Hindawi
Shock and Vibration
Volume 2023, Article ID 9915373, 11 pages
https://doi.org/10.1155/2023/9915373

Research Article

Influence of Initiation Modes in the Bundle-Series Initiation of a Large Number of Shock Tubes by Detonators

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Received 10 March 2023; Revised 15 May 2023; Accepted 30 May 2023; Published 20 June 2023

Academic Editor: S. Mahdi S. Kolbadi

The bundle-series initiation is currently used as the method for simultaneously transmitting blast signals from a detonator to a large number of shock tubes for blasting using shock tubes and its initiation modes affect the ability and probability of signal transmission. A numerical study of the influence of initiation modes on the pressure impulse generated by detonators and transmitted to a large number of shock tubes has been undertaken with ANSYS AUTODYN code and validated through experimental results of signal transmission probability of shock tubes. Numerical simulations and experiments used lateral and frontal bundle-series initiation modes for a large number of shock tubes. For a bundle of many shock tubes, peak pressures of pressure impulses affected within all shock tubes beside the first layer around a detonator, and signal transmission probabilities were higher for frontal bundle-series initiation mode than for lateral bundle-series initiation mode. The magnitude of a numerically obtained pressure impulse to a bundle of shock tubes shows a good correlation with the experimentally obtained signal transmission probability of shock tubes. Finally, the results are employed in the application of a frontal bundle-series initiation mode with the simultaneous bundle-series initiating a large number of shock tubes for blastings in mining and construction.

1. Introduction

Concern about the versatility and reliability of blasting systems has been the focus of mining and large-scale demolition blasting for decades. Current blasting practices widely employ shock tubes (also known as signal transmission lines or nonelectrical tubes, i.e., NONEL tubes) as a nonelectrical means of transmitting blast signals to target detonators for initiating explosive columns in a precise and reliable manner. Nonelectric blasting systems typically comprise a series of shock tubes or signal transmission lines positioned in contact with a donor detonator [1, 2]. Transmission lines, or shock tubes as they are more commonly known, generally consist of a hollow tube housing a gas, and having an inner lining comprising a reactive material. The reactive material typically comprises aluminum powder and HMX or RDX explosive powder. These shock tubes are used to conduct an initiation impulse to the target detonators at remote locations within a blasting arrangement. The shock tube is initiated and detonates pressing adiabatically the mixture of explosive material and air due to a pressure impulse generated by the electric spark of the electrode laid in the shock tube, detonation wave of the shock tube, detonation of detonator, etc. [3–7]. Upon initiation, the pressure of an incoming impulse causes the wall of the shock tube to collapse, pressurizing and subsequently heating the gas within the tube and initiating the reactive lining. The performance of OEA Aerospace Inc. product, for example, was 20 ± 10 mg/g of explosive loading density, 1 750 m/s of propagation speed, 27.58 MPa (4 000 psi) of peak pressure, and 25 μs of pressure pise time.

Safety and reliability are paramount for any blasting system, and efficient shock tube initiation is an important factor in this regard [8–11]. Initiation failure of the shock tube results in unexploded charges at the blast site, with inevitable safety concerns. Moreover, the reliable initiation of shock tubes ensures that the required blasting pattern is affected. Reliable initiation of shock tubes requires sufficient energy to be transferred from the charge of a detonator to the shock tubes, thereby compressing the shock tubes extremely rapidly to initiate them.

There are several modes for initiating a large number of shock tubes according to the arrangement of the detonator and a large number of shock tubes. Current blasting practices widely employ the lateral bundle-series initiation mode that each shock tube is positioned adjacent to the explosive section of a detonator in a parallel [7, 12, 13] or an orthogonal direction [14–17] to the axis of a detonator body. However, this method has the insufficient ability to initiate shock tubes due to the small charge of a detonator, and initiation failures often appear in the case of a large number of shock tubes within connector blocks. For building demolition and tunneling blasting, over 50 even 100 lines of the shock tubes must simultaneously initiate by a detonator. In addition, initiation failures often occur in the case of a large number of shock tubes. Therefore, for the shock tube, the blasting system must have not only the high ability of the blast signal transmission (or initiation) but also the high reliability of the signal transmission on shock tubes. The methods of the bundle-series initiating a large number of shock tubes are subject to possible failure modes that the ability and the reliability of signal transmission on each shock tube can be strongly affected by the coupling mode of a detonator and a large number of shock tubes.

A research program has recently been started by the authors with the goal of reliable initiation mode and a new connecting device for the simultaneous bundle-series initiating a large number of shock tubes with detonator.

For the past few decades, studies on bundle-series initiating a large number of shock tubes by detonators have been constantly published. However, all the researches have focused on the experimental study of lateral bundle-series initiating mode of shock tubes by a detonator. Hu and Han [7], and Li and Xu [13] studied an initiating ability of a detonator to the bundle of shock tubes extended with several layers on the side of the detonator, and Xu [12] presented the number of the shock tubes that could be initiated by a detonator in consideration of the initiation reliability. Several authors such as Li and Xu [13], and Scheid et al. [18] have suggested the connector block, in which a plurality of shock tubes are extended on the side of the detonator therein. Some researchers studied connector blocks where a large number of shock tubes are positioned adjacent to the explosive section of a detonator at an orthogonal direction to the axis of a detonator body to receive a pressure impulse upon detonation [15–17]. It is necessary a large number of shock tubes to experimentally determine the signal transmission probability of a large number of shock tubes. An increasing the number of shock tubes coupled with detonator leads to an increase in the number of shock tubes consumed in experiments. Therefore, understanding the structural energy transmission mechanisms according to initiation modes is very important in an estimate of signal transmission probability of a large number of shock tubes. Detailed information such as the pressure and impulse is required to predict the energy transmission to shock tubes. Furthermore, an increasing amount of energy leads to higher pressures and a greater specific impulse. The pressure, impulse, and duration are also available according to the traveled mediums.

Studies of modeling the blast loading from a detonator to a large number of shock tubes are difficult to find. In general, numerous attempts with varying degrees of success have been made to model the response of simple structures such as varying shapes (circle and rectangular shock tubes) of shock tubes [11] and plates [19, 20], and varying types of clamped structures [8] subjected to either a uniform or local blast and impact loads using finite element models. Bonorchis and Nurick [19] used the ABAQUS model in conjunction with spatial and temporal pressure impulse profiles resulting in the detonation of explosives from AUTODYN simulations to simulate the structural response of the target subjected to blast loads. Figuli et al. [21] proceeded with a numerical analysis of the blast wave propagation due to various explosive charges. AUTODYN has not only preprocessor, postprocessor, and analysis systems but also fast computation speed. AUTODYN is an explicit analysis tool for modeling nonlinear dynamics of solids, fluids, gas, and their interaction and has enough material library and multiprocessing environment to solve variety-engineering problems.

The focus of the studies reported thus far has been on the experimental study of the bundle-series lateral initiating a large number of shock tubes by a detonator and on response simulation of simple structures such as shock tubes subjected to blast or impact loads using finite element models. To the best of our knowledge, there are no results in the literature regarding the experiments and numerical simulation to predict or estimate the dynamic blast load and the initiating probability according to the coupling structure of a detonator with many shock tubes.

The aim of the present work is to find the structural influence of initiation modes on the pressure impulse generated by a detonator and transmitted to the bundle of a large number of shock tubes and the signal transmission probability and to prove an advantage of frontal bundle-series initiating mode over lateral bundle-series initiating mode.

This paper presents the results of a numerical and an experimental investigation into the initiation modes of the pressure impulse generated by a detonator and transmitted to the bundle of a large number of shock tubes and the signal transmission probability. Numerical simulations and experiments used two initiation modes for bundle-series initiating a large number of shock tubes: one was a lateral bundle-series initiation mode that each shock tube surrounds a detonator while extending parallel to the axis of a detonator body, and the other was a frontal bundle-series initiation mode that inlets of shock tubes are aligned at certain distances from the firing end of the detonator.

Pressure impulses according to the initiation mode on the bundle of a large number of shock tubes were predicted through the numerical simulation method. AUTODYN in finite element software ANSYS 18.1 has been used to numerically simulate a pressure impulse. The pressure impulses within shock tubes in a bundle were compared for conventional lateral bundle-series initiation mode and new frontal bundle-series initiation mode. The influences of the bundle-series initiation mode with a large number of shock tubes to the signal transmission mode were also investigated for simultaneously initiating a large number of shock tubes. The correlation with results of the numerically obtained intensity of a pressure impulse within the shock tubes was discussed.

2. Numerical Simulations of a Pressure Impulse Transmitted to a Bundle of Shock Tubes

2.1. Numerical Model Development. In this paper, the influence of the initiation modes on the pressure impulse generated by a detonator and transmitted to the bundle of a large number of shock tubes is numerically modelled. It should be noted that researching only a pressure or a pressure impulse from the simulation could enough estimate the energy transmission effects because the initiation of shock tubes relative to adiabatic compression by the loading affected the inner space of shock tubes. Commercially available AUTODYN software in ANSYS 18.1 was used to numerically simulate a pressure impulse generated by a detonator and transmitted to a bundle of a large number of shock tubes. The distribution of pressure peaks of pressure impulses transmitted from a detonator to shock tubes being at different distances from the center of the bundle of shock tubes was numerically simulated and compared for frontal and lateral bundle-series initiation by a detonator, respectively. The focusing flow in the firing end of a detonator, deformation, and damage to the shock tubes and initiating mechanism were not considered in the simulation.

The model consists of three parts, that is, the air domain, a bundle of a large number of shock tubes, and the blast source as shown in Figure 1. In a bundle, shock tubes are in layers from the center to the outside. The surrounding atmospheric (air) domain was modelled using solid elements whilst the tubular shock tubes were modelled using shell elements. Explosive was modelled using an Eulerian mesh, and the interaction between the air domain and Lagrangian bodies was produced by the default model. The model consists of 2 400 solid elements and 7 500 shell elements.

The mesh size significantly influences the reliability of analysis results and computational time. The mesh density of the air domain near the model was increased to capture pressure changes within shock tubes. Based on our practical experience and previous reference [21], the mesh size sets to 1 mm near the center, while it was increased to 3 mm near the boundaries. In order to capture pressure change within shock tubes at the mid-span, the mesh size of shock tubes was set to 1 mm.

2.1.1. Material Parameters for Polyethylene. The materials of shock tubes and connector blocks are polyethylene (Table 1).

The external and inner diameters of shock tubes are 3 mm and 1.5 mm, respectively. Gauges were in the inner space of a shock tube in every layer, respectively. For frontal bundle-series initiation mode, gauges were in inner space and 1 mm away from the entrance of shock tubes. The number of shock tubes and gauges schematic in every layer of a large number of shock tubes for lateral and frontal bundle-series initiation is listed in Table 2.

The origin of the coordinate axes illustrated in Figure 1(b) is the start point of the firing end of a detonator. The entrance of a bundle of shock tubes within the connector block is a certain distance away from the edge of the firing end of the detonator in the Z direction, and its distance is defined as standoff distance. The initiating time of the first end of the detonator charge was defined as the start time of a pressure impulse generated by a detonator and transmitted to a bundle of shock tubes.

2.1.2. Properties of Air and Explosive Material. The ambient air was modelled with the polynomial equation of state as written in the following equation:

$$P_1 = (\gamma - 1)\frac{\rho}{\rho_0}E, \tag{1}$$

where E is the internal energy, and ρ_0 and ρ are current and reference state densities, respectively. Material parameters C_1–C_5 were defined in Ngo et al. [22] and $\gamma - 1 = C_4 = C_5$ (Table 3).

The propagation characteristics of blast waves affect a sort of explosive and the type, mass, and density of explosive charge [21]. In this study, the numerical investigation was focused on the comparison of the influence of the initiation modes on the pressure impulse generated by the same detonators and transmitted to the bundle of a large number of shock tubes. To this aim, accordingly, it was selected type and mass of explosive charge and sort of explosive. The type of explosive charge is the column, and the mass is 1.5 g of HMX in #8 detonator. The initial explosive (lead nitride) charged in the detonator was disregarded in the simulation since mass and power are smaller than the main charge (HMX).

The explosives were modelled with the Jones–Wilkins–Lee (JWL) equation of state as follows:

$$P_1 = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega}{V}E, \tag{2}$$

where P_1 is the pressure, and $V = \rho_e/\rho$ is defined as the ratio between the density of the explosives and the density of the detonation product. A, B, R_1, R_2, and ω are parameters defined in [22, 23]. The parameters used in the simulation are listed in Table 4.

Selection of the correct detonation velocity and Chapman–Jouget pressure in numerical simulations is important in order to replicate the detonation in the experiments. The detonation was initialised with the initial detonation point set at the center of the dtor block. As the simulation of the Arbitrary Lagrangian–Eulerian (ALE) model is computationally expensive, the boundaries of the surrounding air

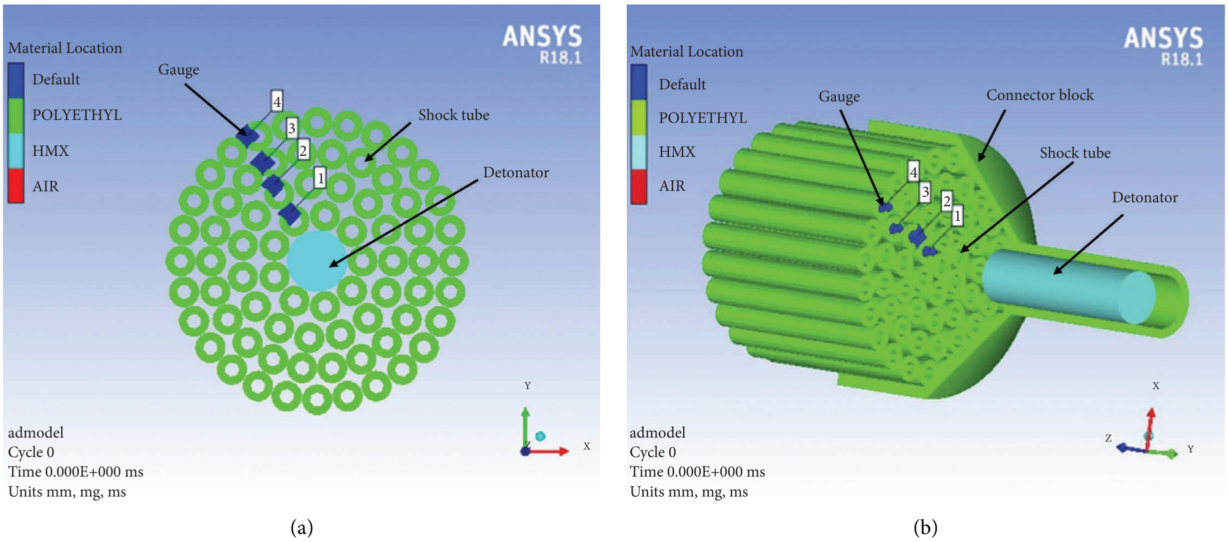

Figure 1: Gauges schematic in the numerical model: (a) lateral bundle-series initiation mode and (b) frontal bundle-series initiation mode.

Table 1: Material parameters for polyethylene.

Parameters	Unit	Value
Equation of state	—	Linear
Density	g/cm^3	0.915
Bulk modulus	kPa	2×10^6
Temperature	K	2.93×10^2
Specific heat	J/kgK	0
Thermal conductivity	W/(m·K)	0
Shear modulus	kPa	5×10^3
Principal tensile failure stress	kPa	3.45×10^4
Maximum principal stress difference/2	kPa	1.01×10^{20}

Table 2: The number of shock tubes and gauges schematic in every layer of a bundle of shock tubes.

Layer	Lateral bundle-series initiation			Frontal bundle-series initiation		
	The number of shock tubes in layer	Accumulated number of shock tubes	Gauge	The number of shock tubes in layer	Accumulated number of shock tubes	Gauge
1	9	9	Gauge 1	6	6	Gauge 1
2	15	24	Gauge 2	12	19	Gauge 2
3	22	46	Gauge 3	18	37	Gauge 3
4	28	74	Gauge 4	26	63	Gauge 4

Table 3: Material and equation of state parameters for air.

Parameter	Value
Density, ρ_0	1.293 kg/m^3
Pressure cut-off, P_c	0
Dynamic viscosity coefficient	0
C_0–C_3	0
C_4	0.40
C_5	0.45
C_6	0
Initial energy, E_0	2.50×10^5
Initial velocity, V_0	1.0

Table 4: The parameters of the Jones–Wilkins–Lee (JWL) equation of state for explosive.

Parameters	Value
Density	1.891 kg/m^3
Chapman–Jouget pressure, P_{cj}	18 GPa
Parameter A	$7.78280E+08$ kPa
Parameter B	$7.07140E+06$ kPa
Parameter R_1	4.2
Parameter R_2	1.0
Parameter W	0.3
E	7×10^9
V	1.0

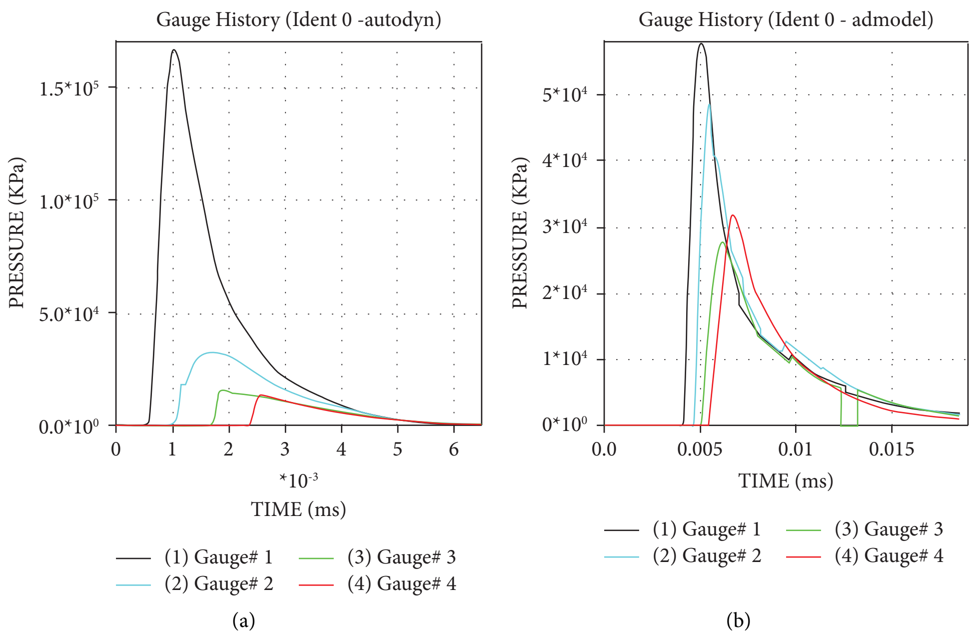

Figure 2: The pressure impulse at different distances from the center of a bundle of shock tubes: (a) lateral bundle-series initiation and (b) frontal bundle-series initiation.

domain cannot be extended too far beyond the outer lines of the subject's geometries. This can cause a reflection of pressure waves at the boundaries of the air domain. To overcome this issue, the boundaries of all surfaces of the air domain were set to *Flow Out*. As the ALE method is computationally expensive, it was set the *Time limit* with 0.05 and *Energy Fraction* with 0.1 to achieve accurate results within a reasonable time period.

2.2. Simulation Results. For bundle-series initiation of a large number of shock tubes by detonator with no having a connector block, the pressure histories obtained from the simulations in the selected control points (i.e., within the shock tube on every layer in a bundle of shock tubes) are proposed in Figure 2. Figure 2(a) shows the pressure impulses transmitted to a bundle of shock tubes placed at a varying distance away from the firing end of the detonator for lateral bundle-series initiation of a large number of shock tubes with no connector block. Figure 2(b) shows the pressure impulses transmitted to a bundle of shock tubes for frontal bundle-series initiation with no a bundle.

Pressure peaks within shock tubes were compared for the lateral and the frontal bundle-series initiation mode. For lateral bundle-series initiation, as shown in Figure 2(a), pressure peaks of pressure impulses were 162.150 MPa, 30.434 MPa, 14.427 MPa, 11.501 MPa, respectively, in measure points within shock tubes surrounding a detonator and thus decrease rapidly from the second gauge. For frontal bundle-series initiation, as shown in Figure 2(b), the peak pressures of a pressure impulse measured at gauge are 61.465 MPa, 50.214 MPa, 31.362 Pa, 20.188 MPa, respectively, and thus, the pressure values of gauge 2, 3, 4 are bigger than lateral bundle-series initiation, and the pressure differences with gauge positions are less than lateral bundle-series initiation.

Simulation results are shown that for frontal bundle-series initiation mode, a bigger pressure impulse affects more shock tubes than for lateral bundle-series initiation mode.

3. Transmission Efficiency Experiments

3.1. Preparations and Method of Experiments. The specimens comprise a large number of shock tubes made of high-pressure polyethylene plastic. The shape of shock tubes is circular tubes with an outer diameter of 3 mm and an inner diameter of 1.5 mm. The inner portion of the tube is coated with a thin layer of explosive mixture, about 20 mg/m, which is HMX (75% by weight) and aluminium (25% by weight). Shock tubes tested were made with a length of 50 cm. Shock tubes are initiated by #8 detonator; the total mass of HMX and lead nitride is 1.5 g, the loaded length is 20 mm, and the outer diameter and length of the detonator are 7.5 mm and 50 mm, respectively.

The shock tubes were tested in coupling with a detonator. The combination of a large number of shock tubes and a detonator uses the two coupling modes, shown in Figures 3 and 4. The coupling modes, shown in Figures 3 and 4, are a lateral and frontal bundle-series initiating mode by a detonator, respectively. In transmission probability experiments, a detonator and a large number of shock tubes were coupled by using the paper or a piece of short shock tube. For lateral bundle-series initiation mode, each shock tube was surrounded by a detonator coupled with a fuse, while extending parallel to the axis of a detonator body, wrapped a coupled part up in paper, and binded by a piece of shock tube. For frontal bundle-series initiation mode,

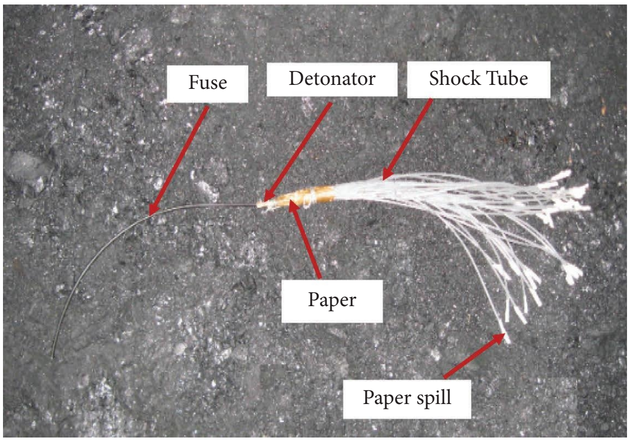

Figure 3: Lateral bundle-series initiation mode.

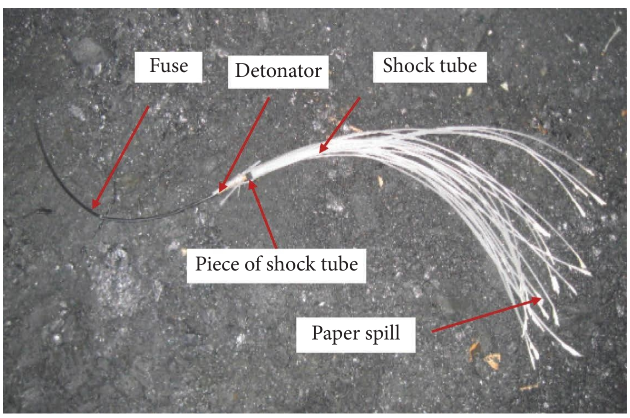

Figure 4: Frontal bundle-series initiation mode.

a detonator and shock tubes were coupled so that the entrance of a bundle of shock tubes is 10 mm distance away from the edge of the firing end of detonator in the same axis.

The experimental procedure used in this investigation was similar to the previous investigation [7]. The signal transmission probability according to the bundle-series initiation modes was determined by investigation of transmission or transmission failure of the specimens including a variable number of shock tubes in a state where the connector blocks are not in existence. The shock tubes extended on the lateral and frontal sides of the firing end of the detonator, respectively, while extending parallel to the axis of a detonator body, and determined the signal transmission probability of a large number of shock tubes by investigating the transmission or transmission failure.

The experiment was performed, changing the number of these shock tubes variously. The investigation, though the reliability of experiments is a few lower, limited the number of shock tubes in a bundle under 50 lines and the experiment number for the same bundles at five times because shock tubes are consumed much in experiments.

3.2. Experimental Results. The entrance shape of a bundle of shock tubes affected by a detonator for frontal bundle-series initiation is as Figure 5. The entrance of a bundle of shock tubes was burned and melted, and some were torn under the strong impulse load of a detonator. Especially, the lateral bundle-series initiation observed the damage of shock tubes positioned in contact with a firing end of a detonator, but the frontal bundle-series initiation was observed in the center and boundary of a cross section of the entrance of a bundle of shock tubes. The transmission or transmission failure of a large number of shock tubes was decided by investigating whether a tap of paper plugged an entrance of the shock tube before the experiment come out or failed by the blast wave propagated along shock tubes after initiating a detonator as shown in Figures 3 and 4.

After initiating #8, detonator investigates the number of signal-transferred shock tubes. Experimental results are as Tables 5 and 6 for frontal and lateral bundle-series initiation.

The signal transmission probabilities for lateral and frontal bundle-series initiation were compared. From Tables 5 and 6, the number of signal transferred to shock tubes according to the number of shock tubes in the bundle is shown in Figure 6.

For lateral and frontal bundle-series initiation, the number of signal transmission failures differs according to the number of shock tubes in the bundle, as shown in Figure 6.

4. Discussion

We compared the pressure peaks within the shock tubes for the lateral and the frontal bundle-series initiation modes.

Shock tube can be initiated by a detonator output or a spark and pressure peak of detonation within the tube is 27.58 MPa (see Ref. [2]). It shows that in order to initiate shock tubes by detonator, it is necessary that pressure peaks within shock tubes are 27.58 MPa and over. For lateral bundle-series initiation, as shown in Figure 2(a), pressure peaks of pressure impulses were 162.150 MPa, 30.434 MPa, 14.427 MPa, 11.501 MPa, respectively, in measure points within shock tubes surrounding a detonator, and thus, the peak dynamic pressures at the third and fourth gauges are lower than 27.58 MPa. For frontal bundle-series initiation, as shown in Figure 2(b), the peak pressures of a pressure impulse measured at gauge are 61.465 MPa, 50.214 MPa, 31.362 Pa, 20.188 MPa, respectively, and thus, the peak dynamic pressures at the first, second, and third gauge are bigger than 27.58 MPa.

From the data in Table 2 and the results of modeling, the number of layers in bundle that can be all shock tubes initiated by a detonator output is approximately estimated at two for lateral bundle-series initiation and three for frontal bundle-series initiation. Thus, the number of shock tubes in bundle that all shock tubes can be initiated by a detonator output is approximately estimated at 24 lines for lateral bundle-series initiation and at 37 lines for frontal bundle-series initiation.

For frontal bundle-series initiation, the stronger pressure impulses as compared with lateral bundle-series initiation are affected besides the first layer around a detonator, because the maximum pressures within shock tubes are bigger. For lateral bundle-series initiation, the more layers of shock

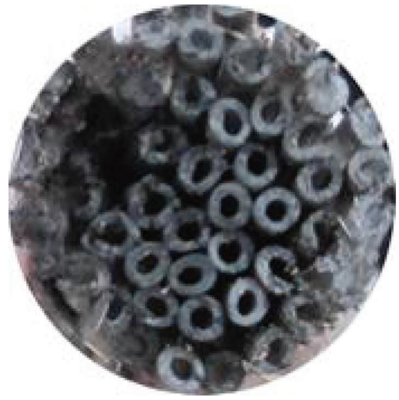

Figure 5: The entrance shape of the shock tubes after the experiment.

Table 5: Experimental results for lateral bundle-series initiation.

Specimen	Number of shock tubes in the bundle	Number of initiated shock tubes	Number of uninitiated shock tubes
Lateral 15-1	15	15	0
Lateral 15-2	15	15	0
Lateral 15-3	15	15	0
Lateral 15-4	15	15	0
Lateral 15-5	15	15	0
Lateral 20-1	20	20	0
Lateral 20-2	20	20	0
Lateral 20-3	20	20	0
Lateral 20-4	20	20	0
Lateral 20-5	20	20	0
Lateral 25-1	25	25	0
Lateral 25-2	25	25	0
Lateral 25-3	25	25	0
Lateral 25-4	25	25	0
Lateral 25-5	25	25	0
Lateral 30-1	30	30	0
Lateral 30-2	30	29	0
Lateral 30-3	30	30	0
Lateral 30-4	30	28	0
Lateral 30-5	30	29	0
Lateral 35-1	35	32	0
Lateral 35-2	35	34	0
Lateral 35-3	35	30	0
Lateral 35-4	35	31	0
Lateral 35-5	35	31	0
Lateral 40-1	40	33	0
Lateral 40-2	40	33	0
Lateral 40-3	40	32	1
Lateral 40-4	40	36	0
Lateral 40-5	40	32	0
Lateral 45-1	45	36	0
Lateral 45-2	45	31	1
Lateral 45-3	45	34	0
Lateral 45-4	45	37	1
Lateral 45-5	45	38	2
Lateral 50-1	50	36	3
Lateral 50-2	50	40	2
Lateral 50-3	50	33	0
Lateral 50-4	50	38	2
Lateral 50-5	50	34	6

Table 6: Experimental results for frontal bundle-series initiation.

Specimen	Number of shock tubes in the bundle	Number of initiated shock tubes	Number of uninitiated shock tubes
Frontal 15-1	15	15	0
Frontal 15-2	15	15	0
Frontal 15-3	15	15	0
Frontal 15-4	15	15	0
Frontal 15-5	15	15	0
Frontal 20-1	20	20	0
Frontal 20-2	20	20	0
Frontal 20-3	20	20	0
Frontal 20-4	20	20	0
Frontal 20-5	20	20	0
Frontal 25-1	25	25	0
Frontal 25-2	25	25	0
Frontal 25-3	25	25	0
Frontal 25-4	25	25	0
Frontal 25-5	25	25	0
Frontal 30-1	30	30	0
Frontal 30-2	30	30	0
Frontal 30-3	30	30	0
Frontal 30-4	30	30	0
Frontal 30-5	30	30	0
Frontal 35-1	35	35	0
Frontal 35-2	35	35	0
Frontal 35-3	35	35	0
Frontal 35-4	35	35	0
Frontal 35-5	35	35	0
Frontal 40-1	40	40	0
Frontal 40-2	40	40	0
Frontal 40-3	40	39	1
Frontal 40-4	40	40	0
Frontal 40-5	40	40	0
Frontal 45-1	45	45	0
Frontal 45-2	45	44	1
Frontal 45-3	45	45	0
Frontal 45-4	45	44	1
Frontal 45-5	45	43	2
Frontal 50-1	50	47	3
Frontal 50-2	50	47	2
Frontal 50-3	50	50	0
Frontal 50-4	50	48	2
Frontal 50-5	50	44	6

tubes far away from a detonator, the more action due to the explosion of detonator on shock tubes decreases rapidly because the shock tubes extended around a detonator have the function of energy absorbent in structural features and material properties. So we can predict that a detonator cannot initiate reliably a large number of the shock tubes for lateral bundle-series initiation.

For lateral bundle-series initiation, a pressure impulse of a detonator decreases rapidly in the process of passing through the plastic material walls of a dense bundle of shock tubes. But, for the frontal bundle-series initiation, a pressure impulse of a detonator decreases only with the propagation in standoff space and is transmitted the energy directly to explosive material of the inside of shock tubes and initiates. Therefore, we can predict that the number of shock tubes initiated reliably limits for lateral bundle-series initiation, but the frontal bundle-series initiation has very more shock tubes than that for the lateral bundle-series initiation.

The signal transmission probabilities for lateral and frontal bundle-series initiation were compared. The signal transmission probability according to the number of shock tubes is as shown in Figure 7.

For lateral bundle-series initiation, signal transmission failures were appeared, while the number of shock tubes was over 25 lines. Moreover, signal transmission failures were increased with increasing the number of shock tubes in bundle. For frontal bundle-series initiation, bundles of shock tubes to 35 lines initiated completely by a detonator, but signal transmission failures appeared in case of more than 20 lines. A definitive improvement in the signal transmission probability of shock tubes was recorded by frontal bundle-series initiation.

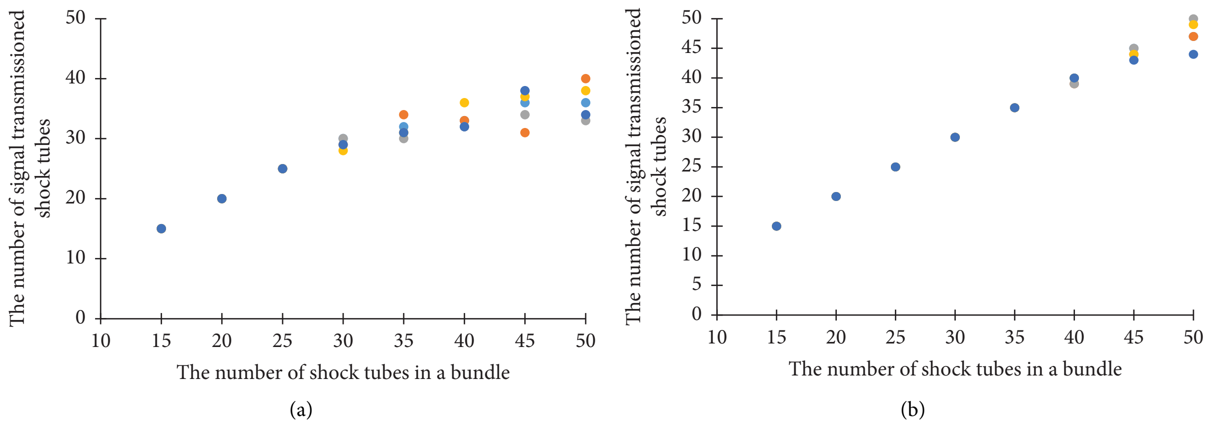

FIGURE 6: The number of initiated shock tubes according to the number of shock tubes in a bundle: (a) lateral bundle-series initiation and (b) frontal bundle-series initiation.

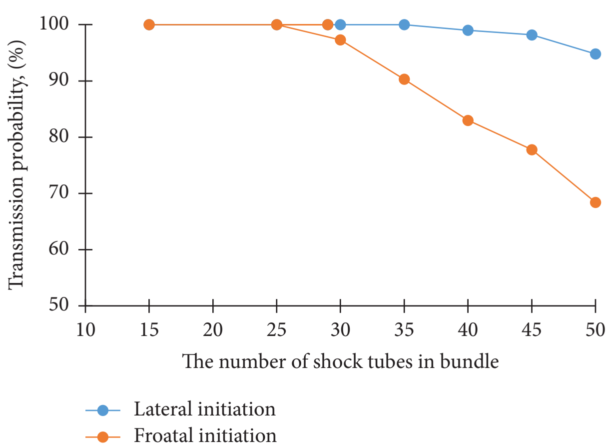

FIGURE 7: The relationship between the number of shock tube in bundle and the signal transmission probability.

Experimental result shows that the frontal bundle-series initiation mode has more signal transmission ability and can initiate a number of shock tubes than the lateral bundle-series initiation mode.

The numerically obtained pressure impulse to a bundle of shock tubes shows a good correlation with the experimentally obtained signal transmission probability of a bundle of shock tubes (Tables 5 and 6) for a variety of bundle-series initiation mode of a large number of shock tubes. Some difference in results in numerical simulations and experiments is caused by the accuracy of a disposition or coupling of some shock tubes and a detonator.

The results of numerical simulation and experiments show that the frontal bundle-series initiation mode is more effective than the lateral bundle-series initiation mode. The energy source for propagating the detonation wave within the shock tube is the explosive exothermic reaction of the explosive mixture (HMX + Al) coated on the inner wall of the shock tube [3]. For lateral bundle-series initiation mode, a pressure impulse generated on the outer side of a detonator makes up the shock tubes extended surround a detonator to have plastic deformation and to affect a thin layer of explosive material coating deposited on the inner wall of the shock tubes and disperse into inner space. Next, the mixture of explosive material and the air within shock tubes are compressed adiabatically and initiated by an explosion wave. So explosive energy acting on the shock tube is consumed much to deform the shock tube (plastic material), and therefore, small energy transmits to lead up to an explosive reaction, and the signal transmission probability is lowered. For a large number of shock tubes in bundle, it is necessary to extend a large number of shock tubes in layers surrounding a detonator. The more away the shock tubes are from a detonator, the more relatively smaller energy acts on the shock tubes due to the rapid energy decrease in the propagation of wave, thus do not may be initiated.

In frontal bundle-series initiation, focusing flow forms in front of the firing end of a detonator and follows that explosion shock wave decreases during propagation and goes into the inner space of the shock tube. This propagates within the shock tube and initiates directly the explosive mixture adhered to the inner side of the shock tube. So the shock tubes extended in the center of bundle can be initiated under a strong pressure impulse. However, for a large number of shock tubes, the shock tubes extended within the boundary of bundle can be failed in signal transmission.

5. Conclusions

This paper presents the results of the numerical and experiments study into the explosive signal transmission of bundle-series initiation structures using the lateral and frontal bundle-series initiation mode for a large number of shock tubes. Pressure impulses according to the signal transmission modes to a bundle of shock tubes were predicted through the numerical simulation method. AUTODYN in commercially available finite element software ANSYS 18.1 has been used to numerically simulate a pressure impulse.

In comparison with the lateral bundle-series initiation mode, this new frontal bundle-series initiation mode has a much higher transmission ability of a pressure impulse, which is a great potential for a connector block with high signal transmission ability in blast-using shock tubes.

The influences of initiation modes were also investigated. Experiments show that the frontal bundle-series initiation mode has the most dominant explosion shock action and the signal transmission probability than the lateral bundle-series initiation.

The numerically obtained pressure impulse to a bundle of shock tubes shows a good correlation with the experimentally obtained signal transmission probability of a bundle of shock tubes for a variety of bundle-series initiation mode of a bundle of shock tubes.

We have found significant evidence of the initiating reliably many shock tubes using the frontal bundle-series initiation mode.

Finally, the results can be employed for a pressure impulse and design of connector blocks for the simultaneously bundle-series initiating a large number of shock tubes. However, it remains to be clarified whether our findings could be applied to the response of tube bundle to blast loads. Further studies may be needed to determine the effects of blast loads of a detonator on a bundle of shock tubes according to its duration.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The research was carried out as part of academic and educational research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the National Science and Technical Development Foundation of DPR Korea (Grant No. 24-20200125). Also, the authors are grateful to our colleagues for their help to make good study results and thank Prof. Il Yong Kang in Kim Chaek University of Technology who helped to improve the quality of our paper.

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