Comparison of blast load results from SHIELD tests with independent numerical simulations

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COMPARISON OF BLAST LOAD RESULTS FROM SHIELD TESTS WITH INDEPENDENT NUMERICAL SIMULATIONS

Morgan Johansson
Adjunct Professor, Norconsult AB / Chalmers University of Technology,
Theres Svenssons gata 11, SE-417 55 Gothenburg, Sweden,
morgan.johansson@norconsult.com (corresponding author)

Leo Laine
Adjunct Professor, LL Engineering AB / Chalmers University of Technology,
Stugvägen 4, SE-438 94 Härryda, Sweden

Ola Pramm Larsen, Joosef Leppänen
MSc, CAEwiz Consulting AS, Grinda 2B, NO-0861 Oslo, Norway
Senior Lecturer, Chalmers University of Technology,
Sven Hultins Gata 6, SE-412 96 Gothenburg, Sweden

ABSTRACT
In summer 2019, a very large full-scale blast test named Super Heavy Improvised Explosive Loading Demonstration (SHIELD) was conducted in Älvdalen, Sweden, resulting in the detonation of ANFO placed on a semi-trailer. Several organizations in various countries took part in the test-program, including the Swedish Civil Contingencies Agency (MSB). The test-program contained extensive measurements of both the resulting blast load and dynamic response of several structures located at various distances from the charge. As part of MSB's research in protective structures, numerical simulations have been conducted in Ansys Autodyn to study the blast load generated by the explosion. These simulations were conducted independent of the results from the experimental test within the SHIELD program and in this paper, blast load results from the simulations are compared with pressure measurements at a large concrete structure (SKUSTA) located 125 m from the semi-trailer. Both a direct comparison of overpressure and impulse intensity, and an indirect comparison using a coherence measure *Coh*, were made of experimental and numerical results. The comparison shows that the numerical simulations were generally successful in predicting the experimental results, and hence can provide a very powerful tool in similar predictions.

Keywords: Super Heavy Improvised Explosive Loading Demonstration (SHIELD), Vehicle-borne improvised explosive device (VBIED), blast load, numerical simulations, Ansys Autodyn, comparison with test, coherence measure

INTRODUCTION

In August 2019, a very large full-scale blast test named Super Heavy Improvised Explosive Loading Demonstration (SHIELD) was conducted in Älvdalen, Sweden. The purpose of this test program was to conduct a very large Vehicle-borne improvised explosive device (VBIED) detonation and study the effects on physical protection solutions for both civilian and military purposes, and by improving and expanding forensic data collection and assessment methodologies [1]. In this case, the heavy vehicle combination consisted of a semi-trailer laden with commercially available ammonium nitrate/fuel oil (ANFO).

The SHIELD test program consisted of the following partner nations and responsible organizations:

- Norway: Forsvarsbygg (Norwegian Defence Estates Agency, NDEA)
- Germany: Bundeswehr Technical Center for Protective and Special Technologies
- Switzerland: Federal Office for Defence Procurement, armasuisse
- USA: U.S. Army Engineer Research and Development Center (ERDC)

Within the respective partner nations, several organizations participated (including Swedish ones), and as such the Swedish Civil Contingencies Agency (MSB) made a prediction of the blast loads from the blast test using numerical simulations in Ansys Autodyn [2]. These simulations were conducted independent of the results from the experimental test and in this paper, blast load results from the numerical simulations are compared with pressure measurements located at a nearby concrete structure.

EXPERIMENTAL SET UP AT ÄLVDALEN TEST SITE

The test area is located about 40 km north of the small town Älvdalen in Sweden, with a total prepared test area of 700 x 1 000 m^2 [1]. Figure 1 shows a schematic overview of the test-site treated in this paper. The explosive charge consisted of a VBIED laden with ANFO placed at ground zero (GZ) at a distance of 125 m from a large concrete structure (denoted SKUSTA) and at 10 m from a 4 m high barrier wall of HESCO baskets, with a pyramid-like cross-section. SKUSTA consisted of a reinforced concrete frame structure (approximately 10 x 7 x 13 m) of four floors in which separate test objects could be attached, see Figure 2.

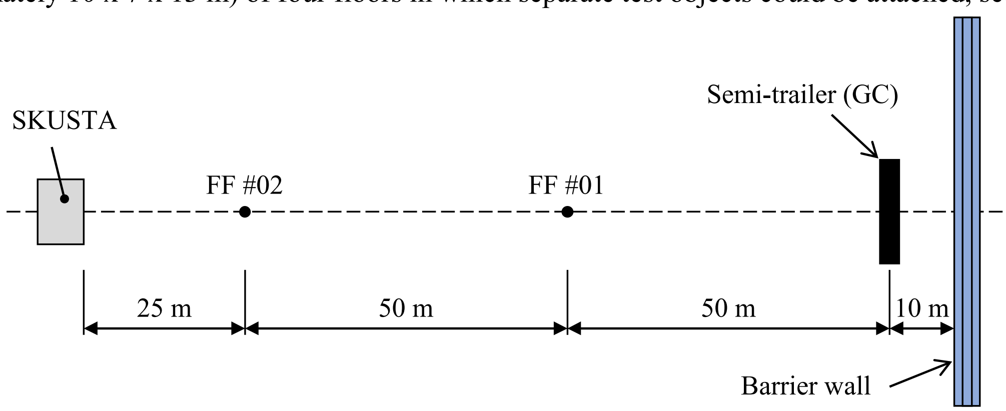


Figure 1. Schematic overview of test-site (plan view), charge placed in semi-trailer at ground zero (GC)

Figure 2. Overview of the large concrete structure SKUSTA without test objects; during testing all compartments were filled with various test objects (photo used with courtesy of the SHIELD group)

NUMERICAL SIMULATIONS

Modelling

The numerical simulation of the test was conducted using the Ansys Autodyn simulation software [2] in a 3-dimensional (3D) version. The computational hardware was a PC with 16 CPUs with dual socket Xeon 3.2 GHz base frequency processors (E5-2687WV2) and with ram 128 GB.

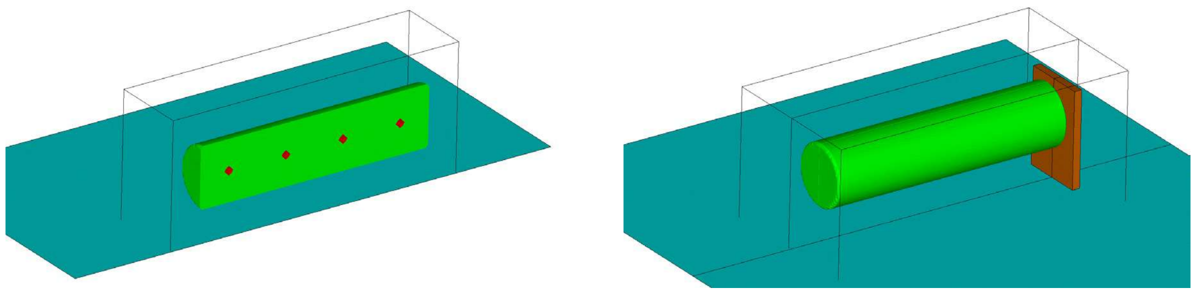
The air was modelled with an ideal gas law with initial density of 1.225 kg/m^3 in which the air was pressurized to one atmosphere (101.33 kPa) and the internal energy was set to 206.8 kJ/kg. Studies were conducted with both a TNT equivalent charge and a charge consisting of ANFO, using the Jones-Wilkins-Lee equations. Further, the influence of different charge shapes (hemispherical charge, spherical charge, cylindrical charge, and a charge consisting of multiple vertical cylindrical charges) was studied. However, in this paper, only results from a horizontal cylindrical charge of ANFO are presented.

As explosive in the test, ANFO Exan [3] was used and in the numerical simulations this was modelled as Prillit A according to [4] since its density of 850 kg/m^3 best corresponded to that of ANFO Exan, see Table 1 for a summary of the JWL parameters used. More details about ANFO JWL parameters are given in [4].

Table 1. JWL parameters for ANFO Exan used in the numerical simulations

Explosive	A	B	R_1	R_2	w	$D_{C\text{-}J}$	$P_{C\text{-}J}$
	[GPa]	[GPa]	[-]	[-]	[-]	[m/s]	[GPa]
ANFO Exan	267	3.44	7.04	1.16	0.39	3 850	3.3

The charge was modelled as a horizontal cylinder with its lower surface located at the level of the semi-trailer's loading platform. This shape was a chosen approximation of the charge shape in the physical experiments in Älvdalen, where the charge consisted of piled sacks of ANFO. A total of four detonation points were used, located along the cylinder's centre line, see Figure 3a. Further, to approximately consider the effect of the large engine mass located in the front of the semi-trailer, a rigid object with a mass of 2 000 kg was included in the simulations as shown in Figure 3b.



(a) (b)

Figure 3. Modelling of charge: (a) location of detonations points, (b) inclusion of a rigid mass 2 000 kg (located in direction α = 90°), simulating the effect of the semi-trailer's engine

The potential effect of ground condition was numerically studied, using simplified spherical charges, and in these it was found that the blast energy transferred into the ground was less than 3 %. Therefore, in the simulation of the test, the ground was modelled as a rigid surface. Further, the barrier wall was modelled both as rigid and deformable but since it was found that this had a negligible effect on the blast load acting on SKUSTA, in this paper, only results assuming a rigid wall are presented. In Figure 4, the locations of the result points on SKUSTA, used in the numerical simulations, are shown. Most of these result points represent the location of pressure gauges used in the test; however, some additional result points were added to provide supplementary information to that of the test. Further, numerical free field results of points FF #01 and #02, according to Figure 1, are presented as reference.

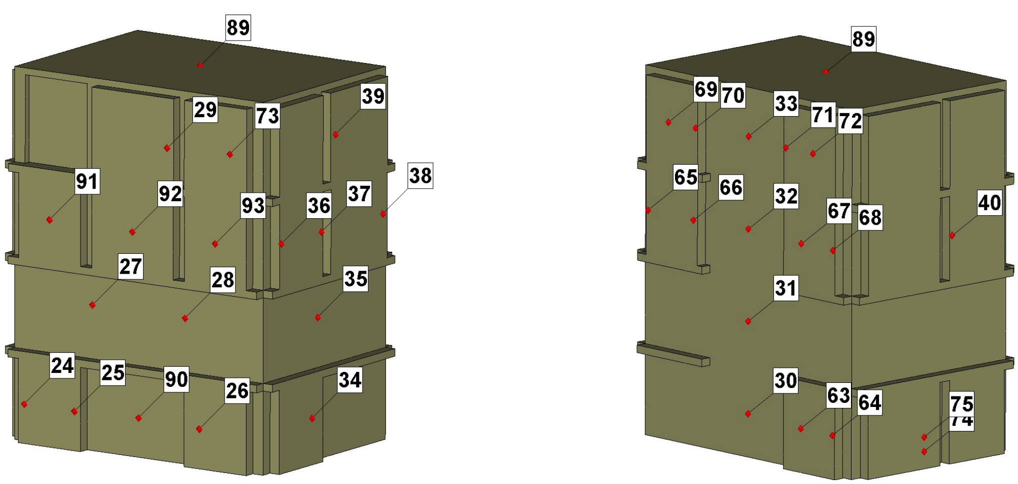


Figure 4. Structure SKUSTA, including detailed shape of the structure surface, with result points in the FE model, representing pressure gauges used in test: (left) front view, (right) back view

FE modelling technique
The main simulation techniques to handle both near and far field accuracy is to use re-mapping techniques. Initially, multi-material Euler was used during detonation until shock wave propagation was properly initiated; after this remapping into Euler Flux Corrected Transport (FCT) elements were used to accurately simulate the airblast. 2D axisymmetric multi-material Euler was initially used until 0.5 ms before the shock wave hit the ground, then remapping to 3D FCT Euler was used. To avoid too much smoothing of the peak overpressures, the 3D model included different fine mesh resolution zones within a radius of 150 m from GC, using cubic elements with a cell size of 0.25 m. Further, geometric coarsening with ratio of 1.1 was used outside this zone to avoid reflections from the mesh. This meant that different models focused on different sectors and radius distances. The model consisted of 60 million cells, which was a hardware limit of the PC. Totally, approximately 25 simulations were needed to reach all points of interest in experimental sectors of 360 degrees with a radius of 150 m.

COMPARISON OF RESULTS

Time shift of arrival time
When comparing the numerical simulations with the pressure $P(t)$ and the impulse intensity $i(t)$ from the experiment, it is found that the blast responses in many cases are rather similar. However, there is a minor difference in arrival time, where the arrival time of the simulated blast load at SKSUTA is consistently somewhat shorter than that obtained in the experiment. To clarify the comparison, the arrival times of the numerical simulations in the results presented here have been adjusted to be the same as in the corresponding result points from the experiment. Hence, the arrival times for the simulations is shifted with time

$$\Delta t_{a,\#} = t_{a,sim,\#} - t_{a,\exp,\#} \tag{1}$$

where $t_{a,sim,\#}$ and $t_{a,exp,\#}$ are the arrival time in result point # from the numerical simulations and experiment, respectively. From this, the original time $t_{sim,\#}$ from the numerical simulations is adjusted to $t_{sim,adj,\#}$ as

$$t_{sim,adj,\#} = t_{sim,\#} - \Delta t_{a,\#} \tag{2}$$

and the value of $\Delta t_{a,\#}$ is given in the legend of the pressure-time graphs presented below.

Normalized blast load values
Full information of the blast load values (i.e., pressure, time and impulse intensity) is, due to current security classification, not presented in this paper. Instead, these values are showed, using normalized values; i.e., normalized overpressure (P^+/P^+_{nom}), normalized time (t/t_{nom}) and normalized impulse intensity (i^+/i^+_{nom}). For this, nominal values P^+_{nom}, t_{nom} and i^+_{nom} were determined based on the maximum pressure (P^+_{max}), positive duration (t^+_1) and impulse intensity (i^+_1), respectively, for the initial positive phase acting on the front of SKUSTA.

Indirect comparison using coherence measure

In Table 2, the key parameters (peak overpressure P^{+}_{max} and impulse intensity i^{+}_{1}) obtained in the numerical simulations and the experiments for all result points are presented. To get a better overview of how well the results coincide, a coherence measure

$$Coh = 1 - \frac{\int_{0}^{t_{end}} \left| P_{sim}(t) - P_{exp}(t) \right| dt}{i^{+}_{exp} + i^{-}_{exp}} \tag{3}$$

in accordance with [5] was used. Here $P_{sim}(t)$ and $P_{exp}(t)$ are the relations of pressure and time obtained in the numerical simulations and experiments, respectively, while

$$i^{+}_{exp} = \sum_{k=1}^{n} i^{+}_{k} = \sum_{k=1}^{n} \int_{t_{a,k}}^{t_{end,k}} P^{+}_{exp}(t)\,dt \quad \text{where } P^{+}_{exp}(t) \geq 0 \text{ kPa} \tag{4}$$

$$i^{-}_{exp} = \sum_{k=1}^{n} i^{-}_{k} = \sum_{k=1}^{n} \int_{t_{a,k}}^{t_{end,k}} \left| P^{-}_{exp}(t) \right| dt \quad \text{where } P^{-}_{exp}(t) \leq 0 \text{ kPa} \tag{5}$$

are the sum of all positive and negative impulse intensities in the experiment within time period t_{end}. Here, t_{end} was chosen as the time when i^{+}_{max} was reached, i.e., most often at the time when the first positive phase ended. Using this measure, in which $Coh = 1.00$ signifies a perfect match, it is possible to easily compare many numerical and experimental results at the same time and get a rough measure of how well they coincide with each other. As illustrated in Figure 5, $Coh \geq 0.70$ corresponds to what is here deemed to be a good agreement between simulated and experimental results. In Table 2, the value of Coh is listed för all result points with valid experimental data and in Table 3, the distribution of these values are shown. From this it can be concluded that 9 out of 12 (75 %) of the result points at SKUSTA have a $Coh \geq 0.70$; i.e., a limit that indicates good agreement.

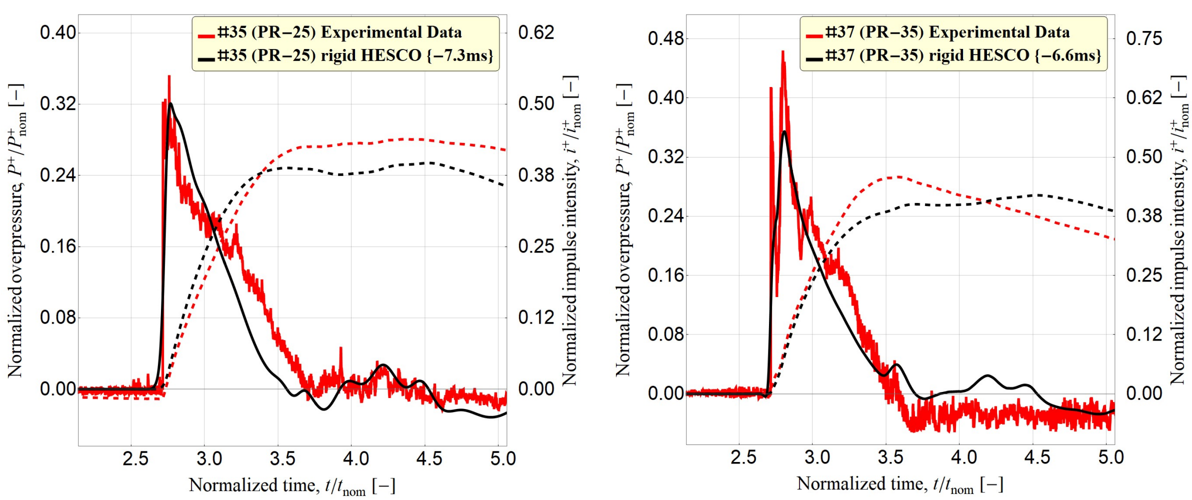


Figure 5 Examples of correlation between experiments and numerical simulations: (left) #35 with *Coh* = 0.66, (right) #37 with *Coh* = 0.77

Table 2. Summary of key parameters P_{max}^{+}/P^{+}_{nom}, and i^{+}_{I}/i^{+}_{nom} from experiments and numerical simulations ("-" means that no experimental result was available to compare with)

Result point	Location	Experiments		Ansys Autodyn		
		P^{+}_{max}/P^{+}_{nom} [-]	i^{+}_{I}/i^{+}_{nom} [-]	P^{+}_{max}/P^{+}_{nom} [-]	i^{+}_{I}/i^{+}_{nom} [-]	*Coh* [-]
#01	Free field	-	-	9.04	3.65	-
#02	Free field	-	-	1.07	0.81	-
#24	Front	-	-	0.96	0.89	-
#25	Front	-	-	0.94	1.01	-
#26	Front	1.25	1.05	0.99	1.00	0.90
#27	Front	-	-	1.00	1.05	-
#28	Front	1.16	1.09	1.00	1.04	0.91
#29	Front	1.03	0.90	0.97	0.91	0.82
#30	Back	0.21	0.54	0.16	0.53	0.86
#31	Back	-	-	0.21	0.53	-
#32	Back	0.28	0.55	0.23	0.54	0.86
#33	Back	0.19	0.49	0.17	0.47	0.89
#34	Side	-	-	0.35	0.39	-
#35	Side	0.36	0.47	0.32	0.40	0.66
#36	Side	0.85	0.23	0.34	0.31	0.41
#37	Side	0.46	0.45	0.36	0.42	0.77
#38	Side	0.35	0.35	0.33	0.44	0.61
#39	Side	0.34	0.51	0.30	0.44	0.78
#40	Side	-	-	0.36	0.42	-
#63	Back	-	-	0.13	0.45	-
#64	Back	-	-	0.12	0.33	-
#65	Back	-	-	0.11	0.37	-
#66	Back	-	-	0.19	0.49	-
#67	Back	-	-	0.16	0.47	-
#68	Back	-	-	0.12	0.37	-
#69	Back	-	-	0.16	0.45	-
#70	Back	-	-	0.16	0.48	-
#71	Back	-	-	0.15	0.47	-
#72	Back	-	-	0.16	0.45	-
#73	Front	-	-	1.00	0.83	-
#74	Side	-	-	0.32	0.40	-
#75	Side	-	-	0.32	0.40	-
#89	Roof	0.36	0.50	0.28	0.45	0.75
#90	Front	-	-	1.00	1.09	-
#91	Front	-	-	1.00	0.93	-
#92	Front	-	-	1.01	1.01	-
#93	Front	-	-	1.01	0.93	-

Table 3. Distribution of coherence measure *Coh* for result points in Table 2

	Coh [-]							
Description	<0.40 [-]	0.40-0.49 [-]	0.50-0.59 [-]	0.60-0.69 [-]	0.70-0.79 [-]	0.80-0.89 [-]	0.90-1.00 [-]	0.00-1.00 [-]
Number	0	1	0	2	3	4	2	12
Percentage	0 %	8 %	0 %	17 %	25 %	33 %	17 %	100 %

Direct comparison of overpressure and impulse intensity over time

In Figure 6, the incident overpressure $P^+(t)$ and impulse intensity $i^+(t)$ from numerical simulations are presented for the free field result points #01 and #02 shown in Figure 1. These results are not compared with experimental results; instead, their purpose is to give an orientation of the blast load approaching SKUSTA. In Figure 7 to Figure 9, comparisons of overpressure $P^+(t)$ and impulse intensity $i^+(t)$ from experiment and numerical simulations are made for result points located on SKUSTA. From these figures and Table 2, it can be concluded that the numerical simulations were in most cases successful in predicting the resulting $P^+(t)$ and $i^+(t)$ from the experiment. Apart from one single result point (#36) located on the side of SKUSTA, the coherence values reached $Coh \geq 0.61$. The highest coherence values were obtained in two result points (#26, #28) located on the front of SKUSTA, for which $Coh \geq 0.90$ was reached.

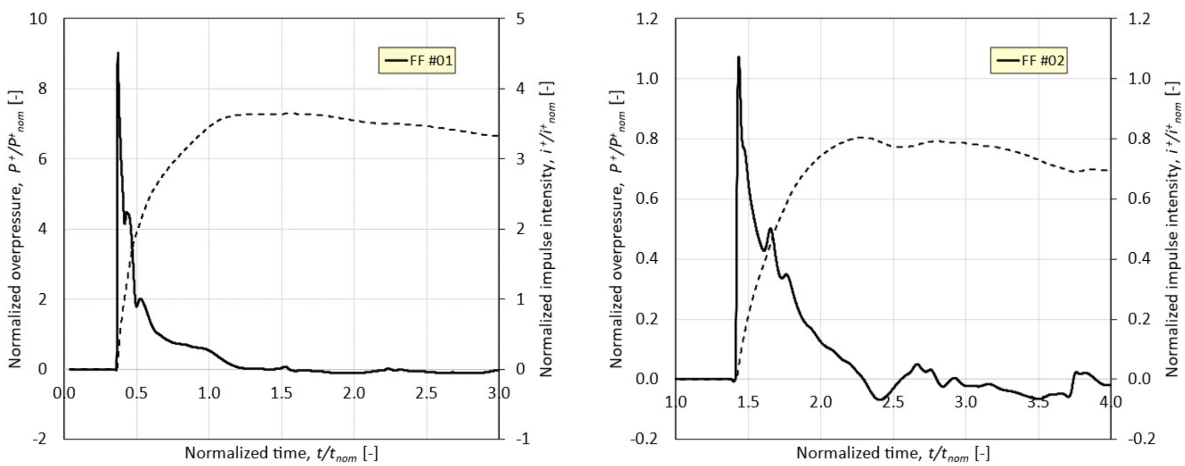


Figure 6. Free field results of $P^+(t)$ and $i^+(t)$ from numerical simulations at #01 (r = 50 m) and #02 (r = 100 m)

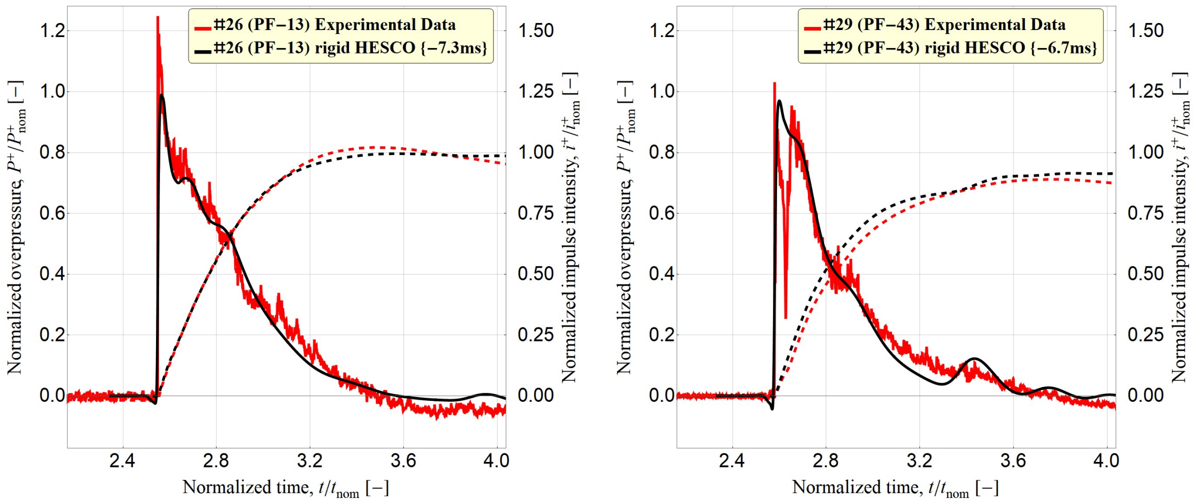


Figure 7. Comparison of $P^+(t)$ and $i^+(t)$ from experiment and numerical simulations on SKUSTA at #26 and #29 (front)

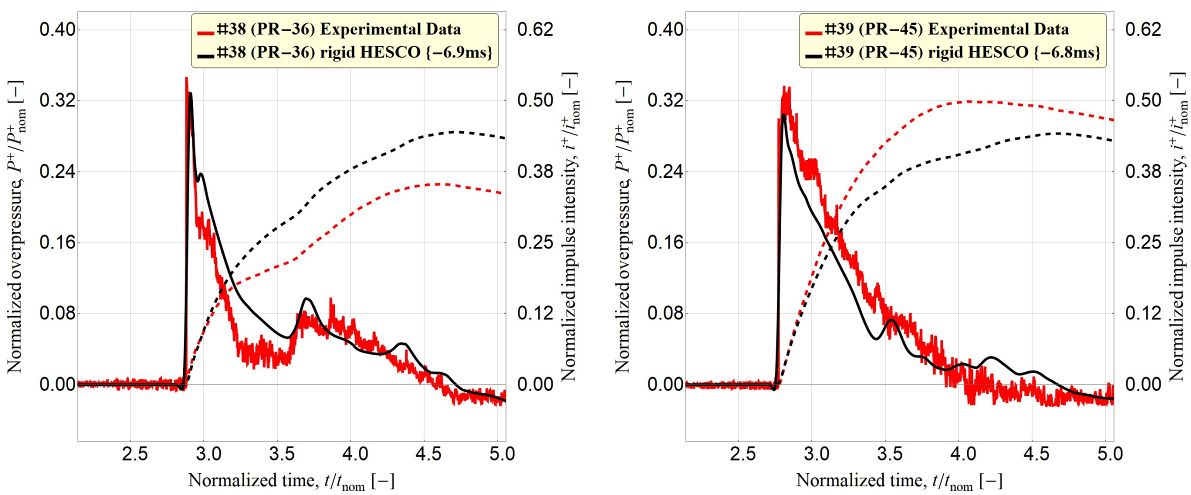


Figure 8. Comparison of $P^+(t)$ and $i^+(t)$ from experiment and numerical simulations on SKUSTA at #38 and #39 (side)

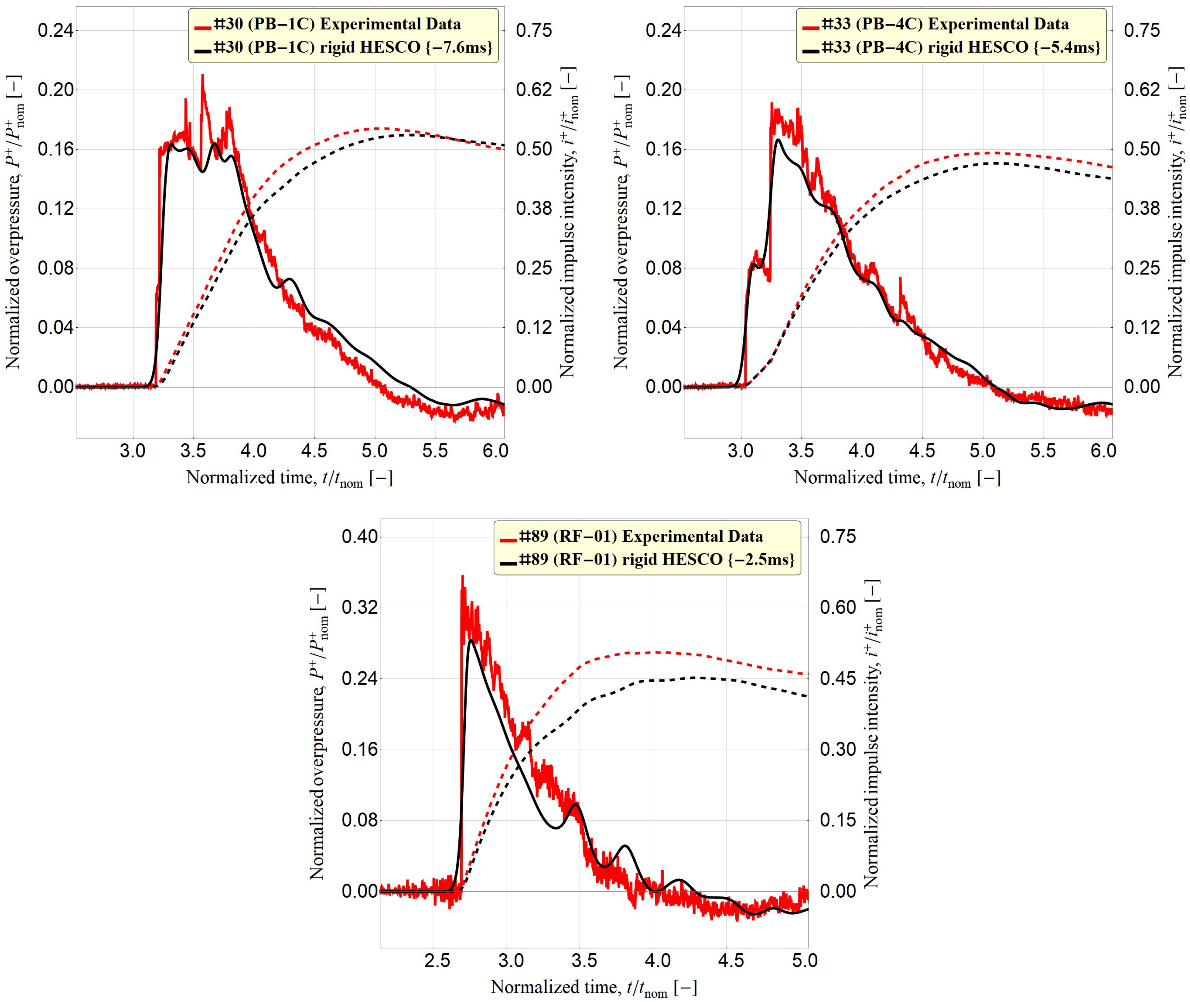


Figure 9. Comparison of $P^+(t)$ and $i^+(t)$ from experiment and numerical simulations on SKUSTA at #30, #33 (back) and #89 (roof)

CONCLUSIONS

In this paper, a comparison is made of numerical simulations, carried out independently in Ansys Autodyn, and experimental data of a large high explosive charge (ANFO, carried by a semi-trailer), detonating near ground surface. The comparison shows that the numerical simulations were generally successful in predicting the resulting blast load acting on a nearby structure, and hence can provide a very powerful tool in similar predictions. In addition to a direct comparison of the normalized overpressure $P^+(t)/P^+_{nom}$ and normalized impulse intensity $i^+(t)/i^+_{nom}$, an indirect comparison using a coherence measure *Coh*, was also used. This measure has proven to be a convenient method to get an estimate of how well the experimental and numerical results coincide.

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