

# Scaling of Air Blast Effect on Square Metal Plates with Experimental and Numerical Methods

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**Abstract:** Today, scaling laws are used frequently to evaluating the blast effects on structures and soil. These laws significantly are used for generalizing the results of scaled-down experimental tests to real and full- scale tests. in this paper, with both of experimental test and numerical simulation by LS-DYNA program software, we are proceeding to scaling of air blast effect in close- ranges on st-37 steel plates with square geometry and completely bonded perimeter. Full-scale experimental tests which include of real scale structures and charges, in preparation, as well as data recording and final results, are implicated of high costs and lower level of safety. So, scaled-down experimental tests are properly advantageous and desirable. Hence, assessing the results of these experimental tests are the main subject of this paper. Scaling of geometrical parameters is done based on geometrical similarity and blast effect scaling by well-known Hopkinson's law. At the end, a very good agreement obtained between results of numerical simulation and experimental test. Therefore, the main message of this paper is that by using scaling laws, one can prevision dynamical response of metal plates that exposed on real scale blasts in close ranges.

**Keywords:** Air Blast, Scaling, LS-DYNA, Steel Square Plates, Dynamical Response

## I. INTRODUCTION

In past decades, expensive activities have performed in field of explosive loadings. Importance of research in this domain, not only for observing the damage caused by explosion, but in order to predict the vulnerability of human and structures to blast, and design, development and fabrication of blast resistant material, too. A key of success in defense projects is accurate understanding the behavior of metal plates that exposed to explosions. According to subject of blast wave in metals, dynamical response of structure depends on several parameters such as distance from charge, weight of charge, type of metal plates, so on [1-7]. Performed studies in this domain, besides illustration of different destruction states, also describe the relations between deforming and rupturing of constrained metal plates that subjected under blast loading. For the first time, destructive states of metal plates have been described by Menkes & Opat, for cases that metal shafts subjected under explosion loadings [8]. Performed classification is as follows: a) large non-elastic deforming, b) rupturing, c) shear destructing.

Other classifications have been performed by other researchers. Wen & Jones studied the scaling of metal plats which subjected under impact, and concluded that geometrical scaling is a proper approach in this field. Jacob *et.*, all studied different aspects of scaling the blast effects on square metal plates. They examined and analyzed the effect of changing the parameters like weight of explosive material, geometry of plate and deforming level of structure. Moreover, for analyzing the effect of small charge explosions on metal plates, one dimensionless number was defined that by using it, deforming level of plate due to blast, was predicted. Nonetheless, evaluating the results in this method depends on conditions of blast loadings and limited to metal plates with small geometries,

while for larger explosions there is need for numerical simulations and experimental tests. Raftenberg has performed series of studies about small blast loadings on metal discs, and compared the results of experimental tests with numerical simulations of finite element method.

According to scaling of blast effects in metal structures, performed studies and works, in comparison with other fields of explosion, are not broadened.

With last information and research of authors, scaling the effect of relatively big explosions on metal plates in close ranges, has performed rarely (or because of classification levels, a few have been published). A closest report that is similar to present work, have reported by Neuberger in 2007 [1]; However, in fundamental parameters such as charge type, shape of charge, material and geometry of metal plates, are different.

This study includes the numerical simulations by finite element method and experimental tests of air blast effect on metal square plates. Numerical calculations and experimental tests have performed by scale factor of  $s = 5$  (this factor means scale of 1:5). Result and main output of this study is this point that, by using of scaling laws, one can analyze the metal plates that subjected under real scale blast loadings in air and close distances.

## II. MATERIAL AND METHOD

### A. Fundamental theory of scaling

One of the most important points for scaling of any phenomena is physical evaluation of that phenomenon. Performing of experiments on model and scaled down sample before creation of main and bigger model is so necessary and logical. However, we must know that how can generalize the results of performed tests on model and scaled down sample to main and real scale sample.

Scaling principles and relations between real and sample model, have been formulated. In the following, scaling parameters are mentioned in kind of relations between sample model, M and main model, P:

Dimensions in relation to scaling coefficient, are linear:

$$X_i^P = X_i^M \cdot S \quad (1)$$

Angles are similar:

$$\alpha_i^P = \alpha_i^M \quad (2)$$

Densities of materials are similar:

$$\rho_i^P = \rho_i^M \quad (3)$$

Stresses are same for any material:

$$\sigma_i^P = \sigma_i^M \quad (4)$$

Characteristic time is the ratio of scaling coefficient:

$$\tau_i^P = \tau_i^M \cdot S \quad (5)$$

Loadings are similar and must consider in scaled points:

$$F_i^P = F_i^M \cdot X_i^P = X_i^M \cdot S \quad (6)$$

Deforming measure for specific characteristic times is ratio to scaling coefficient:

$$\delta_i^P = \delta_i^M \cdot S : \tau_i^P = \tau_i^M \cdot S \quad (7)$$

Angular deforming is similar:

$$\omega_i^P = \omega_i^M \quad (8)$$

It must be noted that, there are several phenomena that are not scalable with above principles. For example, gravitational force can't be scaled from geometrical scaling principles. However, in here, we are involved with high accelerations, so, gravitational forces are not important and can be neglected.

Most conventional method in scaling of spherical shock waves, is using of Hopkinson's scaling rules with third root. This law claims that, when two charges from same type and with similar geometrical shape but with different weights are exploded in a medium, then in specific scaled distance, similar explosion waves will be created. Relations of hopkinson's law for air blast, are as follows:

$$Z = \frac{R}{E^{\frac{1}{3}}} \quad (9-a)$$

$$\tau^* = \frac{1}{E^{\frac{1}{3}}} \quad (9-b)$$

$$I^* = \frac{1}{E^{\frac{1}{3}}} \quad (9-c)$$

Where  $Z$  is scaled distance,  $\tau^*$ , scaled characteristic time for shock wave;  $I^*$ , scaled impulse;  $R$  distance from center of charge and  $E$  energy outcome from explosion. In above relations, it is remarkable that,  $E$  can be substituted by weight of explosive material,  $W$ .

## B. Numerical simulation

In this paper, for performing numerical simulation of considered problems, we have used Arbitrary Lagrangian Eulerian (ALE) method in LS-DYNA nonlinear code. This finite element code has high ability in simulation of complicated engineering problems, such as simulation of explosions and their effects on different structures. In this program, particular material models and equations of state have been used for every section. The aim of this simulation is investigation the behavior of given metal plates and estimation of deforming level of them. Numerical simulation has performed with finite element method in three general stages. (i) First stage includes the creation of geometrical model of problem such as explosive charge, air and metal plate by using of Ls-Prepost software, (ii) In second stage, nonlinear dynamical analysis and (iii) post processing the results of analysis have performed by Ls-Prepost software for interpretation of obtained results.

ALE method includes three different material models that being used for metal plates, explosive material and environmental air. By using of LS-Prepost pre-processor software, metal plate being meshed and prepared. Here, explosive charge has been modeled by Initial Volume Fraction method, and for meshing the surrounding air and metal plates, we used 4-node solid elements that total number of elements was 16000. In this software, for every section, their own material model and

equations of state are used. According to this fact that problem has axial symmetry, problem modeled by ratio of 4:1 and naturally the solving time of problem is reduced. Applied axial symmetry is presented in Fig.1.

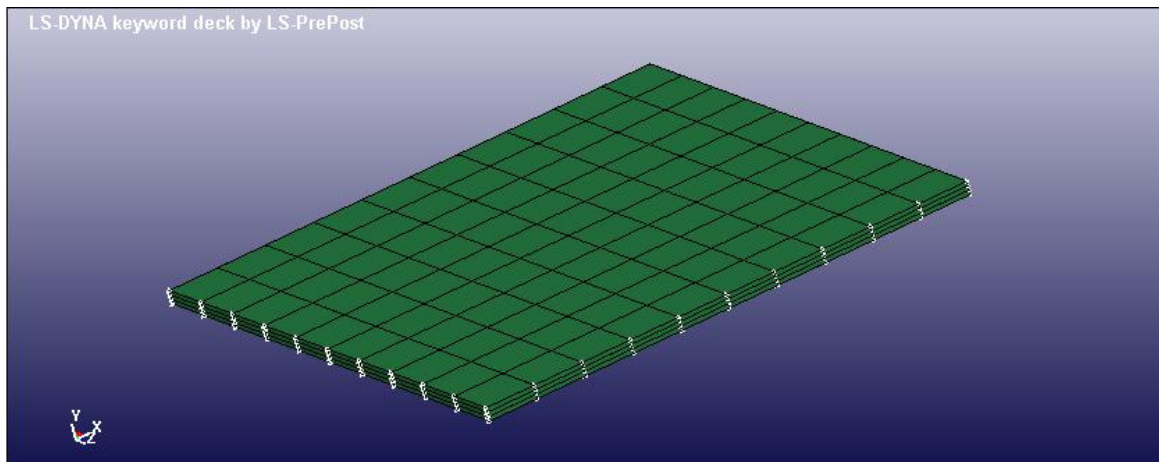


Figure 1: Applying the boundary conditions of symmetry

Material model that considered for metal plate, was Johnson-Cook model that its equation is as follows:

$$\sigma_y = (A + B \cdot \varepsilon_p^{-n}) \cdot (1 + C \cdot \ln \dot{\varepsilon}^*) \cdot (1 - T^m) \quad (10)$$

Where  $A$ ,  $B$ ,  $C$ ,  $n$  and  $m$  are coefficients of material that were mentioned in Table 1.  $\varepsilon_p$  is effective strain and  $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}$  is the rate of effective plastic strain in the rate of reference strain of  $\dot{\varepsilon}_0 = 1s^{-1}$  and  $T = \frac{T^* - T_{room}^*}{T_{melt}^* - T_{room}^*}$  where  $T^*$  is the temperature of materials and  $T_{room}^*$  is room temperature and  $T_{melt}^*$  is melting temperature.

Table 1: selected coefficients for material model

$m$	$n$	$C$	$B$ (MPa)	$A$ (MPa)
0.917	0.9	0.0936	510	365

Along with Johnson-Cook equation, Polynomial equation of state has been used, which is a linear equation versus internal energy and is as follows:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (11)$$

Where  $C_2\mu^2$  and  $C_6\mu^2$  are zero if  $\mu = (\frac{\rho}{\rho_0}) - 1 < 0$ , that  $\frac{\rho}{\rho_0}$  is the ratio of instant density to initial density.

Used equation of state for explosion products is Jons-Wilkins-Lee equation (JWL) that is as follows:

$$P = A \left(1 - \frac{\omega}{R_2 V}\right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E'}{V} \quad (12)$$

In above equation,  $R_1$ ,  $R_2$ ,  $A$ ,  $B$  and  $\omega$  are coefficients that are available in valid references and

$V = \frac{\rho}{\rho_0}$  ratio of resulting gases from explosion to initial condition of explosive material and  $E'$  is energy per unit volume.

Equation of state for intermediate fluid, that is air, is polynomial equation of state:

$$P = C_0 + C_1 m + C_2 m^2 + C_3 m^3 + (C_4 + C_5 m + C_6 m^2) E^* \quad (13)$$

Where,  $m = \left(\frac{\rho}{\rho_0}\right) - 1$ , and  $\frac{\rho}{\rho_0}$  is ratio of instant density to initial density.  $C_{1...6}$  are polynomial coefficients and  $E^*$  has pressure unit. For modeling the air, one can use Gamma law. Hereon,  $C_0 = C_1 = C_2 = C_3 = C_6 = 0$ , and  $C_4 = C_5 = \gamma - 1$ , where  $\gamma$  is the ratio of specific heat capacities. So, equation 13 transforms to:

$$P = (\gamma - 1) \frac{\rho}{\rho_0} E^* \quad (14)$$

### C. Test configuration

One cylindrical explosive charge from C4 with 7kg weight in distance of 10 cm from center of steel plate, thickness of steel plate was 15 mm and scale factor of 1:5; and one cylindrical explosive charge from C4 with 0.056 kg weight in distance of 2 cm from center of steel plate with thickness of 3 mm, was examined. In this test, for all of explosions, we have used a number 8 electrical detonating agent. Structure of accomplished tests is presented by photograph in Fig. 2 and Fig. 3 for full- scale and scaled- down test, respectively.



Figure 2: Structure setup of full scale test



Figure 3: Structure setup of scaled- down test

Schematic diagram of performed setup for all of the tests is shown in Fig. 4. Where  $L$  is the length side of steel plate,  $R$  distance from center of plate to center axis of explosive charge and  $\delta$  is maximum of deformation.

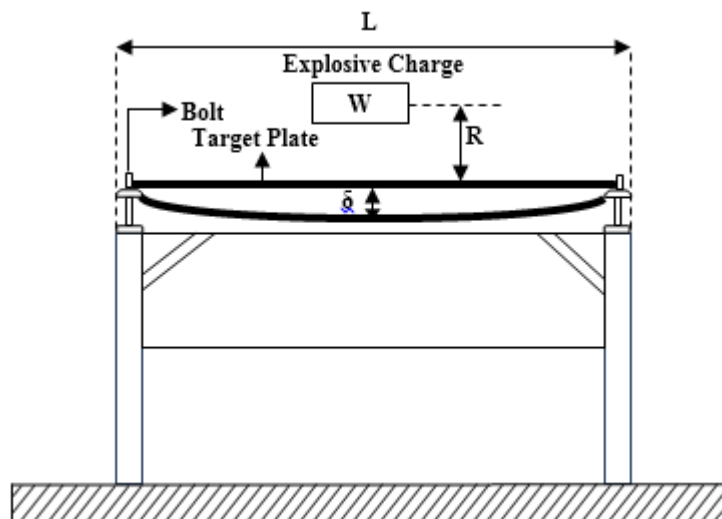


Figure 4: Schematic diagram of all of the tests

### III. RESULTS AND DISCUSSION

#### A. Simulation Results

Displacement diagram of selected central node in all of plates was used in order to study and comparison the effects of blast on metal plates. As we can see from Fig. 5 and Fig. 6, central deforming quantity for scaled-down and full- scale case is 3.7 and 13.4 cm, respectively. So, scaling with scale factor of 1: 5 for performed simulation has been vindicated by 73%.

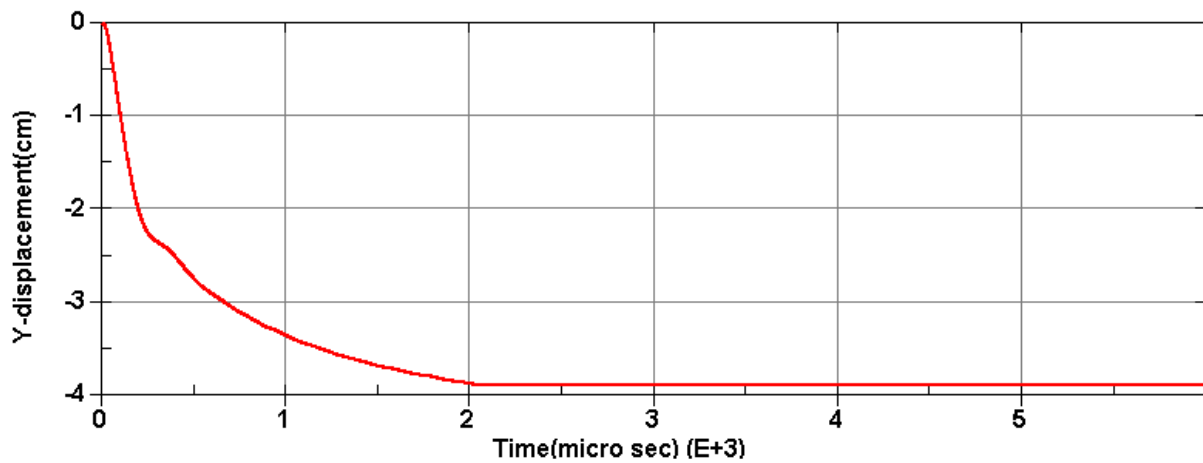


Figure 4. Constructed central deforming quantity in scaled- down case

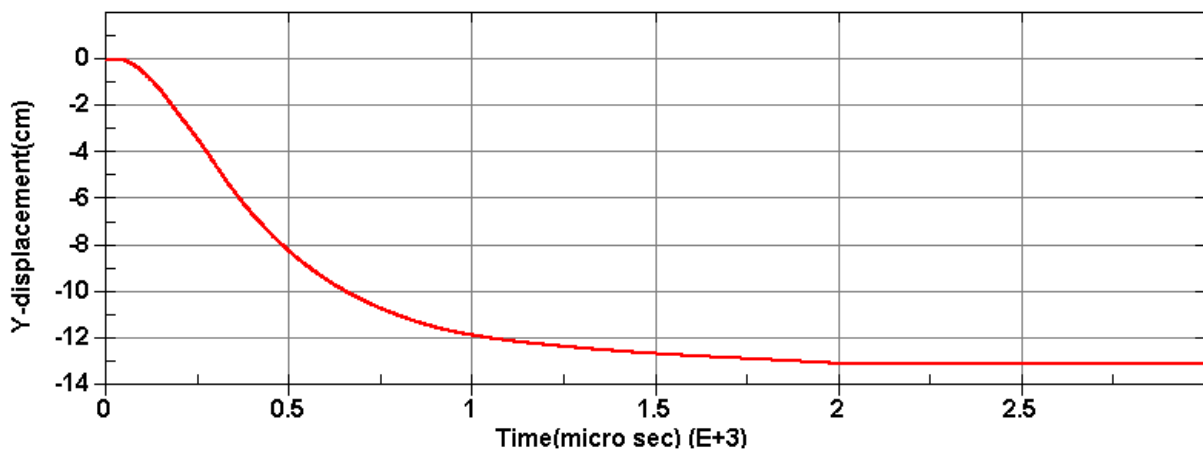


Figure 5: Constructed central deforming quantity in full- scale case

Also, counters of created plastic strain for both cases are presented in Fig 7 and Fig. 8. As we can see from following pictures, the maximum of created strain is constructed in central elements, because charges are precisely located in the middle of metal plates.

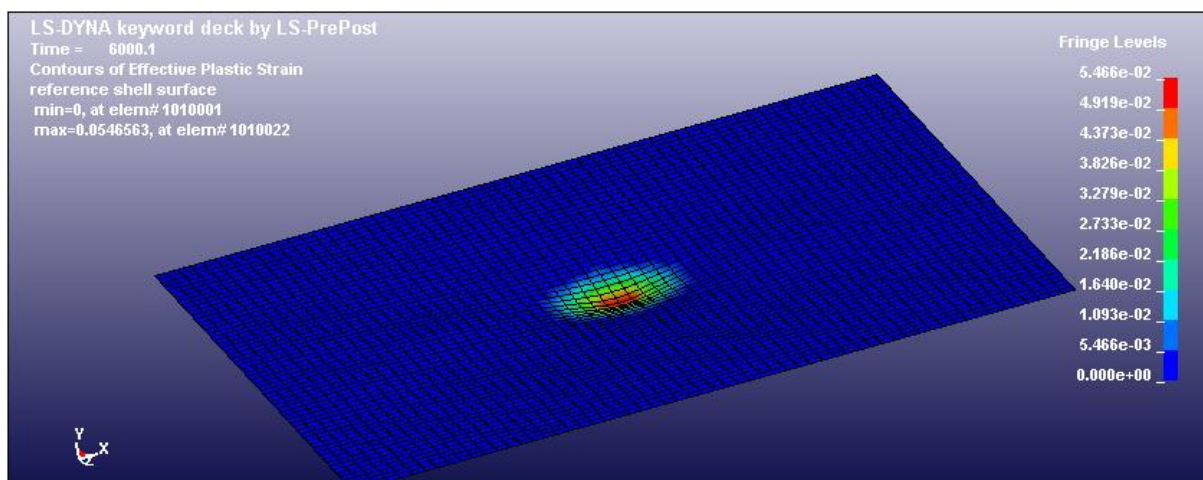


Figure 6: Counter of plastic strain in scaled down case

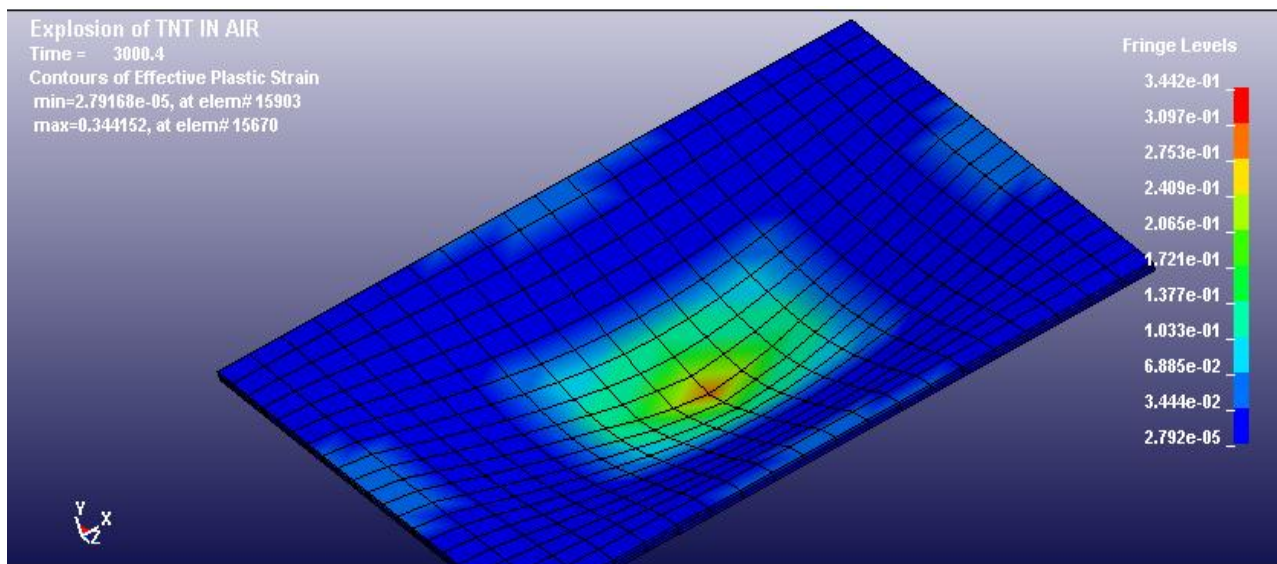


Figure 7: Counter of plastic strain in full- scale case

### B. Experimental test results

After the blast and examining the deformation created by resulting impact of explosion, we have observed that shape and deformation caused by blast is different in full- scale and scaled- down sample. As can be seen from Fig. 9 and Fig. 10, depth of created central deformation in scaled- down and real- scale samples is 3.2 and 14.5 cm, respectively. So, scaling with scale factor of 1: 5 for performed test has been vindicated by 91%.



Figure 8: Measurement of created central deformation in scaled- down case





Figure 9: Measurement of created central deformation in full- scale case

Results of numerical simulation and experimental tests are summarized in table 2.

Table 2: summarized results of numerical and experimental tests

$\delta/t$ <i>numerical</i>	$\delta/t$ <i>Experimental</i>	$R$ (cm)	$W$ (kg)	$L$ (cm)	$t$ (mm)	$s$
8.93	9.70	10	7	200	15	1
12.33	10.70	2	0.056	40	3	5

Obtained data in above table show that performed simulation results are close to real scale and there is a good correlation between numerical simulation and results of experimental tests.

#### IV. CONCLUSION

Scaling of air blast effect was performed on st-37 steel plates in both methods of numerical simulation and experimental test. Where, results of numerical simulation are about 90% close to experimental test and the results of scaled- down test in both method are precisely extendable to real-scale results.

Performing the real- scale blast includes high financial costs, safety problems and hard data accumulation. So, with performing the scaled down test and by using suitable scaling laws; one can estimates the results of real- scale test, by using results of scaled- down tests. In fact, by using the scaling law, not only the destruction caused by real scale blast, but, human trauma and structure demolition are anticipated; and we can use these information for fabrication of resistant and refractory materials to explosions in different environments, where software simulations are very useful in this area.

**Conflict of interest:** The authors declare that they have no conflict of interest.

**Ethical statement:** The authors declare that they have followed ethical responsibilities.

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