Prediction of injuries caused by explosive events: A case study of a hand grenade incident in South Africa

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Abstract

An M26 hand grenade was accidentally detonated by a group of eight children, six of whom were killed, in the Mthatha area of South Africa. The M26 grenade is designed to produce casualties through the high velocity fragments that it expels. However, if one is close enough to the grenade primary blast injuries will occur in addition to penetration injuries caused by the fragments. Simulations were conducted to obtain pressure profiles that could be produced by the explosive charge contained in the grenade. Injury predictions were then made, using currently available injury criteria and compared to one another and to the actual injuries that were sustained by the children. The validity of currently available pressure-based injury criteria to predict injuries when the subject is in very close proximity to the explosive charge is still unknown. Further such case studies and research into injury mechanisms and injury criteria are necessary to enable injuries caused by explosive events to be accurately predicted. This will allow improved protection strategies against explosive events to be developed.

1. Introduction

In this case report, an M26 hand grenade containing high energy explosives was found and unintentionally detonated by children who were minding cattle. Eight children were involved. Six of them died instantly, and the other two sustained minor injuries. These children were between 9 and 16 years of age. The police said the device was an M26 grenade of South African origin.

Several hand grenade incidents have been reported in the Transkei area since 1998. Eleven such incidents were reported in the Daily Dispatch, Herald, South African Broadcasting Channel (SABC) News, Mail & Guardian. There were 14 explosive devices involved in which 16 children and 5 adults were killed (See Table 1).

<table>
<thead>
<tr>
<th>Date of incident</th>
<th>Number of Child deaths</th>
<th>Number of Adult deaths</th>
<th>Type and number of hand grenades involved</th>
</tr>
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<tr>
<td>03/01/1998</td>
<td>2</td>
<td>0</td>
<td>M26 (x 2)</td>
</tr>
<tr>
<td>01/06/1998</td>
<td>6</td>
<td>0</td>
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</tr>
<tr>
<td>28/12/1998</td>
<td>1</td>
<td>1</td>
<td>Unknown (x 1)</td>
</tr>
<tr>
<td>02/07/1999</td>
<td>3</td>
<td>0</td>
<td>M26 (x 1)</td>
</tr>
<tr>
<td>28/11/2000</td>
<td>0</td>
<td>0</td>
<td>M26 (x 1)</td>
</tr>
<tr>
<td>28/11/2000</td>
<td>0</td>
<td>0</td>
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</tr>
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<td>1</td>
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</tr>
<tr>
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<td>M26 (x 1)</td>
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<td>0</td>
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<tr>
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<td>0</td>
<td>M26 (x 1)</td>
</tr>
<tr>
<td>18/07/2007</td>
<td>0</td>
<td>0</td>
<td>M26 (x 1)</td>
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<tr>
<td>04/09/2007</td>
<td>1</td>
<td>0</td>
<td>M26 (x 1)</td>
</tr>
</tbody>
</table>

Table 1: Hand Grenade incidents in the Mthatha area of South Africa

The South African manufactured M26 hand grenade was the most common threat in these incidents. There is evidence that a substantial number of small arms are unaccounted for following apartheid era South Africa (Greenstein, 2003). With the integration of the Transkei Defence Force into the South African National Defence Force in 1994, 715 firearms were not accounted for (Greenstein, 2003). Presumably, in this process hand grenades were also unaccounted for. A Commission of Inquiry into politically-motivated violence, led by Judge Richard Goldstone, found that the Transkei government had supplied the Azanian People’s Liberation Army with arms. This finding could explain a portion of the unreturned firearms. It is hoped that this study will raise public awareness that people in South Africa are still being killed by these explosive devices.
M26 hand grenades were designed to supplement small arms fire against enemy in close combat. They were designed to be thrown into the vicinity of enemy targets to produce casualties through the high-velocity projection of fragments (Hand Grenades, 2007). The grenade is 113 mm in length with a diameter of 60 mm (Denel: M26 HE Hand Grenade, 2007) and is filled with 160 g of high-energy Composition B\(^1\) charge. The total weight of the grenade is 465 g and it produces approximately 1000 small fragments weighing about 200 mg each (Denel: M26 HE Hand Grenade, 2007). The grenades can be identified by an olive drab body with a single yellow band at the top with yellow markings which are indicative of the high-explosive filler. A diagram of the M26 grenade can be seen in Figure 1 and a photograph of the grenade is shown in Figure 2.

**Figure 1: Diagram of an M26 fragmentation hand grenade (Hand Grenades, 2007).**

\(^1\) Composition B consists of RDX (Cyclonite) and TNT (trinitrotoluene) in the ratio 60:40 (Köhler and Meyer, 1993).

A fragmentation grenade such as the M26 produces a complex set of injury mechanisms that produce injury to humans within certain ranges. Wounding mechanisms caused by explosive events can be categorised as follows (White, 1968) (Ripple and Phillips, 1997) (Cooper et. al., 1991):

- **Primary** blast injury (PBI) caused by the direct effects of the blast (blast induced variations in the environmental pressure). This could result in injuries to the lungs, upper respiratory tract, gastrointestinal tract and solid intra-abdominal organs. These injuries could occur when the victim is in very close proximity to a grenade containing high-energy explosives.
- **Secondary** ballistic injuries due to fragmentation and flying debris. This is the mechanism by which the M26 grenade is intended to cause injury.
- **Tertiary** injuries are caused by whole body displacement.
- **Miscellaneous** injuries such as burns and toxic fume inhalation. Burns could possibly be caused if the subject was in the fire-ball resulting from an explosive event.
Criteria have been developed which relate measurements that can be taken during explosive events to possible injury severities caused by the wounding mechanisms described above. A case study, as is presented in this paper, provides researchers with an opportunity to gauge the validity of criteria that have been developed to predict injuries. The M26 grenade is designed to inflict injury through high-velocity fragments under normal operating conditions. In this case study, the children were handling the grenade directly at the time of detonation (which would not usually be the case as the grenade is designed to be thrown into the general vicinity of the enemy and relies on the fragments inflicting injury over a 15 m radius). Thus, in addition to the fragments causing serious injury, due to the close proximity of the children to the exploding device, primary blast injuries caused by pressure effects may also be observed.

It is well known that the higher the peak pressure, the more severe the injuries caused by this pressure will be. It is also accepted that longer positive phase pressure durations result in more severe injuries than if the duration was shorter (Cooper, 1996) (White, 1968) (Axelsson and Yelverton, 1996) (Bowen, Fletcher and Richmond, 1968) (Richmond et al., 1968) (Bouamoul, Williams and Levesque, 2007).

Two commonly used injury criteria for predicting injuries caused by pressure profiles arising from explosive events are the Bowen criterion (Bowen, Fletcher and Richmond, 1968) and the Chest Wall Velocity Predictor (CWVP) (Axelsson and Yelverton, 1996).

The Bowen criterion is used to predict injuries caused by explosive events in a free field environment (i.e. not in an enclosure or near objects which may cause complex reflected waves to interact with the subject). This criterion requires an incident overpressure and a duration measurement. The criterion was derived from mortality studies conducted on mammals and risk curves were produced to predict human injuries for various peak overpressures and positive-phase durations of the blast wave (Yelverton, 1996). Modifications to the Bowen criterion for short duration blasts were proposed by Bass et al. 2006, however, the original Bowen curves are currently used for overpressure injury assessment in armour testing standards (e.g. Test Methodologies for Personal Protective Equipment Against Anti-Personnel Mine Blast, 2004).

An alternative to the Bowen criterion (Bowen, Fletcher and Richmond, 1968) is the CWVP (Axelsson and Yelverton, 1996) which takes into account the upper respiratory tract, gastrointestinal tract and solid intra-abdominal organs, in addition to the lungs which were also considered in (Bowen, Fletcher and Richmond, 1968). This criteria was developed to take into account complex blast waves (as one might find if an explosive was to detonate in an enclosed space or near reflecting surfaces), but it is also valid for the free field case. Tests were conducted by exposing sheep to explosive events. The injuries were graded per body region using an alphanumeric scoring system (Axelsson and Yelverton, 1996).

In this study, a simulation of the M26 hand grenade was performed and predicted pressures from the literature were obtained. By using these pressure profiles at various distances from the grenade, injury criteria can be used to predict possible injuries at those positions. The mechanisms of injury resulting from the primary and secondary effects of the explosive event, in relation to the distance of a victim to the grenade, will be discussed.

2. Incident Analysis

2.1 Incident description

At autopsy, all children had their ventral aspects mutilated or greatly lacerated. A bluish green substance was deposited over the abdomen and chest. The boy closest to the blast sustained abdominal and chest mutilation, while those near him sustained deep lacerations to the torso. The lungs and intestines were diffusely contused in three of the boys. The two boys who were a considerable distance from the blast escaped with minor injuries.

2.2 Simulation of the M26 hand grenade and predicted pressures from literature sources

ANSYS AUTODYN2D software was used to calculate the pressure at three locations of a 160 g spherical TNT charge that approximates the M26 hand grenade. The explosive and air are modelled with the Euler Gudonov solver in an axial
symmetric geometry. The air and explosive gas are allowed to escape across the boundaries. The ideal gas equation of state models the air and the explosive is modelled with the Jones-Wilkens-Lee (JWL) (Lee, Hornig and Kury, 1968) equation of state. In Figure 3 the overpressure time histories at locations 0.1 m, 0.2 m and 0.5 m are shown. The reflected pressure time histories at 0.2 m, 0.5 m and 1.0 m are shown in Figure 4.

Figure 3: Graph showing simulated overpressure (side-on pressure) predictions at various distances from 160g spherical TNT charge.

Figure 4: Graph showing simulated reflected pressure predictions at various distances from 160g spherical TNT charge.

Peak pressure values were obtained from various formulae based on experiments (e.g. (Petes, 1968), (Swisdak, 1975), (Swisdak, 1999) and (Kinney and Graham, 1985)). Peak pressure values from the literature together with the computational results are shown in Figure 5.

Figure 5: Graph showing the predicted peak overpressure values at various distances from a 160 g TNT charge as by simulations and in the literature.

The computation of the peak reflected pressure at the various locations by ANSYS AUTODYN and the formula from (Swisdak, 1975) are shown in Figure 6.

The overpressure at a location is the effect of the shock pulse without any obstruction, that is, the pressure wave passes without any interference across the location. This pressure is also known as side-on pressure. The reflected pressure is the effect at the location when the pressure wave is obstructed by a surface so that the pressure wave has to change its flow, that is, the pressure wave is reflected back towards its origin. The peak reflected pressure is between 2 and 8 times the peak overpressure (according to (Swisdak, 1975)).
Both these values therefore give an indication of the effect of a blast on an object or a person.

Although the M26 grenade is designed to cause injury through the projection of high-velocity fragments, due to the close proximity of the children to the grenade, the primary effects (such as blast overpressure) may result in more severe injuries than would be expected due to the fragments alone.

From the peaks and durations of these pressure curves, injury criteria can be used to predict possible injuries that could occur at certain distances from the charge.

2.3 Injury predictions using pressure based injury criteria

The simulated peak overpressure and positive-phase durations shown in Figure 3 can be used to predict primary injuries at various distances from the grenade. Unfortunately the positive-phase durations used in (Bowen, Fletcher and Richmond, 1968) only go down to 0.2 ms and the durations shown in Figure 3 for distances less than 0.5 m from the grenade fall below 0.2 ms. However, at 0.5 m from the grenade the positive-phase duration is approximately 0.3 ms. The peak overpressure at this distance is approximately 1507 kPa which is above the threshold for lung damage but below the 99% chance of survival curve (as deduced from the curves indicated in (Bowen, Fletcher and Richmond, 1968) for a 70kg man applicable to a free field situation where the long axis of the body is perpendicular to the blast winds.

Although it is unclear if the CWVP criterion is valid for positive-phase durations of less than 0.4 ms, as tests were not conducted for that loading rate, Matlab™ simulations using this criterion were conducted. This was achieved though the use of the pressure profiles obtained from the simulations shown in Figure 4. The results are shown in Figure 7.

At a distance of less than or equal to 0.5 m the injury severity was moderate to extensive and corresponded to a greater than 50% chance of lethality (Axelsson and Yelverton, 1996). At a distance of 1 m the severity decreases to slight or slight to moderate (Axelsson and Yelverton, 1996).

Although the M26 hand grenade has been predicted to cause serious injury using the pressure profile criteria outlined above, as mentioned before, the grenade is primarily designed to produce injury via high velocity fragments. In the simulation conducted to predict the pressure profiles at various distances from the grenade, the velocities of the fragments were also measured. From 0.01 ms it was found that the fragments already achieved peak velocities in excess of 1400 m/s which was maintained until at least 0.3 ms, at which stage they are approximately 0.5 m from the original centre of the grenade. The fragments cause damage by transferring kinetic energy to the body tissue which causes the tissue to be damaged (Zajtchuk, 1990). These high velocity fragments result in the grenade having a 50% casualty radius of 15 m, however the fragments are able to disperse out to 230 m (Denel: M26 HE Hand Grenade, 2007).

Injuries in very close proximity to the grenade would be more severe due to the dramatic increase in peak pressure values as the distance to the grenade decreases. However, this is speculation and further work needs to be conducted to
understand the injury mechanisms when the body is exposed to excessive peak pressures with very short positive-phase durations, for which the currently used pressure based injury criteria may not be valid.

Figure 8 shows the regions within which injuries due to primary and secondary injuries caused by a M26 hand grenade may be expected. The grenade is positioned in the centre of the diagram. The orange circles indicate limits described for various levels of injury severity due to primary effects and the black circles indicate areas in which injuries caused by fragments could occur.

![Diagram showing the regions within which primary and secondary injuries caused by a M26 hand grenade may be expected.](image)

**Figure 8: Diagram showing the regions within which primary and secondary injuries caused by a M26 hand grenade may be expected.**

By speculating the proximity of the children to the grenade, one can correlate the injuries described in the autopsy reports with the predictions made surrounding the primary and secondary effects of the explosion.

2.3.1 Children in the inner circle:

The child holding the grenade could have been within 0.2 m of the grenade and another child could have been within 0.3 m of the grenade. Both children in the inner circle could thus have exceeded the threshold for lung damage (Using the Bowen criterion (Bowen, Fletcher and Richmond, 1968)) due to the primary effects of the explosive event. Using the CWVP criterion (Axelsson and Yelverton, 1996), within 0.3 m the children would have a 50% chance of lethality due to the primary injuries which they sustained. They were all within the 50% casualty range due to the fragments produced by the grenade.

2.3.2 Children in the outer circle:

Four children may have crouched over the inner two and could have been within 0.3 m to 0.5 m of the grenade. At 0.5 m all of the children could have exceeded the threshold for lung damage, however they would have a less than 1% chance of lethality due to the primary effects of the explosive event alone (Using the Bowen criterion (Bowen, Fletcher and Richmond, 1968)). Using the CWVP criterion (Axelsson and Yelverton, 1996), at 0.5 m the children would have a 50% chance of lethality due to the primary injuries which they sustained. They were all within the 50% casualty range due to the fragments produced by the grenade.

2.3.3 Children witnessing the event:

The two children who witnessed the event were outside the range of injury due to the primary effects of the blast, but the minor injuries which they sustained may have been due to the fragments which dispersed.

3. Discussion of explosive event injury criteria and research applications

It can be concluded that the injuries described in the autopsy reports correlate well with the predictions made surrounding the primary and secondary effects of the explosion.

This study focussed on predicting primary injuries caused by the explosive charge, which, although it is understood that the fragments are the intended injury mechanism of the M26 hand grenade, provide insight into the use of current pressure based injury criteria to predict injuries in very close proximity to explosive charges.

It was found that the Bowen criterion (Bowen, Fletcher and Richmond, 1968) predicted less severe injuries within a meter of the explosive charge than the CWVP criterion. The differences in severity are highlighted in Table 2.
Table 2: Descriptions of primary injury levels predicted at various distances from the 106 g spherical TNT charge.

<table>
<thead>
<tr>
<th>Distance from charge</th>
<th>Bowen et al. 1968 predicted injury level</th>
<th>CWVP predicted injury level</th>
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</thead>
<tbody>
<tr>
<td>0.5 m</td>
<td>Less than 1% chance of lethality</td>
<td>Greater than 50% chance of lethality</td>
</tr>
<tr>
<td>1 m</td>
<td>Threshold for lung damage</td>
<td>Trace to moderate injury</td>
</tr>
<tr>
<td>15 m</td>
<td>No lung damage</td>
<td>No injury</td>
</tr>
</tbody>
</table>

Predictions of injury severities at distances of less than 0.5 m from the grenade are not included in Table 2 as simulated pressure profiles at 0.1 m and 0.2 m from the explosive charge have positive-phase durations of less than 0.4 ms. The validity of the Bowen criterion for pressure profiles with positive-phase durations less than 0.2 ms (Bowen, Fletcher and Richmond, 1968) or 0.4 ms for the CWVP criterion (Axelsson and Yelverton, 1996) has yet to be determined. Further research is required to develop criteria suitable for this loading regime.

4. Conclusions and recommendations

This study focussed on the explosive charge contained in an M26 hand grenade. However, pressure based injury criteria can be applied to many different explosive event scenarios. A few of these include:

- The development and testing of body armour for humanitarian de-mining purposes;
- Validation testing of armoured vehicles to assess the protection offered against landmines or improvised explosive devices;
- The development and testing of bomb suits.

In many of these scenarios, the injury mechanisms are complex and may arise from a combination of primary, secondary, tertiary and/or miscellaneous wounding mechanisms. Developing a detailed understanding of these injury mechanisms and their interactions during explosive events is essential in enabling improved protection concepts to be developed.

5. Acknowledgements

Duarte Goncalves is acknowledged for his contribution to researching hand grenade incidents that occurred near Mthatha over the last ten years. Professor Manfred Held provided valuable practical insight into the physics behind explosive event research and the relevance of certain parameters in predicting injuries. The NATO RTO HFM-148/RTG workgroup provided a forum at which to discuss injury criteria relevant in predicting injuries, including overpressure injuries, within protected vehicles.

References


