Peak Displacement Comparison of RC Slabs from Blast Test Measurement and SDOF Analysis

Fausto Batista Mendonça[1], Girum Urgessa[2], Koshun Iha[1], Roberta Jachura Rocha[1] e José Atílio Fritz Fidel Rocco[1]
[1]ITA - Instituto Tecnológico de Aeronáutica – Departamento de Química – Pça. Mal Eduardo Gomes, 50 – Vila das Acácias – S. J. dos Campos – SP CEP: 12228-900
[2]George Mason University - Civil, Environmental, and Infrastructure Engineering - 4400 University Drive, MS 6C1, Fairfax, VA 22030, USA

***Abstract* — Both civil and military facilities are increasingly targeted by terrorist attacks. Understanding the mechanical behavior of reinforced concrete (RC) structures subjected to blast is of paramount importance. A full-scale experimental program consisting of four reinforced concrete slabs with compressive strength of 60 MPa, measuring 1.0 x 1.0 x 0.08 m, and subjected to 2.7 kg of non-confined plastic bonded explosive, was conducted in blast test area of Science and Technology Aerospace Department (Brazilian Air Force). This paper presents theoretical peak displacement and compares with experimental displacement measured from the tests. Theoretical analysis was carried out using single degree of freedom (SDOF) models. The comparison showed that SDOF analysis worked very well in predicting the reinforced concrete slab peak displacement against blast effects.**

***Keywords* — blast effects, single degree of freedom, reinforced concrete.**

I. Introduction

Blast due to terrorist attacks, wars and accidental explosions have become a growing concern around the world. These blasts can undermine the integrity of structures such as those made from reinforced concrete (RC), which is one of the common materials used to construct most buildings and bridges around the world. Most of these structures are not designed to resist the effect of explosions. Even those structures designed adequately for the effects of typical out-of-plane loading (such as earthquakes) may have load carrying capacity [1], they may not perform well against blast loads depending on the size of the explosive charge and the location of the charge. These explosions generate dynamic loads against essential supporting structural elements, such as slabs, columns or beams.

An explosion is a sudden release of energy and can be classified as physical, nuclear or chemical, depending on the source [2], [3]. This paper deals with chemical explosions, which is result of exothermic chemical reaction. The sudden elevation of temperature and pressure in the environment where the explosion occurs are the main factors that can bring damages to constructions close to the epicenter. The released energy moves toward all directions around the epicenter compressing the air and generating a front wave, called shock wave or blast wave [3]–[5] which has supersonic velocity.

Fausto Batista Mendonça, fausto@ita.br, Tel. +55-12-98173-6600, Girum Urgessa, gurgessa@gmu.edu, Tel. +1-703-268-9183, Koshun Iha, koshun@ita.br, Tel. +55-11-97142-9751, Roberta Jachura Rocha, robertajr@gmail.com, +55-12-98114-8086, José Atílio Fritz Fidel Rocco, friz@ita.br, +55-12-99605-2233

Understanding how a structure behaves under blast is of paramount importance for designing for the safety of both the general public and infrastructure. Since the second part of the last century, research related to blast loading on structures and their behavior has been growing [3], [6]–[8], especially after lessons learned from the two World Wars, several terrorist attacks, and accidental explosions. In order to design RC structures that are capable of resisting blast loads, it is imperative that structural engineers need to incorporate short-duration dynamic load effects of the blast loads. Hence, knowledge of blast wave parameters, and how the energy coming out from the blast damaged structures are very significant. In this study, both theoretical model that uses a Single Degree of Freedom (SDOF) approach and experimental tests were performed to determine peak displacement of a slab due to blast. Comparison of results found from the theoretical models and experimental tests indicated that the theoretical model predicts the behavior of the RC slab under blast loading reasonably [9]–[12].

Losses in both peaceful time and during conflicts generated from explosions close or in buildings have been concern of many agencies around the world [13]. Several codes and standards have been published giving guidance for better constructions to resist blast wave [10], [14], [15] in order to increase survival rates of structures and people after a blast event. These documents take into account that structural elements have different behavior under static and dynamic loads [16]–[18]. This paper presents comparison of experimental and theoretical dynamic reinforced concrete slab response subjected to blast wave. Widely known equations of SDOF models were applied.

Full-scaled tests with four RC slabs subjected to blast wave generated from non-confined explosive was the experimental data source used for comparison with the SDOF analysis. This paper is a follow-up of Mendonça *et al.* [19].

II. Material and Methods

The shock wave rises suddenly above the ambient pressure and shocks against the structures around the epicenter generally bringing damages. The peak value of the pressure is called incident peak pressure (Pso). Pso decays rapidly and oscillates around the ambient pressure before back to stability [1], [4], [9]. However, when shock wave from an explosion shocks to a surface comes up a reflection, called reflected pressure (Pr) that is the amplifier of Pso. The higher amplifying ratio is given when the front wave angle of incidence is perpendicular to the surface [1]. Fig. 1 shows a typical time-history curve recorded by a pressure sensor during the blast experiment.

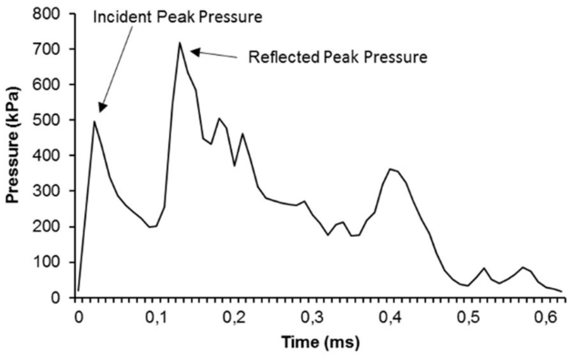

Fig. 1. Typical time-history curve.

Prediction of Pso can be made by calculating the scaled distance (Z). This parameter depends on the stand-off distance (R) in meters and the equivalent TNT mass of the explosive (W) in kg, as can be seen in (1) [20], [21].

$$Z = \frac{R}{W^{1/3}} \quad (1)$$

There are many equations available in literature to predict Pso as published in [20]. The equations (2) and (3) of Kingery and Bulmash [22], [23] were used for predictions of Pso in the analysis. To get the value of Pso, it is necessary to determine the value of the constant U beforehand using T, which is a function of the logarithm of Z.

$$Pso = 2{,}611 - 1{,}690\ U + 0{,}008\ U^2 + 0{,}336\ U^3 - 0{,}005\ U^4 - 0{,}080\ U^5 - 0{,}004\ U^6 + 0{,}007\ U^7 + 0{,}0007\ U^8 \quad (2)$$

$$U = -\ 0{,}214 + 1{,}350\ T \quad (3)$$

Equation (4) brings prediction of Pr [22], [23] using (3) to get U value.

$$Pr = 3{,}229 - 2{,}214\ U + 0{,}035\ U^2 + 0{,}657\ U^3 + 0{,}014\ U^4 - 0{,}243\ U^5 - 0{,}015\ U^6 + 0{,}049\ U^7 + 0{,}002\ U^8 - 0{,}003\ U^9 \quad (4)$$

Time of duration of blast load positive phase (t_d) is an important parameter for blast wave analysis. The equations widely used in the literature for predictions are (5) [24] for spherical charge in free air and (6) [23] for hemispherical TNT surface bursts.

$$\frac{t_d}{W^{\frac{1}{3}}} = \frac{980\left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.02}\right)^{3}\right]x\left[1+\left(\frac{Z}{0.74}\right)^{6}\right]x\sqrt{\left[1+\left(\frac{Z}{6.9}\right)^{2}\right]}} \quad (5)$$

$$t_d = EXP(0{,}544 + 2{,}7082\ (LN(Z)) - 9{,}7354\ (LN(Z)^2) + 14{,}3425\ (LN(Z)^3) - 9{,}7791\ (LN(Z)^4) + 2{,}8535\ (LN(Z)^5) \quad (6)$$

For targets with finite dimensions, t_d for Pso and Pr are almost the same and these equations of time duration can be employed in a simplification of time-history curve [1], [25].

Simplified Dynamic Response Analysis

The main difference between static load and dynamic load on structures is the time duration of the load. For dynamic loads, time duration is measured in milliseconds, as shown in Fig. 1. Therefore, the materials behavior are different in each type of load. Concrete and steel have an increase of strength when subjected to dynamic load, characterized by the Dynamic Increase Factor (DIF). The value of DIF for the concrete is about 20% and for steel is about 10% [1], [3]. Concern about accurately determining the dynamic behavior of structures under blast event has been reported in literature [14], [15], [19]. For dynamic analysis and design, time-history curve can be simplified using a triangular pulse as shown in Fig. 2 [3], [16], [25], where P_0 is the maximum peak of the blast load.

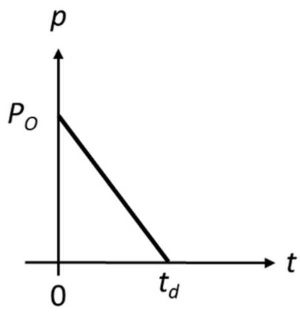

Fig. 2. Simplification of time-history curve.

Each structure with an assumed single-degree-of-freedom has a natural period of vibration (Tn) as shown in (7) [3]. The structure has a natural frequency that depends on its stiffness (k) and mass (m) as (8).

$$T_n = \frac{2\pi}{\omega_n} \quad (7)$$

$$\omega_n = \sqrt{\frac{k}{m}} \quad (8)$$

The stiffness for slabs can be verified in the reference of Clough and Penzien [16] and De Araújo [26], depending on the thickness and material properties of the slab.

Maximum static peak displacement $(u_{st})_0$ is used to get maximum dynamic peak displacement (u_0), from the maximum peak of the blast load (P_0), as (9).

$$(u_{st})_0 = \frac{P_0}{k} \quad (9)$$

Deformation response factor (R_d) is applied to get the final value of dynamic peak displacement, as (10).

$$u_0 = R_d (u_{st})_0 \quad (10)$$

R_d value can be reached by the curve of the shock spectra for triangular pulse (Fig. 3) and depends on the time of duration of blast load positive phase and natural period of vibration.

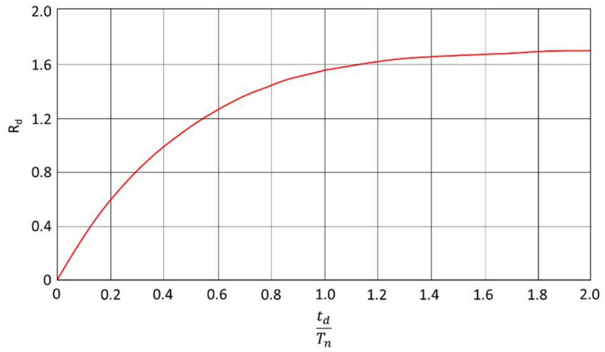

Fig. 3. Shock spectra for triangular pulse.

Set up for Experimental Test

Four slabs having the same reinforced concrete design with dimensions of 1.0 x 1.0 x 0.08 m were subjected to blast in a field test program. The concrete compressive strength was 60 MPa and the reinforcement ratio was 0.25% in two ways. Reinforcement was positioned in the bottom face of the slab to carry positive moment during the blast load, as can be seen in Fig. 4. One of the slabs (Slab 3) was retrofitted on top with 5.0 cm Styrofoam in order to verify if this foam material has an effect on the structural behavior of the slab.

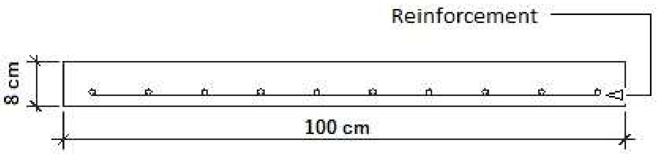

Fig. 4. Cross section of the slab.

The slabs were simply supported on two sides and the explosive was suspended in 2.0 m above. Scaled distance for the tests was 1.4 m/kg$^{1/3}$. Non-confined cylindrical PBX explosive, measuring 20 cm in high and 10.5 cm in diameter, was triggered by an electrical fuze on top of the cylinder. The set-up is shown in Fig 5.

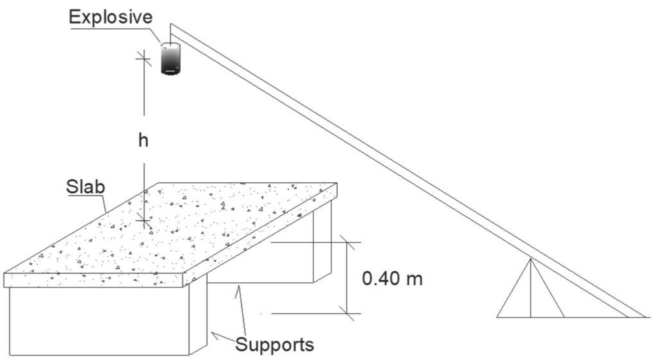

Fig. 5. Test setup.

Plastic non-confined explosives have been widely used for blast tests in order to measure blast wave effects [19], [27]. The main reason for this is that records from blast effects are more reliable when there are no explosive fragments.

Displacement meters were used to measure the displacement of the slab due to the blast waves. They were attached to the bottom surface of the slab by a wire emanating from a potentiometer that records the upward or downward movement of the wire during the explosion. The potentiometer was placed in a metallic box to protect it from the blast wave and surrounding debris generated during the explosion event. A hook was pasted on the lower surface of the slab near the mid-span using a two-part epoxy resin. The hook was needed to hold the wire in place. Two hooks with two potentiometers were attached to increase the likelihood of data collection in case there is a failure during the experiment.

III. Results

Explosions near structures, such as the case in this experimental test, will experience a reflected pressure (Pr) [19], [28], as shown in Fig. 1, developing damages. The records of displacement meter showed peaks of incident and reflected pressure actions against the slabs as can be seen in Fig. 6. First peak of displacement was 18.74 mm and the second downward movement produced a total displacement of 50.41 mm. Predicted displacement values were developed with the equations of dynamic load. The first peak was compared to predicted u_0 with P_0 as Pso given by (2) and the second peak by (4). Time duration for the first peak was given by (6) and for the second peak by (5). The first peak seems to be action of incident pressure and the second, reflected pressure. The records of displacement meter for all slabs and the comparisons can be seen in Table 1.

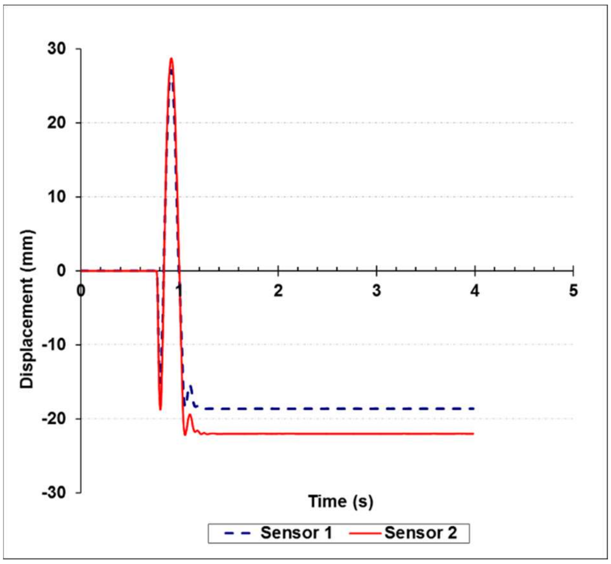

Fig. 6. Record of displacement meter of slab 1.

TABLE I COMPARISON OF PREDICTED AND EXPERIMENTAL RESULTS OF MAXIMUM DISPLACEMENT

Slab	Pso		Pr	
	Predicted u_0 (mm)	Recorded u_0 (mm)	Predicted u_0 (mm)	Recorded u_0 (mm)
1	36.4	18.74	58.70	50.41
2	35.5	22.90	57.70	33.34
3	38.0	40.99	61.00	71.39
4	39.1	22.22	65.20	25.70

It is worth to note that predicted values for three of the four slabs were higher than the experimental values. Only in the case of slab 3, which was retrofitted with Styrofoam on top, the predicted values were less than the experimental value, pointing that the foam worked against the protection of the target. Fig. 7 shows the comparison of predicted and recorded values of displacement with Pso as P_0 in the analysis. Results of maximum displacement with Pr as P_0 for calculations showed more reliable values, as shown in Fig. 8.

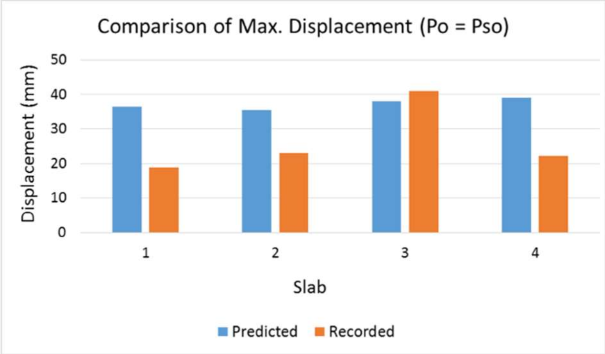

Fig. 7. Comparison of predicted and recorded maximum displacement with Pso as P_0.

The average of theoretical displacement values was 37.25 mm and for recorded value, it was 26.21 mm using Pso as P_0. Still, using Pr as P_0, the average of theoretical and recorded values were 60.65 mm and 45.26 mm.

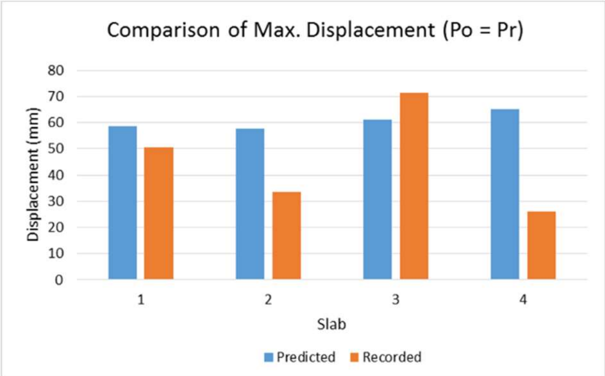

Fig. 8. Comparison of predicted and recorded maximum displacement with Pr as P_0.

Equations for dynamic analysis worked well in predicting values of maximum displacement, once the difference of the average from predicted values and recorded values for reflected pressure was 25%. For incident pressure, this average was 30%. For structural dimensioning 40% is a reasonable value of load safety coefficient [29].

The difference shown in the results of predicted and recorded values can be attributed to the slab support conditions. The slabs were not fixed, but just supported on two sides. In this way, the slabs could move up and down giving a lower value of recorded displacement. Equations of time duration approaches influenced the differences found in the comparisons, as one of them is for explosions in free air and the other for explosions on a surface. Equations for predictions of pressure are used for spherical shape of explosions, in this test, the explosive shape was cylindrical, and it can insert some differences in the comparison results. The retrofitting with Styrofoam showed that it could actually increase the value of displacement. This is in good agreement with observations of previous published works [19], [30], [31].

IV. Conclusions

Blast tests were carried out to compare experimental to predict displacement of the mid-span of four reinforced concrete slabs having 60 MPa compressive strength and 0.25% reinforcement ratio in two way. The slabs were simply supported and subjected to an explosion from a non-confined PBX explosive suspended at a stand-off distance of 2.0 m. One of the slabs had 5.0 cm Styrofoam retrofit in order to verify if it can partially absorb the blast energy.

The dynamic load analysis presented gives reasonable predicted displacement and pressure values when compared to experimental tests. Equations of Kingery and Bulmash worked very well to predict values of incident pressure and reflected pressure. Duration of time prediction worked better with equation of Kinney and Graham for t_d in period of reflected pressure and for incident pressure, was the equation of Kingery and Bulmash. The maximum displacement prediction using SDOF analysis was reasonable close to what was measured during the experiments.

Styrofoam on top of the slab increased the displacement recorded, showing that this material could not reduce the displacement for the same structure without this retrofit.

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