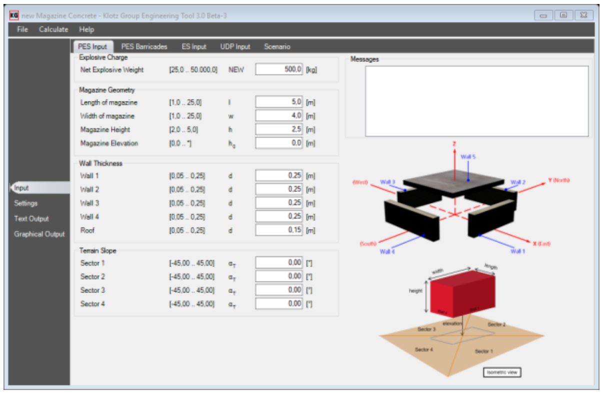


Figure 15. Scheme of the calculation kernels (blue boxes)

The structure is such that for each type of magazine (PES) a calculation kernel is developed, dedicated to the specific properties and characteristics of that magazine. Currently the RC magazine and ISO container kernel have been fully implemented. Additionally, the provision of an "arbitrary magazine" has been implemented in the form of a "free form source function". The kernels are combined with the generic modules of data processing and the GUI taking care of the input and output processes. This "free form source function" s quite novel in that it allows a user to produce a debris throw prediction model for any PES type, given that the required input information is known and sufficiently validated. That last aspect cannot be over-stated, as the KG has spent many years validating the underlying theory of the RC and ISO-container models. Still, the "free form source function" allows a user to test new models or make minor alterations to existing KG-ET models (e.g., an ISO container with earth cover).

The most appropriate way to validate the results of the tool is to compare the debris density predictions against test data that was not used to develop the underlying theory of the KG-ET. Figure 16 shows the debris field generate by the SciPan 5 test [20], which consisted of 3000 kg of non-fragmenting explosives in a 9x9x3.4 m RC operating building. The post-event debris collection was consistent with the mass classes defined in Table 2. Figure 17 illustrates a screenshot of the basic user input of the KG-ET. The input required is incredibly simple, but there are extensive calculations generated at run-time based on the input data. The KG-ET does have an "Expert" mode, where various hard-wired parameters can be changed if desired. For example, the vertical launch angle of a specific mass could be changed if desired, but note that the default values were generated by extensive empirical and analysis assessments of representative debris launch angles. Finally, Figure 18 shows the debris density plot predicted by the KG-ET for the SciPan 5 test. The output interface allows the results to be expressed in a multitude of ways, and all of the data generated is available in a tabular format as well. Debris density is presented as a function of both distance and angle, and the debris included in that calculation can be filtered as well, either as a function of mass class or impact kinetic energy. If a target is defined as part of the user input, detailed hit information is provided for that ES.





Explosive Charge

Net Explosive Weight	[25,0 .. 50.000,0]	NEW	500,0	[kg]

Magazine Geometry

Length of magazine	[1,0 .. 25,0]	l	5,0	[m]
Width of magazine	[1,0 .. 25,0]	w	4,0	[m]
Magazine Height	[2,0 .. 5,0]	h	2,5	[m]
Magazine Elevation	[0,0 .. *]	h_g	0,0	[m]

Wall Thickness

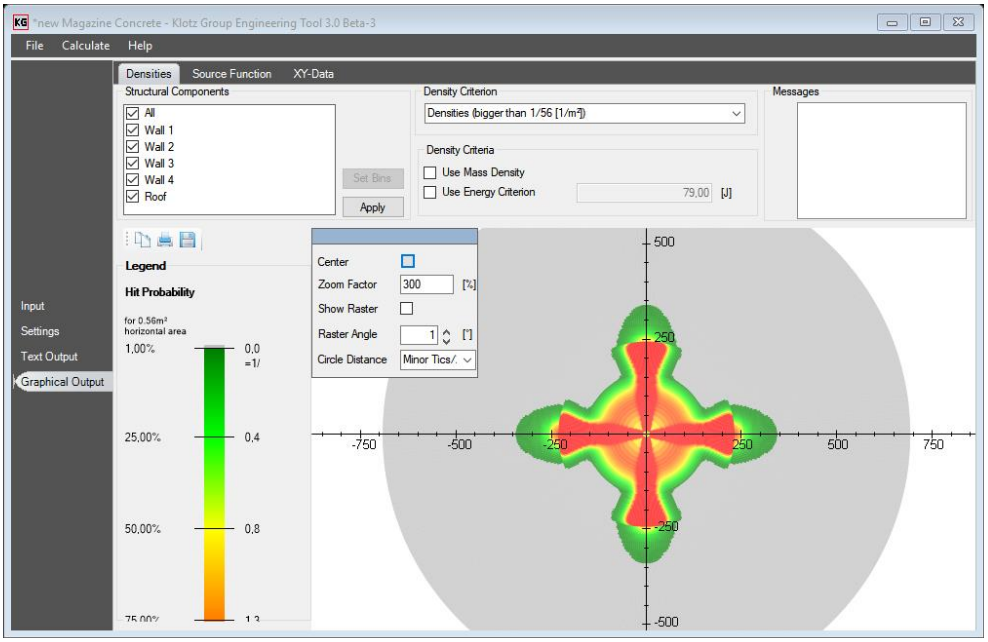
Wall 1	[0,05 .. 0,25]	d	0,25	[m]
Wall 2	[0,05 .. 0,25]	d	0,25	[m]
Wall 3	[0,05 .. 0,25]	d	0,25	[m]
Wall 4	[0,05 .. 0,25]	d	0,25	[m]
Roof	[0,05 .. 0,25]	d	0,15	[m]

Terrain Slope

Sector 1	[-45,00 .. 45,00]	α_T	0,00	[°]
Sector 2	[-45,00 .. 45,00]	α_T	0,00	[°]
Sector 3	[-45,00 .. 45,00]	α_T	0,00	[°]
Sector 4	[-45,00 .. 45,00]	α_T	0,00	[°]

Figure 16. KG-ET 3.0; select magazine type

Figure 17. Screen shot magazine input data



Structural Components

- ☑ All
- ☑ Wall 1
- ☑ Wall 2
- ☑ Wall 3
- ☑ Wall 4
- ☑ Roof

Density Criterion: Densities (bigger than 1/56 [1/m²])

Density Criteria

- ☐ Use Mass Density
- ☐ Use Energy Criterion 79,00 [J]

Center ☐

Zoom Factor 300 [%]

Show Raster ☐

Raster Angle 1 [°]

Circle Distance Minor Tics/.

Figure 18. Screenshot debris density plot

The current models of the RC magazine and ISO-container have been developed via extensive work by the Klotz Group. They are based on extensive empirical and analytical data, but that information is limited. The models for mass distribution, launch velocity, and launch angle are implicitly tied to the information available, and each of those parameters have a range of applicability. The range of applicability is fairly extensive and should cover most ammunition storage structures of those types, but care must be made to ensure that the scenario being modeled with the KG-ET is within that range of applicability.

KG-ET Summary:
The extensive work and research performed by the KG has been transitioned into the development of an engineering tool (KG-ET) for the prediction of debris throw. The tool is based on state of the art knowledge, and available debris pick-up data and other relevant information from a number of trials.

With the help of this data, relations have been obtained for the initial distributions of debris mass, velocity and launch direction, as a function of the loading density. In combination with trajectory calculations and the source function theorem, the model is used as a prediction tool for the debris effects. These explosion effects are intended to then be utilized in national consequence assessment and risk prediction tools, as well as for the improvement of explosives safety quantity distance.

The current focus for enhancement of the KG-ET is development of a primary fragment source function. This work is two-fold, as the hazards from a stack of primary fragments in the open or in an ISO container needs to be developed, but conversely the effects of the primary fragments have on the source functions of the RC magazine and ISO container must also be considered.

Concluding remarks

The Klotz Group, and its predecessors, have provided extensive contributions to the explosives safety community for over five decades. The member countries have varied over the years, but the focus has remained on technical solutions for explosives storage and a comprehensive understanding of explosion effects. Pursuit of a fundamental understanding of blast effects has resulted in state of the art research programs that have provided a foundation for the current knowledge base of debris throw prediction.

The current organizational structure and cooperation mechanisms have been very successful. The focus remains solely on technical issues. The yearly contribution and technical contribution by participants are equally important to have sufficient commitment to the group and enable projects to fill the gaps and realize links between the national research programs. The KG-ET is an integrator of extensive expertise and comprehensive prediction results to be used for enhancing explosives safety distances and supporting quantitative risk assessments. The KG-ET is a tool available to persons supporting the Department/Ministry of Defense for KG nations, and supports KG visibility in the NATO community and the national explosive safety communities.

The future plans of the Klotz Group are :

- Develop the KG-ET source function for primary fragments; generate validation test data; quantify stack effects for the model
- Develop the KG-ET ECM source function
- Balance between testing, engineering models & computational analysis to develop further the KG-ET dedicated to the need for safety distances as well as input for risk analysis

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