Fragmentation of tubes by ammonium nitrate based explosives

Hiroyuki Arai[*,**], Yuji Ogata[***], Yuji Wada[***], Woo-Jin Jung[***], Jun Nakamura[*], Atsumi Miyake[**], and Terushige Ogawa[**]

In order to procure a just evaluation of the damage and the effect of explosion phenomenon, it is necessary to evaluate the fragments created by the explosion. In this study, the fragmentation of steel and resin tubes by two ammonium nitrate-based explosives was examined. The fragment velocity of the water-gel explosive and ANFO were measured, and the fragment velocity was influenced by the size of fragments. The Gurney equation was adapted, and the energy related to the fragmentation of the resin tube was different from that of the steel tube. The fragments of tubes by ANFO were collected and adapted to the Held type distribution model. The Held model was a good adaptation for the distribution of fragments of not only steel but also resin tubes. The value of the constant B was influenced by the tube materials.

1. Introduction

A bombing incident or an accidental explosion may cause serious hazard to people and properties. Fragments are one of the major factors of the explosion hazards. In order to procure a just evaluation of the damage and the effect of these explosion phenomena, it is necessary to evaluate the fragments created by the explosion. The fragmentation of steel tubes was already reported[1], but the discussion about the fragmentation of resin tubes was not enough[2].

Ammonium nitrate (AN) based explosives have been widely used as commercial explosives, such as ammonium nitrate-fuel oil mixture (ANFO), water-gel explosives and so on.

In this study, the fragmentation of steel and resin tubes by the AN-based explosives was examined with measurements of velocities and distributions of the fragments.

Received : May 17, 2002
Accepted : July 13, 2002
*National Research Institute of Police Science, 6-3-1 Kashiwanoha, Kashiwa, Chiba 277-0882, JAPAN
TEL +81-4-7135-8001
FAX +81-4-7133-9169
e-mail arai@nrips.go.jp
**Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, JAPAN
TEL +81-45-339-3993
FAX +81-45-339-4011
***National Institute of Advanced Industrial Science and Technology, 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, JAPAN
TEL +81-298-61-8740
FAX +81-298-61-8708

2. Experimental

ANFO and a commercial low density water-gel explosive (Asahi Kasei Corp.) were used as the AN-based explosives. ANFO was prepared by blending prilled AN with No.2 diesel fuel oil with the weight ratio of 94:6. The average diameter of the AN was 1.1 mm and the oil absorption capacity was 11.6 wt%. ANFO was placed at room temperature for about 5 days before the test.

In all experiments, the AN-based explosives were confined in tubes made by steel (JIS G3452) and three kinds of resins; polymethylmethacrylate (PMMA), polyvinylchloride (JIS K6741, PVC) and polycarbonate (PC). The inner diameter of the tubes was about 40mm for ANFO and about 28mm for the water-gel explosive, and the length was 300mm. The tube was put on a steel plate with 9mm thickness. The loading density was 0.86 g·cm^{-3} for ANFO and 0.95 g·cm^{-3} for the water-gel explosive.

Table 1 Tube sizes used in experiment.

Explosive	Tube Material	Inner Diameter [mm]	Outer Diameter [mm]	Wall Thickness [mm]	Length [mm]	Weight [g]
Water-gel	Steel	27.2	34.0	3.4	300.9	763.6
	PMMA	28.0	34.0	3.0	300.5	106.8
	PVC	28.0	34.0	3.0	300.5	118.2
	PC	29.0	34.0	2.5	301.1	88.1
ANFO	Steel	35.7	42.7	3.5	300.8	909.7
	PMMA	40.0	48.0	4.0	300.5	199.5
	PVC	41.0	48.0	3.5	300.1	196.4
	PC	41.0	48.0	3.5	301.3	172.6

Table 2 Detonation and fragment velocities of water-gel explosive.

Tube Material	Loading Density [g·cm⁻³]	Detonation Velocity [km·s⁻¹]	Initial Fragment Velocity [km·s⁻¹]	c/m	Gurney Constant [km·s⁻¹]	Gurney Energy [kJ·g⁻¹]
Steel	0.98	4.31	0.98	0.223	2.18	2.37
PMMA	0.96	4.07	1.52	1.66	1.59	1.27
PVC	0.96	4.12	1.56	1.50	1.68	1.42
PC	0.95	4.15	1.56	2.15	1.53	1.17

As a booster, 30g of emulsion explosive (Nippon Kayaku Co., Ltd, loading density=1.2g·cm^{-3}, detonation velocity=5.8km·s^{-1}) were used and it was initiated with a No.6 electric detonator (Asahi Kasei Corp.). The experimental conditions are listed in Table 1.

The detonation velocity measurements were made using the optical fiber method. The ends of each optical fiber were mounted in drill holes at every 50 mm interval along the confining tube axes. In order to obtain the fragmentation characteristics, the velocity of flying fragment was measured with foil targets. Two foil targets were placed at about 1.0 m away from the test tube. An initial fragment velocity was calculated by the distance from the tube to the target and the time of the target signal.

With ANFO, deformation behaviors of resin tubes were observed with a framing high-speed camera (Cordin model-124). A xenon flash floodlight was used and the exposure time of camera was 2.5 μs. The fragments of tubes were recovered.

3. Results and discussion

3.1 Fragment velocity of water-gel explosive

The detonation velocities and the fragment velocities of the water-gel explosive are shown in Table 2. Even though the detonation velocities of the water-gel explosive were similar in steel and resin tubes, the fragment velocities of resin tubes were higher than that of the steel tube. Since some fragments of the steel tube by the water-gel explosive were in long strips, and all fragments of resin tubes were too small to be collected, the fragment velocity seemed to be influenced by the size or weight of fragments.

The terminal velocity of fragments was calculated by the Gurney method[3)4)]. The Gurney formula for the cylinder filled with explosives is follows:

$$V=\sqrt{2E_G}\sqrt{\frac{\frac{c}{m}}{\left(1+0.5\frac{c}{m}\right)}} \qquad (1)$$

where V is the fragment velocity, $\sqrt{2E_G}$ Gurney constant which depends on the characteristics of explosives, E_G Gurney energy, c the mass of the explosive and m the mass of the tube.

Gurney constants and Gurney energies of the water-gel explosive were calculated by Eq. (1) with the result value of fragment velocities and the mass of the explosives and the tubes, and are shown in Table 2.

The Gurney constant and the Gurney energy of the resin tubes were lower than that of the steel

Table 3 Detonation and fragment velocities of ANFO.

Tube Material	Loading Density [g·cm⁻³]	Detonation Velocity [km·s⁻¹]	Initial Fragment Velocity [km·s⁻¹]	c/m	Gurney Constant [km·s⁻¹]	Gurney Energy [kJ·g⁻¹]
Steel	0.86	2.85	1.01	0.284	2.01	2.03
PMMA	0.83	1.36	0.99	1.58	1.05	0.56
PVC	0.87	1.58	1.05	1.76	1.08	0.58
PC	0.87	1.24	1.05	2.01	1.04	0.54

tube, despite the detonation velocities being similar in steel and resin tubes. The energy related to the fragmentation of the resin tube was different from that of the steel tube.

3.2 Fragment velocity of ANFO

The detonation velocities, the fragment velocities, the Gurney constants and the Gurney energies of ANFO are shown in Table 3. The fragment velocities were similar in the resin and the steel tube, even though the detonation velocities of the resin tubes were lower than that of the steel tube.

The Gurney constant and the Gurney energies of ANFO were lower than that of the water-gel explosive in all tubes, and as a result, the fragment size by ANFO was larger than the water-gel explosive on each of the tubes.

3.3 Tube Fragments by ANFO

The High-speed photographs of detonation behavior of ANFO with PMMA, PVC and PC tubes are shown in Fig. 1, 2 and 3, respectively. From these photographs, different behaviors were observed in the deformation of each of the resin tubes on the detonation of ANFO. The PMMA tube fractured into many small pieces after the detonation front was passed through. PVC and PC

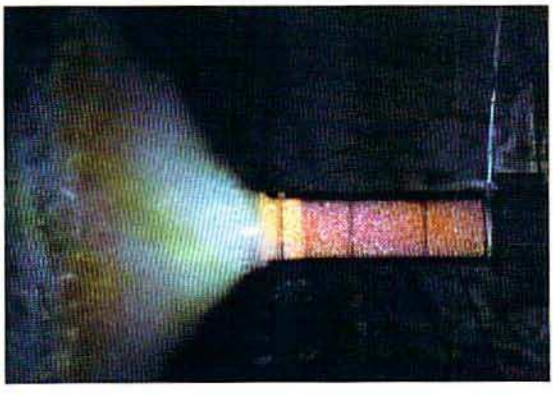

Fig.1 High-speed photographs of detonation behavior of ANFO with the PMMA tube.

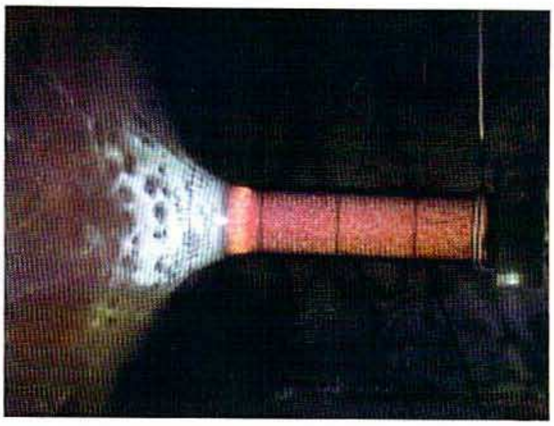

Fig.2 High-speed photographs of detonation behavior of ANFO with the PVC tube.

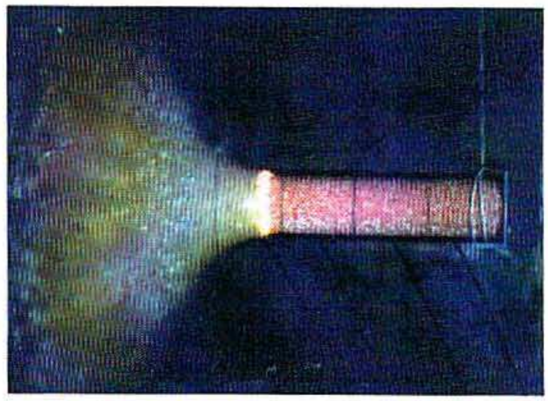

Fig.3 High-speed photographs of detonation behavior of ANFO with the PC tube.

tubes expanded behind the detonation front and then fractured into long strips.

Collected fragments of PMMA, PVC and PC tubes are shown in Fig. 4, 5 and 6, respectively. Shapes of the collected resin fragments showed their deformations, i.e., the PMMA fragments were only small pieces and many of the PVC and PC fragments were long strips.

Many fragments of the steel tube were also long strips which are shown in Fig. 7. The mass distributions of fragments of PMMA, PVC, PC and steel are shown in Fig. 8 to 11, respectively.

A model of fragments mass distribution was

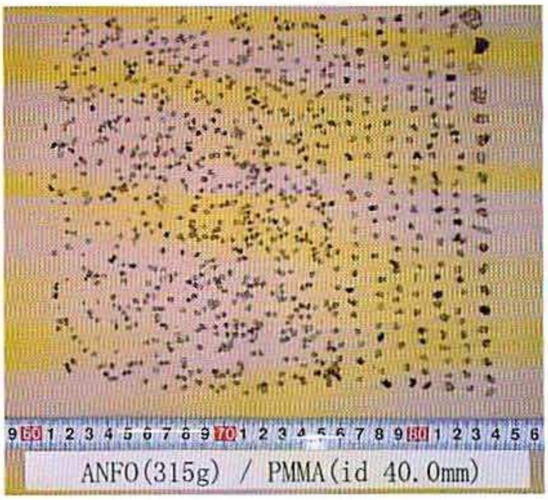

Fig.4 Collected fragments of the PMMA tube by the detonation of ANFO.

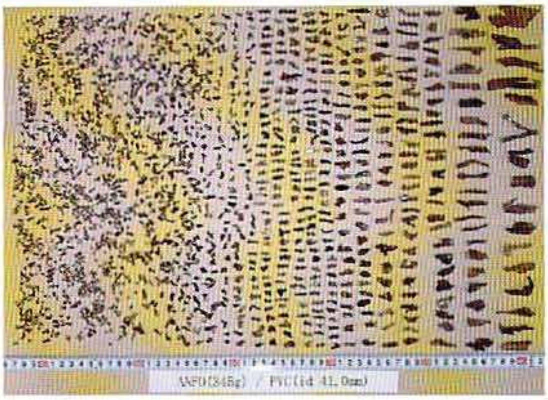

Fig.5 Collected fragments of the PVC tube by the detonation of ANFO.

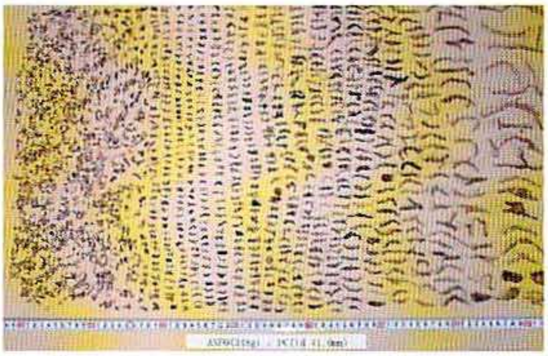

Fig.6 Collected fragments of the PC tube by the detonation of ANFO.

proposed by Held et al[5][6]. The Held type distribution model was given by:

$$M(n) = M_0\left[1 - \exp\left(-Bn^{\lambda}\right)\right] \tag{2}$$

where $M(n)$ is the cumulative fragment mass, M_0 the total mass of the tube, n the cumulative

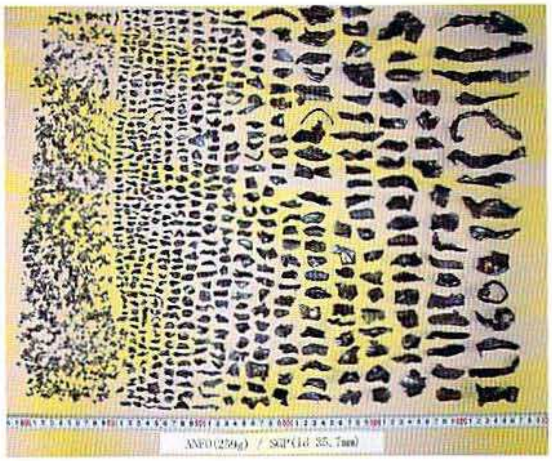

Fig.7 Collected fragments of the steel tube by the detonation of ANFO.

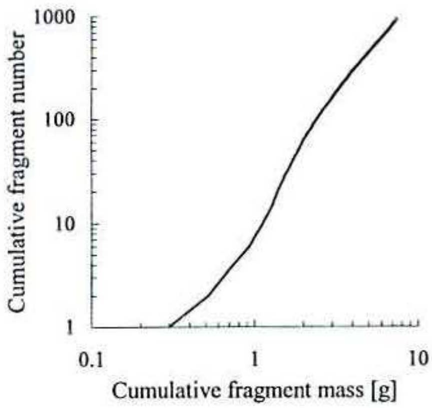

Fig.8 Fragment mass distribution of the PMMA tube detonated by ANFO.
(recovery of fragments was 3.7 wt%)

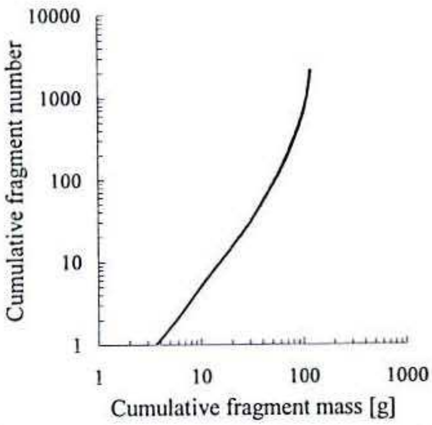

Fig.9 Fragment mass distribution of the PVC tube detonated by ANFO.
(recovery of fragments was 60.3 wt%)

fragment number and B and λ the constants.

Eq. (2) gives follow equation:

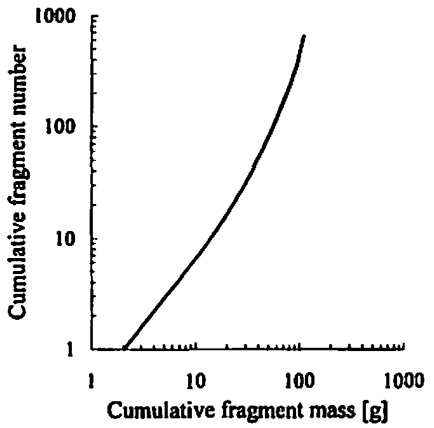

Fig.10 Fragment mass distribution of the PC tube detonated by ANFO.
(recovery of fragments was 67.0 wt%)

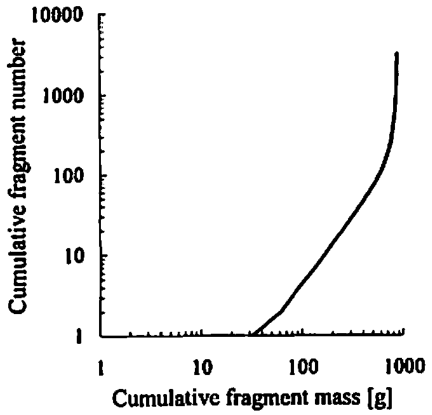

Fig.11 Fragment mass distribution of the steel tube detonated by ANFO.
(recovery of fragments was 95.3 wt%)

$$\log\left(-\ln\frac{M_0 - M(n)}{M_0}\right) = \lambda \log n + \log B \qquad (3)$$

The value of $-\ln[(M_0\text{-}M(n))/M_0]$ were plotted on a log-log graph as the cumulative number of collected fragments, and approximated by the linear relationship, then the value of the constant B and λ were calculated by Eq. (3). The plots about the fragments of resin and steel tubes by ANFO were shown in Fig. 12.

Since the fragments of all tubes with a cumulative number of up to 1000 were too small to be adequately approximated by the linear relationship, the value of B and λ were calculated with the fragment number from 1 to 1000 using the linear least square fits. The calculated values of the two constants are shown in Table 4.

The constant λ was similar in steel and resin

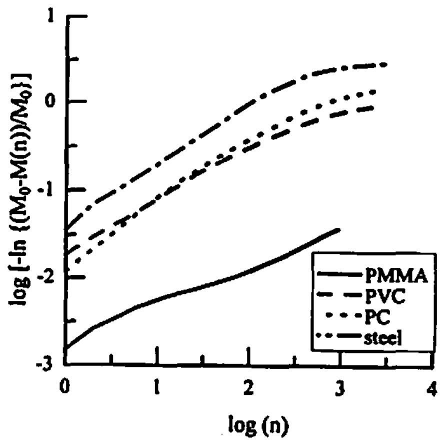

Fig.12 Fragment mass distribution log-log diagram for the Held equation detonated by ANFO.

Table 4 Held type distribution equation parameters calculated with the fragment number ranging from 1 to 1000.

	λ	B
Steel	0. 52	0. 086
PMMA	0. 47	0. 0015
PVC	0. 46	0. 036
PC	0. 55	0. 030

tubes and the constant B differed between tube materials.

Komatsu reported[7] that the constant B was expressed by the linear function of both the Charpy impact value of the shell body and the weight ratio of the explosive to the shell body with the test using PBX for the explosive and steel for the shell body.

In this study, even though the value of the constant B was expressed, not withstanding the two parameters of the resin tube, the constant B seemed to be influenced by the properties of the tube materials.

4. Conclusions

The Fragment velocity of steel and resin tubes by the water-gel explosive and ANFO were measured. The fragment velocity was influenced by the size of fragments.

The Gurney equation was adapted, and the energy related to the fragmentation of the resin tube was different from that of the steel tube.

The fragments of tubes by ANFO were collected, and adapted to the Held type distribution model. The Held model adapted well for the distribution of fragments of not only steel but also resin tubes. The value of the constant B was influenced by the tube materials.

References

1) J. Nakamura, Research on Disasters, 32, 226 (2001)
2) K. Nagayama, M. Fujita and K. Kiyota, Kogyo Kayaku Kyokaishi, 40, 300 (1979)
3) S. M. Kaye, "Encyclopedia of explosives and related items", Vol.10, pp. V60-V94 (1983) Picatinny Arsenal
4) J. A. Zukas and W. P. Walters, "Explosive Effects and Applications", pp. 221-249 (1998)
5) M. Held and P. Kuhl, Propellants and Explosives, 1, 20 (1976)
6) M. Held, Propellants, Explosives, Pyrotechnics, 15, 254 (1990)
7) M. Komatsu, Tech. Rep. Tech. Res. Dev. Inst. Jpn. Def. Agency (1990)