



ENGINEERING SCIENCES

Damage diagram of blast test results for determining reinforced concrete slab response for varying scaled distance, concrete strength and reinforcement ratio

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Abstract: Dynamic loads continue to draw the interest of structural engineers. The sources of these loads can be earthquakes, blast effects or transportation loads from railroads or highways. Especially for blast loads, terrorist attacks or military actions have caused many loses of lives and damages in several buildings. The verification of structural behavior is necessary to help designers to plan structures that support these loads and reduce damages. Although computer simulation with, specific software, have helped these designers, full-scale tests can provide valuable information about the real response of the structure. This paper presents damage diagram from ten full-scale field tests using approximately 2.70 kg of non-confined plastic bonded explosive against reinforced concrete slabs with different scaled distance, reinforcement ratio and concrete strength. The damage diagram is expected to be a help tool for designers to understand the effects of blast loads on slabs.

Key words: Blast field test, dynamic load, reinforced concrete, non-confined plastic explosive.

INTRODUCTION

Blast resistant design became an integral part for designers in recent decades, due to different threats arising from conflicts, wars, accidents and terrorist actions. Construction of safe structures is the aim of structural engineers. Facing these threats, designers need to verify the behavior of structural elements during explosions from different sources. Around the world, there are many constructions made from reinforced concrete (RC), especially in big cities that may became a target during a conflict, or even accidental explosion. Understanding RC behavior is essential for designers to work in a safety project, ensuring live prevention and avoid structural collapses. Unfortunately, many

accidents and attacks with explosive actions were reported around the world, resulting in loss of lives and building damage including, World Trade Center attacks in 2011 and industrial accidents. The failure of structures or part of them may develop a progressive collapse, and compromise the use of the structure (MacGregor & Wight 2005). Research in RC new technologies have been expanding in the last few years and could provide more options for designers that are trying to ensure safe conditions for buildings facing to explosive threats (Riboli 2012, Rocco 2000). In the last decade, researchers have reported that RC is the most appropriate material to support blast effects (Dusenberry 2010, Mays et al. 2012). Researches of Zhao &

Chen (Zhao & Chen 2013) demonstrate that reinforced concrete and reinforcement increase in resistance when subjected to blast, due the dynamic increase factor as presented by Li et al. (Li et al. 2016). Additionally, the construction of physical barriers is one of the techniques against blast effect to protect people and buildings (Department of Defense 2008). Coatings to mitigate blast effects in structures for reducing damages are studied, these materials generally presents higher yield than RC and can absorb part of the energy of blast wave (Shim et al. 2013, Wu & Sheikh 2013).

There are many definitions of explosion in the literature (Akhavan 2004, Keller et al. 2014, Ngo et al. 2007), but what is common for all definitions is the sudden, quick and high scale release of energy, generated due to physical, chemical or nuclear reaction. Especially for chemical explosion, the sudden elevation of temperature and pressure surrounding the epicenter of an exothermic oxidation reaction is the classical definition. This reaction occurs very fast (Sabatini et al. 2016).

Chemical explosives are substances capable of producing fast reactions enough to generate very high pressure, temperature and blast wave self-sustaining. These explosives can be classified as high or low explosives (Kubota 2007) depending on the energy of activation they need. High explosives need higher energy of activation, which can be given by a low explosive that needs few amount of energy to start its burn.

Depending on the distance of the epicenter and the construction different kind of damage can be determined for the same weight of explosive (ASCE 2010, UNODA 2011). Also, for this verification, the standardization of the explosive is needed considering the scaled distance (Z). Scaled distance is the value of stand-off distance (R) in meters, over the cubic root of the

mass in kg of equivalent TNT(W) (Brode 1955), as shown in Equation 1.

$$Z = \frac{R}{\sqrt[3]{W}} \quad (1)$$

This paper presents qualitative results of ten slab responses with different RC strength and reinforcement ratio, subjected to different scaled distance by chemical plastic bonded explosive in full-scale field tests. Three of the ten slabs were retrofitted with 50 mm thick expanded polystyrene foam (EPS) to verify if this material may change the structure behavior against blast. Mendonça et al. (2020) presented characterization results of this EPS foam. Researches have been done to verify the capacity of different materials and foam to influence structures response (Elshenawy et al. 2019, Sandhu et al. 2019). Results of simulation demonstrate that 5 cm thick foam can mitigate the blast load, transferring through the layer part of the blast energy (Elshenawy et al. 2019). Rubber foam and synthetic foam were able to mitigate acceleration of blast wave in field tests, as pointed by Sandhu et al. (2019), increasing of foam thickness generate more reduction of acceleration peak as well. The higher efficiency to reduce peak of acceleration was verified using rubber foam.

Blast effect

Detonation of high explosives can generate around 7000°C in the epicenter and decrease quickly, losing energy to the environment. In addition, pressure waves around 300.000 bar can be generated and moves from the epicenter compressing the surrounding air and propagating the blast wave toward the objects close to the explosion. This blast wave have supersonic velocity (Anandavalli et al. 2012, Dharma Rao et al. 2015, Ngo et al. 2007) and high capacity to produce damages to buildings,

assets and people. Blast wave parameters have been studied well, and a typical pressure time-history is presented in Figure 1 (ASCE 2010, Goel et al. 2012, Mendonça & Urgessa 2017). Where t_A is the time of arrival of blast wave front, t_o is the positive phase of the pressure, known as time of duration of positive phase, and t_{o-} the negative phase (a lower pressure than the ambient pressure). The highest value measured in the first peak of the graphic in Figure 1 is the peak overpressure (P_{so}). There are empirical equations available in literature for predicting P_{so} (Chiquito et al. 2019, Kingery & Bulmash 1984, Ngo et al. 2007).

To predict effects against structures the equations developed by Kingery and Bulmash have been widely used (Kingery & Bulmash 1984) to predict P_{so} , t_A and t_o . Integration of the positive phase of the curve gives the positive specific impulse (I), which is the main factor to generate damages in structures under blast (UNODA 2011). Equation 2 gives the expression to find positive specific impulse (ASCE 2010, Kinney & Graham 1985). Where t_{oi} is the time of beginning of the positive phase and t_{of} the final time for positive phase.

$$I = \int_{t_{oi}}^{t_{of}} P dt \tag{2}$$

MATERIALS AND METHODS

Ten slabs measuring 1.0 x 1.0 x 0.08 m were made from 40, 50 and 60 MPa concrete and different reinforcement ratio. The slabs were simply supported in two sides and the explosive was suspended above the slab. Due to this, the reinforcement was placed in the bottom face of the slab to support positive moment. Tensile strength for the reinforcement was estimated as 350 MPa. Table I gives the details of the slab and the explosive for the set-up of the ten tests. Reinforcement of the slabs have different ratio in each direction in four slabs. Stand-off distance was the same for eight tests, just for test 1 and test 10 they were changed. Concrete compressive strength (f_{ck}) was tested as Brazilian Standardization Norm and gave the results presented in Table I. Tensile strength for the concrete was estimated as 10 per cent of compressive strength. Figure 2a presents the set-up for the tests (Mendonça et al. 2017). Supports for the slabs were made from wood and have the dimensions shown in Figure 2b.

The explosive was non-confined due to the needs to have more reliable results without fragments influence (Mendonça et al. 2018), but just the blast wave. It was cylindrical in shape, have dimensions of 20 cm high and 10.5 cm

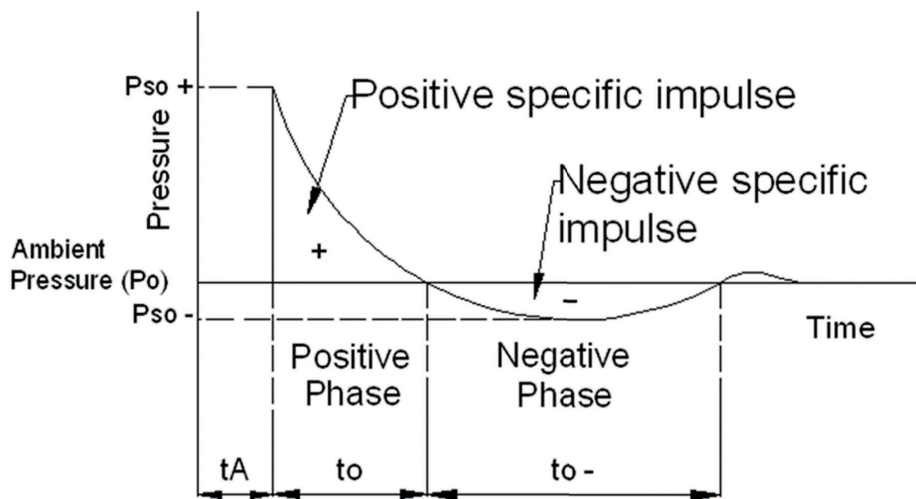


Figure 1. Typical pressure time-history for chemical explosion in free air.

Table I. RC slabs and explosive information. Slabs with (*) have 5.0 cm thick foam retrofit (Mendonça et al. 2017).

Slab	Fck (MPa)	Age (days)	Bar Diam. (mm)	Rebar Spacing (cm)	Rebar Direct.	Reinforc. Ratio	TNT Mass (kg)	Stand-off Dist. (m)	Z (m/kg ^{1/3})
1	40	28	5	15	Two way	0.17%	2.76	1.3	0.93
2	50	28	5	15	Two way	0.17%	2.72	2	1.43
			10	10	One way	0.37%			
3*	50	28	5	15	Two way	0.17%	2.71	2	1.43
			10	10	One way	0.37%			
4	60	28	5	10	Two way	0.25%	2.69	2	1.44
5	50	28	5	15	Two way	0.17%	2.58	2	1.46
			10	10	One way	0.37%			
6*	50	28	5	15	Two way	0.17%	2.72	2	1.43
			10	10	One way	0.37%			
7	60	28	5	10	Two way	0.25%	2.60	2	1.45
8*	60	28	5	10	Two way	0.25%	2.76	2	1.42
9	60	28	5	10	Two way	0.25%	2.72	2	1.43
10	40	28	5	15	Two way	0.17%	2.60	1.6	1.16

width, and the weight information can be found in Table I. In addition, the scaled distance is presented in Table I. The explosive was triggered by electrical fuse mounted on top completing an explosive train.

Multiple reflected pressure can be generated in explosions near structures as verified in this test (Li et al. 2016, Maji et al. 2008). Integration of positive phase of the time-history pressure curve is the main factor that causes damages in structures. Reflections can increase the integration result and increase the damages. Figure 3 shows a typical time-history pressure curve with some reflections that increase the area under the curve (Mendonça 2017).

Abbreviations

EPS – Expanded Polystyrene
 fck – Concrete Strength
 I – Specific Positive Impulse
 L – Light Damage

M – Moderate Damage
 Pso – Peak overpressure
 R – Stand-off Distance
 RC – Reinforced Concrete
 RR – Reinforcement Ratio
 S – Severe Damage
 t_A – Time of Arrival
 t_{of} – Final Time of Positive Phase
 t_{oi} – Time of Beginning of Positive Phase
 t_o – Time of Positive Phase Duration
 t_{o-} – Time of Negative Phase Duration
 W – Equivalent TNT Explosive Weight
 Z – Scaled Distance

RESULTS AND DISCUSSION

As expected, slabs with lower stand-off distance presented higher damages and collapsed during the explosion. Slabs with lower reinforcement ratio and lower concrete strength resulted in rupture of concrete. Slabs with reinforcement

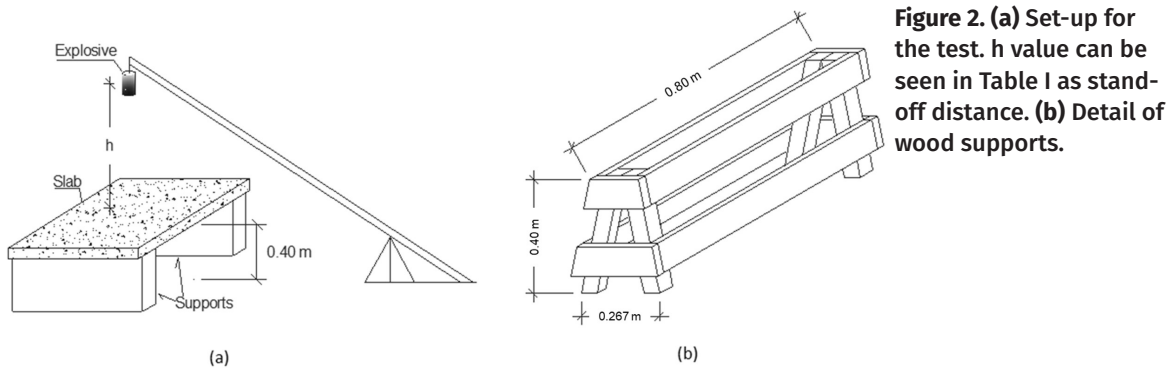


Figure 2. (a) Set-up for the test. h value can be seen in Table I as stand-off distance. (b) Detail of wood supports.

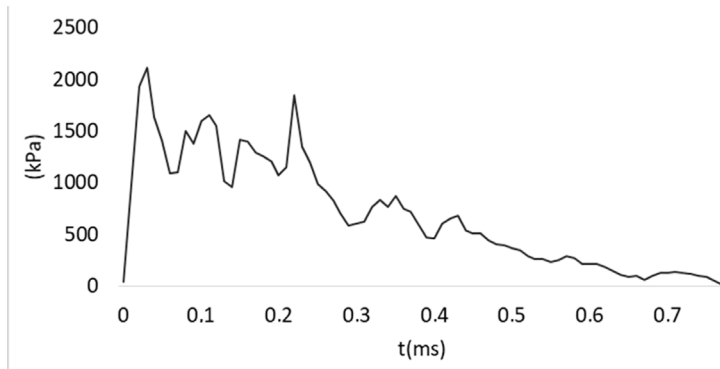


Figure 3. Example of time-history pressure curve with peak of reflections (Mendonça 2017).

ratio higher than 0.25% could support blast effect without collapse. All these cases had concrete with 50 or 60 MPa. Concrete with 40 MPa had the lower reinforcement ratio, and was destroyed during the explosion. The position of the explosive drive the main energy of the explosion to the center of the slabs, as can be seen in Figure 4a. The shape of explosion was the same for all tests due to the cylindrical shape of the explosive and the trigger position (Mendonça et al. 2018). Figure 4b presents slab 1 after test. As can be seen in Table I, it had the lower stand-off distance, reinforcement ratio in both directions and concrete strength (40 MPa). Additionally, the scaled distance is lower than $1 \text{ m/kg}^{1/3}$. The slab collapsed completely.

Slabs with two reinforcement ratios had collapse just in direction with lower reinforcement ratio. As can be seen in Figure 4c, slab 5 had a main crack across the section with lower reinforcement ratio (0.175%), in other direction with 0.37% there was fewer and smaller

cracks. Slab 5 had 50 MPa of concrete strength, higher value than slab 1 shown in Figure 4b. However, its scaled distance was higher.

Slab 2 had a similar result as shown in slab 5. These slabs had the same configuration test. Different results pointed for many configurations of test were displayed in a damage diagram to help structural designers to verify the effects of reinforcement or concrete strength on blast response. Figure 5 presents a damage diagram showing the results for all experiments. Simply supported in two sides slabs and having reinforcement just in the bottom face, allowed to identify the slab behavior. The following steps are necessary to read the diagram:

- 1) Choose the combination of scaled distance (Z) and equivalent TNT explosive weight (W) values in the center of the diagram;
- 2) Select concrete strength (fck);
- 3) Choose or verify the available reinforcement ratio (RR);

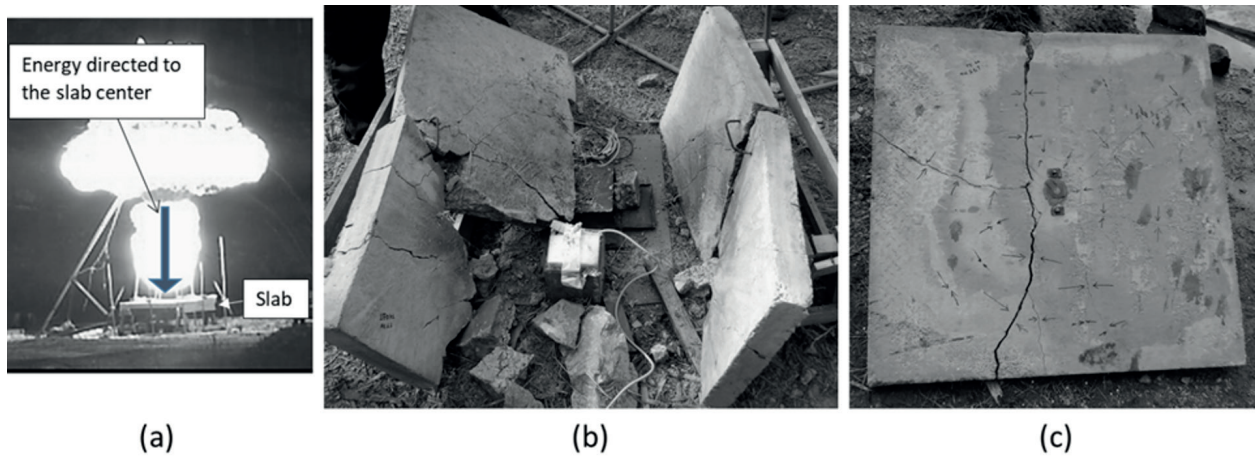


Figure 4. (a) Concentration of energy. (b) Collapse of slab 1 after test. (c) Main crack across weakness section after slab 5 test.

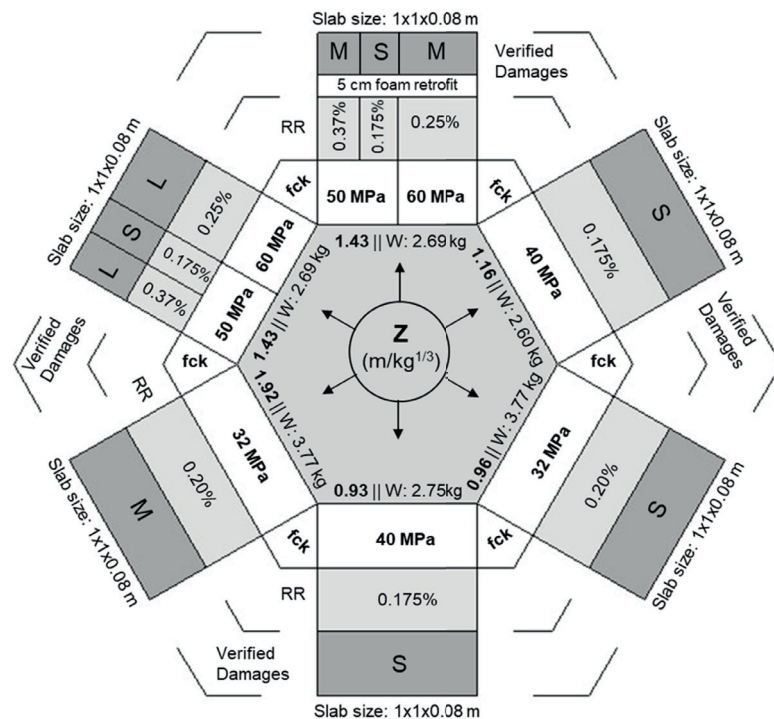


Figure 5. Damage diagram for full-scale field test of reinforced concrete slabs supported in two sides and reinforced in the bottom face.

4) Read the damage classification as Severe (S), Moderate (M) or Light (L) and verify if there is 5cm foam retrofitted for the chosen configuration.

Damage classification was adopted according to the damage verified in qualitative analysis and follows these criteria: S – represents failure of the fully concrete cross section; M – represents generalized cracks in preferred

direction without failure of reinforcement or concrete and L – represents minor visible cracks in only one side of the structure. Slab size is the last information given and can be expanded if future blast tests results are to be obtained.

In general, slabs with higher concrete strength and reinforcement ratio could support the blast effect better. These slabs will have light damages compared to others. Displacement

sensors having accurate within plus or minus 0.001 mm were able to ensure the verification of different slabs behavior. The structures with fewer reinforcement ratio and lower concrete strength had severe damages; their response mostly leading to collapse. Lower values of scaled distance provide higher damages.

CONCLUSIONS

A damage diagram from ten full-scale field tests using non confined plastic explosive was presented. The slabs had different reinforcement ratio, concrete strength and three different scaled distance. The damage characteristics of the slabs were determined using qualitative analysis. The classification of the damages was presented in a diagram where all the results could be visualized. This diagram is a useful tool to help designers in determining probable damages that structures with similar configuration could potentially experience. The diagram can be used for many explosive scenarios as long as the scaled distance values (Z) is used. Further works can be developed using different scaled distance and increasing the reinforcement ratio. The use of different thick foam and quality can be done to verify foam capacity to protect the structure.

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Dr. Fausto Batista Mendonça: His contribution to the current study include setup preparation, field test and full paper preparation. Dr. Girum Solomon Urgessa: He has contributed in the methodology used for field test and review of results. Dr. Luiz Eduardo Nunes de Almeida: He has contributed in the conceptualization of the damage diagram and analysis of field test results. Dr. José Atilio Fritz Fidel Rocco: His contribution include supervision in the field test and conclusion through results.

