Reference values for damage predictions of reinforced concrete slabs subjected to blast from field tests

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Abstract – **Destructive blast testing using explosives is one of the methods to verify the lethality of military weapons against potential military target structures. Adequate damage prediction on these structures allows for optimized planning of resources and materials for the field test. This work focuses on validating responses to recent experiments and proposing a mathematical expression to aid in predicting expected structural responses. Results from full-scale experiments were gathered to seek mathematical reference values for predicting damage in future experiments involving damage to reinforced concrete slabs. The observed damages were classified on a proposed scale with varying absolute values. A reference value equation was proposed as a prediction solution. It was concluded that variations in reinforcement ratio, scaled distance, concrete compressive strength (fck), and support conditions in the same experiment adhere to the proposed damage prediction equation.**

Keywords – **destructive blast test, damage levels, reinforced concrete slab, explosions, full-scale blast test**

I. INTRODUCTION

An explosion generates large amounts of energy rapidly, and it can emanate from a boiler explosion, a chemical reaction, or a nuclear reaction. Formally, an explosion, is classified as physical, chemical or nuclear explosion [1]. A chemical explosion results from an exothermic chemical reaction or a phase change that occurs in an exceedingly short period, generating a substantial amount of energy in the form of heat and usually producing a large volume of gas. During this explosion, an extremely rapid exothermic reaction results in the production of very hot gases and vapors. Despite the speed of this reaction, for a fraction of this time, the gases produced occupy the same space previously held by the reactants. Since this space is exceedingly small for the quantity of gases produced in the post-reaction phase, the temperature and pressure become extremely elevated, reaching several thousand degrees Celsius and multiple atmospheres. This pressure is sufficiently high to produce a shock wave, which ruptures the container walls and causes damage to objects near the event [1].

The products of an explosion are complex, as they include those formed directly by the reaction and those resulting from its impact on the surrounding environment [2], [3]. The direct products include gases such as carbon dioxide (CO_2), carbon monoxide (CO), water vapor (H_2O), and nitrogen (N_2), among others, as demonstrated in the computational simulation of a chemical explosion reaction [4].

Chemical explosives are employed in all aerial weapon platforms. The primary damaging effects of their use are the formation of shock waves [5], also known as the "blast effect", and fragmentation - it is a direct consequence of the rapid expansion of gases during detonation, causing the ejection of fragments from the casing and/or objects within the explosion area [6]. In a conflict scenario, the use of weapon equipped with high explosive charges is decisive when seeking to inflict greater damage than that caused by weapon direct impact. The ability of explosives to release a substantial amount of energy against a target, even having practical and safe to handle, has made them the primary element in modern conflicts [7]. After World War II, the behavior of structures that could be potential military targets, subjected to the terminal effects of detonating military artifacts, has continue to be explored [8]–[10]. The development of new construction materials, as well as construction techniques such as prestressed concrete and composite material, continue to be evaluated for their ability to withstand explosion effects [11]–[15].

Terrorist actions that were intensified around the world by the end of last century correspond to another factor in increasing research in this area [16]. Researchers analyzed blast effects (shock wave, fragmentation and heat) against new construction materials such as CFRP (carbon fiber-reinforced plastic) and GFRP (glass fiber reinforced plastic) [17], [18]. Field tests have been done to verify the capacity of these materials to withstand blast subjected to dynamic load caused by explosion, whether accidental or intentional [19], [20]. Structures to protect buildings and people during an explosion have been studied, by structural designers and engineers [21]–[23].

Loss of life in explosion events has been a concern for researchers in recent decades. Developing systems or materials capable of mitigate damage to people and buildings have become the objectives in the studies of terminal effects absorbing materials [24]–[26].

A. Blast effects and fragmentation

Detonation of high explosives generates hot gases, overpressure above 300,000 bar and temperatures between 3,000 and 4,000°C. Hot gases expand, generating a volume greater than the original previously occupied by the charge, moving away from the initial epicenter. This event results in the formation of a layer of compressed air, known as a shock wave [27], and develops damages to people and structures. When metallic casing confines the explosive, such as in aerial bombs and howitzers, the rupture of the casing during detonation generates high-energy fragments, which are equally important for calculating the lethal power of the weapon.

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B. Shock wave

Research indicating the development of shock waves through free air detonation has been presented for several decades [27]–[29], however, as studies are directed towards practical applications, it becomes necessary to investigate behaviors that closely resemble real-world scenarios, such as when an environment is subjected to a terrorist attack. The study of interactions between shock waves and structures can be highly complex, given the multitude of variables that may be considered in a real environment[30].

This paper aims to survey damages caused by the main terminal effects, observed in recent studies on the behavior of the most commonly found construction materials, such as reinforced concrete, proposing levels of damage observed according to factors inherent to the target material and the distance from it to the explosive.

II. MATERIAL AND METHODS

A survey of records on terminal effects published in experimental tests with explosives targeting reinforced concrete structures was conducted. This material was chosen because it is commonly found in most buildings and constructions as the primary structural support. The 11 destructive tests identified were listed according to 9 characteristics, as follows:

- Material (frame material);
- fck (concrete compressive strength, in MPa);
- Thickness of the slab;
- Reinforcement spacing;
- Reinforcement ratio (ρ_s);
- W (explosive charge weight, in TNT);
- Standoff distance (R);
- Scaled distance (Z, in m/kg$^{1/3}$),
- Observed damage (damage presented after the interaction of the explosive with the structure, according to visual analysis).

The analyzed works provided concrete compressive strength (fck) values. Reinforcement ratio values (ρs) are obtained by the ratio of the steel cross-sectional area (As) to the concrete cross-sectional area (Ac), according to (1) [20].

$$\rho_s = \frac{A_s}{A_c} \quad (1)$$

Scaled distance depends on the standoff distance (R) in meters and the equivalent TNT mass of the explosive (W) in kg as presented in (2).

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad (2)$$

To compare damage to structures tested in different research and sources, a classification was created under four levels of damage in concrete structures, through qualitative observation. Table 1 presents the classification of each level of damage.

TABLE I. CLASSIFICATION OF DAMAGE LEVEL OBSERVED IN EACH TEST

Level	***Description of the damage***
I	Apparent damage not observed
II	Cracks, fissures, or detachment of small parts were observed, without altering their original shape
III	In addition to the damage observed at Level II, a rupture of the concrete section was observed, keeping the reinforcement preserved, but the structural element presented curvature
IV	Destruction of the concrete structural element, characterized by its collapse and rupture of the concrete and steel reinforcement

In order to linearize the responses of damage, a relationship between scaled distance and the reinforcement rate in each structure analyzed was proposed. To get a relationship value, called Vr, and relate it to the damage, the reinforcement rate and scaled distance were multiplied, and this result was multiplied by 1000 to facilitate comparison as shown in (3).

$$Vr = \rho_s * Z * 1000 \quad (3)$$

III. RESULTS AND ANALYSIS

The first analyzed study involved damage assessment of a simply supported reinforced concrete slabs, measuring 1.0 × 1.0 × 0.08 meters subjected to PBX (Plastic Bonded Explosive). Experimental destructive tests were conducted, allowing for the adjustment of certain factors to analyze the resulting damage [20]. The compressive strength of the concrete slabs (fck) and the reinforcement ratio of the cross-section (ρs) were varied. Additionally, small variations in the scaled distance (Z) were observed in this study. The main objectives of the study were to compare theoretical results with experimental data obtained from sensors and to suggest a minimum reinforcement ratio for reinforced concrete elements subjected to the blast wave effects from an explosion. The explosive was not encased in a metallic shell; therefore, the observed terminal effects included only blast and heat, without fragmentation. The characteristics of the slabs and each experiment are presented in Table II, for slabs 1 through 7. Fig 1 shows the results of the experiment for slab 1.

Fig. 1. Slab 1 after explosion [20].

Figure 2 shows the observed results for slab 6 after the explosion. By comparing it with Fig. 1, it is possible to verify how the increase in reinforcement ratio and the concrete compressive strength, combined with the increase in scaled distance, contributed to the reduction in damage caused by the explosive action.

Fig. 2. Slab 6 after explosion [20].

Work carried out by Wang et. al [31] was the second result analyzed. This study aimed to compare experimental results with numerical results obtained from computer simulations of the detonation of a suspended explosive (TNT) over simply supported concrete slabs, measuring 1.0 × 1.0 × 0.04 meters. The differences in the results of the destructive field tests were due to variations in the explosive charges, as the slabs had the same concrete compressive strength and reinforcement ratio. The analyses in this article focused solely on the qualitative results identified by the authors in the experimental field tests; a comparative analysis between the field test and the computer simulation was not conducted. The characteristics of the experiment and the slabs are described in Table II, slabs 8 to 11.

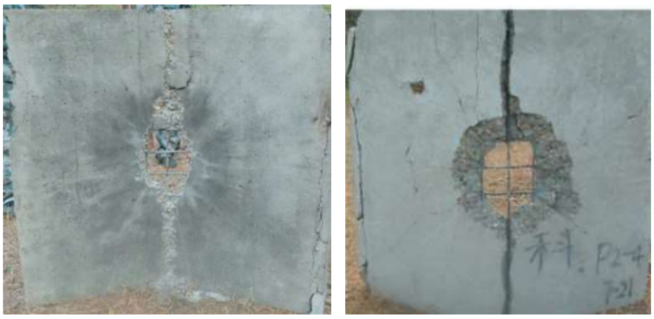
Figure 3 presents the results of the experiment conducted on slab 10. The left side shows the upper surface, while the right side displays the lower surface, where concrete spalling can be observed. The reduction in the scaled distance (Z) led to an increase in the damage to the slab, as can be seen in Fig. 4, which shows the results of the test on slab 11.

TABLE II. SLABS CHARACTERISTICS AND EXPERIMENTS CONDITIONS

Slab	*fck (MPa)*	*ρ_s (%)*	*Z ($m/kg^{1/3}$)*	*Support*
1	40	0.17	0.93	double supported
2	50	0.17	1.43	double supported
3	60	0.25	1.44	double supported
4	50	0.17	1.46	double supported
5	60	0.25	1.45	double supported
6	60	0.25	1.43	double supported
7	40	0.17	1.16	double supported
8	39.5	1.43	0.68	double fixed
9	39.5	1.43	0.59	double fixed
10	39.5	1.43	0.52	double fixed
11	39.5	1.43	0.49	double fixed

(a) (b)

Fig. 3. Slab 10 after explosion, (a) upper face and (b) bottom face [31].



(a) (b)

Fig. 4. Slab 11 after explosion, (a) upper face and (b) bottom face [31].

A. Relationship: characteristics of materials x lethality

A comparison of the experimental results was sought to demonstrate the relationship with the levels of damage observed in each test. The factors considered were the reinforcement ratio (ρ_s) and scaled distance (Z). Scaled distance points to the magnitude of the explosion concerning to the reference distance. By comparing the values of scaled distance with the observed damage levels, we can indeed confirm the purpose of the scaled distance for structures with similar composition and elements. However, caution is necessary in the analysis, as the values are not subjected to a nonlinear relationship, and thus the damage does not adhere to a simple numerical correlation. For example, doubling the value of the scaled distance does not result in half the magnitude of the damage. For smaller scaled distance values, slight variations can lead to significantly different damage levels, as evidenced by the tests on slabs 8 to 11 in Table III.

TABLE III. DAMAGE LEVELS AND REFERENCE VALUES VERIFIED

Slab	*R (m)*	*W (kg)*	*Damage Level*	*Vr*
1	1.3	2.76	III	1.581
2	2.0	2.72	II	2.431
3	2.0	2.69	II	3.600
4	2.0	2.58	II	2.482
5	2.0	2.60	II	3.625
6	2.0	2.72	II	3.575
7	1.6	2.60	III	1.972
8	0.4	0.20	I	9.724
9	0.4	0.31	II	8.437
10	0.4	0.46	II	7.436
11	0.4	0.55	III	7.007

The result of the relationship proposed in (3) was consistent only when used in isolation, for the same work, when the changes in reinforcement ratio and scaled distance are subtle. It is important to note that similar Z values do not necessarily imply the same impact on a structure, as the value of the specific positive impulse, the actual cause of damage to a structure, can vary for the same Z. Within the same analyzed work, the values of the scaled distance were consistent with the observed damage, meaning that the smaller the Z value, the greater the qualitatively observed damage.

For the tests conducted on slabs 1 to 7, it was observed that Vr values less than 2.0 indicate a level III of damage, which can escalate to level IV when the value falls below 1.0. For the tests on slabs 8 to 11, the range that influences the damage levels differed: values above 9.7 indicate level I of damage, between 9.7 and 7.4 indicate level II, and values below 7.4 correspond to level III of damage. These analyses indicated that the damage thresholds can only be applied to experiments with identical boundary conditions. Having the same type of support, dimensions of the structural element, and its design characteristics, such as reinforcement ratio and concrete compressive strength (fck).

IV. CONCLUSIONS

The results of eleven destructive tests using explosives positioned above reinforced concrete slabs were analyzed. The experimental conditions varied in terms of concrete compressive strength (fck), reinforcement ratio in the cross-section, standoff distance, explosive weight in TNT equivalent (W), and slab support conditions. These variations, when not significantly different within the same experiment, did not result in abrupt changes in the damage classification according to the proposed scale. However, for experiments with significant differences in these aspects, the damage level scale shows substantial changes. Therefore, it is concluded that for experiments maintaining the same boundary conditions, with minor variations in material characteristics and the positioning and composition of the explosive, the method presented here can provide qualitative damage predictions according to the developed damage scale.

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