Lethality of Loitering Munitions Against Concrete Structures

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Abstract* – Advancements in military technology since the 20th century have facilitated the development of sophisticated weaponry, including loitering munitions (LM). These systems have seen increasing deployment in modern armed conflicts, notably in the Russia-Ukraine War. Given their growing prevalence in military operations, it is critical to assess the effectiveness of LM in targeting reinforced concrete structures, which are commonly found in military infrastructure. This study evaluates the destructive capacity of LM against reinforced concrete structures of varying dimensions and material compositions through a comprehensive literature review. The analysis compares the performance of warheads in field experiments, focusing on scenarios involving near-detonation and direct-contact detonation. The findings indicate LM have significant destructive potential against reinforced concrete structures, with damage varying by reinforcement ratio and concrete compressive strength. These results highlight LM's ability to cause substantial damage to military targets, especially standard building structures.

***Keywords* – Loitering munition, lethality, suicide drones**

I. INTRODUCTION

The continuous advancement of technology has facilitated the enhancement and creation of numerous military artifacts, particularly since the Second World War. Among these artifacts, loitering munitions (LM), also known as suicide drones or kamikaze drones [1], have been developed and employed in armed conflicts since the 1980s. Some of the more recent conflicts in which they have been used include the Libyan Civil War (2014–2020), the Nagorno-Karabakh War (September–November 2020), and the Russian-Ukraine War (February 2022 to the present) [2].

These artifacts represent a disruptive innovation in contemporary warfare, combining the precision of missiles with the versatility of drones. These missile-drone hybrids are characterized by their ability to loiter or hover over targets, awaiting the optimal moment to strike [3].

In 2017, a report by the Center for the Study of the Drone at Bard College (USA) identified approximately 35 types of LM of varying sizes and capabilities that were either in use or under development in eight countries at that time.

Since then, this market has undergone significant transformation. A 2023 study by the Vertical Flight Society (VFS) identified over 210 types of LM, ranging from hand-carried micro-drones to those weighing more than 150 kilograms, with approximately 87% of these systems in some stage of development or active use [4].

Recent conflicts, such as those in the Middle East, Nagorno-Karabakh, and particularly in Ukraine, have highlighted the significance of LM.

The Lancet-3, developed by Zala Aero Group, is one of the primary types of loitering munitions employed by Russian forces in the war. According to the manufacturer, between the onset of the conflict and December 29, 2023, Lancet munitions were deployed 872 times, destroying approximately 698 Ukrainian targets [3].

In 2022, the Argentine government signed a contract for the acquisition of Hero-30 and Hero-120 LM models from the Israeli manufacturer UVision®. Common characteristics of these types of weapons include their versatility for use against a range of military targets, such as light and armored vehicles, anti-aircraft artillery, radars, command posts, bunkers, as well as their application as anti-personnel weapons and against other targets that provide a military advantage in combat zones [5]. Some of these potential military targets are partially or entirely constructed from reinforced concrete or masonry.

Given the increasing use and significance of these emerging technologies in military contexts, it is critical to understand the extent to which they are effective in attacking civil construction structures. Accordingly, the objective of this study is to evaluate the capacity of LM to cause significant damage to reinforced concrete structural elements that constitute buildings.

II. THEORETICAL FOUNDATION

It is important to highlight the distinction between the concepts of Unmanned Combat Aerial Vehicle (UCAV) and loitering munition. The term UCAV refers to armed unmanned aerial vehicles that serve as platforms for the deployment of air-based weaponry [6].

In contrast to Unmanned Combat Aerial Vehicles (UCAVs), which are reusable and deploy armaments through launching mechanisms, LM are expendable and detonate upon impact with the target due to their explosive warhead. The primary advantage of LM compared to guided missiles, for instance, lies in their aforementioned ability to loiter or hover over a target area prior to striking [7].

They are portable and equipped with high-resolution electro-optical and infrared sensors and cameras, which enable target search, monitoring, acquisition, and guidance of the LM to a specific target [8]. Fig. 1 and 2 illustrate examples of a UCAV and an LM, respectively.

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Fig. 1. Bayraktar TB-2 UCAV equipped with weapons [9].

Fig. 2. Switchblade 600 LM [10].

The volume and quantity of explosives in LM directly impact their flight autonomy, necessitating design adjustments to achieve an optimal balance between the mass of the warhead (WH) and the total mass of the LM [11].

There is a wide variety of warhead types; however, their effects are primarily generated through three main damage mechanisms: blast, fragmentation, and directed explosive energy. Most explosive warheads do not rely solely on a single damage mechanism but rather employ a combination of these three primary types to create a more effective warhead [12]. Fig. 3 presents a simple configuration of LM main components.

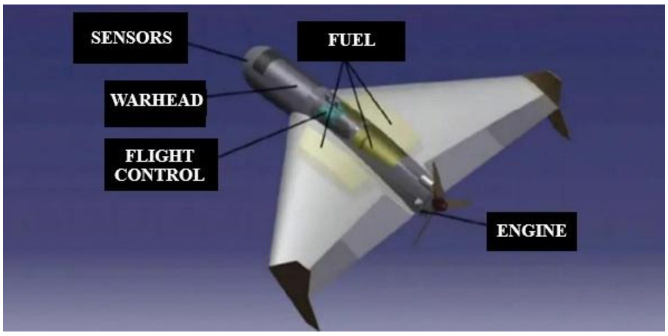

Fig. 3. A LM Components [13].

A comprehensive database containing 52 LM developed in 16 countries was published based on data available in the public domain [11]. The database includes information such as maximum takeoff weight, warhead mass, dimensions, and other parameters; some of these data can be viewed in Table I.

TABLE I. *LOITERING MUNITIONS DATABASE* [11]

Country	***Name***	***Dep. Max. Weight. (kg)***	***WH Mass (kg)***	***Flight time (min)***
Armenia	*Hreesh*	7	-	-
Australia	*Drone*-40	-	-	20
Belarus	*Burevestnik* MB	-	10	40
China	CH-901	9.1	2.7	120
South Korea	*Devil Killer*	25	2	10
USA	*Switchblade* 300	2.5	0.3	20
	Switchblade 600	22.7	1.5	40
	Persistent	27	-	-
	Munition	6.8	1.4	60
	Cutlass	2.7	0.4	30
	Terminator	5.9	0.9	60
	Coyote	2.4	0.4	30
	Battlehawk	1.8	0.2	20
	Hero-20	3	0.5	30
	Hero-30	7	1.2	45
	Hero-70	12.5	3.5	60
	Hero-120	12.5	4.5	60
	Hero-120NG	25	5	180
	Hero-250	25	8	240
	Hero-400	40	10	120
	Hero-400EC	97	20	420
	Hero-900	125	30	-
	Hero-1250			
Europe	*Fire Shadow*	200	22	360
Yemen	*Samad*-2	87.5	18	402
	Samad-3	107.4	18	808
Indonesia	*Enrol Pilot*	3	0.8	20
Iran	*Qasef*-1/*Ababil*-2t	85	30	120
Israel	*Orbiter* 1 K	11	2.6	150
	Sky Striker	-	5 – 10	60 – 120
	Green Dragon	15	3	150
	Harop	-	23	360
	Harpy	135	32	120
	Harpy NG	160	16	540
	Mini Harpy	40	8	120
	Rotem	5.8	1.2	45
	Spike Firefly	3	0.35	15
Poland	*Warmate*	5.3	1.4	70
	Warmate 2	30	3	120
	Warmate TL	-	-	-
	Warmate V	7	-	30
Russia	KYB-UAV	19	3	30
	Lantset 1	5	1	30
	Lantset 3	12	3	40
Türkiye	*Alpagu*	1.9	-	10
	Kargu	6.3	1.4	15
	Kargu-2	6.8	1.4	30
Ukraine	RAM	8 – 10	2 – 4	60 – 30

A. Effects of explosives detonation

One of the destructive effects caused by the detonation of an explosive results from the blast effect generated by the reaction gases at extremely high pressure and temperature, reaching overpressure values exceeding 300,000 bar and temperatures between 3,000–4,000°C [14]. These gases expand around the detonation site in the form of a bubble, with its surface consisting of a concentrated layer of air known as a shock wave. This wave, due to its supersonic velocity, causes an abrupt increase in pressure, density, and temperature in the areas it traverses [15].

Parameters such as pressure, time, and distance can be standardized using a cubic scaling method. This methodology is widely employed as it simplifies graphs and aids in calculations. The most commonly scaled parameter is distance, as presented in Equation (1) [16], where Z represents the scaled distance, R denotes the distance from the epicenter in meters (m), and W indicates the mass of the explosive in TNT equivalent, in kilograms (kg) [17].

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

B. Explosive damage to structures

To evaluate the behavior of a reinforced concrete slab subjected to the effects of a shock wave resulting from the detonation of a military-grade plastic explosive, an experimental test was conducted using PBX (plastic-bonded explosive), composed of 86% HMX (high melting explosive) [17].

For the experiment, three masses of four kilograms of PBX were placed at distances of three meters, one and a half meters, and in direct contact with the slab, which was simply supported. The concrete slab had a characteristic compressive strength of 32.6 MPa and dimensions of 0.7 x 0.7 x 0.10 m, with positive reinforcement consisting of a steel mesh with 5.0 mm diameter bars spaced at 15 cm intervals. The schematic illustrating the experimental setup is represented in Fig. 4.

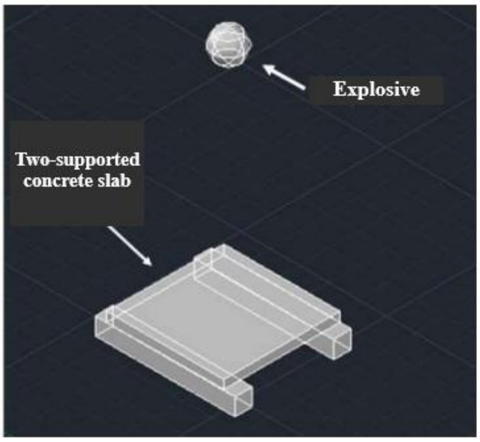

Fig. 4. Schematic diagram of the experimental setup, illustrating the arrangement of components (not to scale) [17].

At a distance of three meters, the detonation of the explosive caused cracks in the slab, compromising its load-bearing capacity, though it did not lead to the complete failure of the structure. At a distance of one and a half meters, the effect of concrete rupture was observed on the underside of the slab. The internal steel mesh remained intact, without yielding to the point of complete rupture. On the underside of the slab, it was noted that several pieces of concrete had detached and were propelled, separating from the slab. The detonation of the explosive charge in direct contact with the slab resulted in the total destruction of the structure, as shown in Fig. 5.

Following a visual assessment of the results, it was possible to infer the damage that would be caused to structural elements and, consequently, to buildings subjected to the shock wave loads observed in this experiment. These inferences can be verified in Table II.

Fig. 5. Detonation of the PBX in contact with the concrete slab [17].

TABLE II. INFERENCE OF RC SLAB CONDITION AFTER SUBJECTED TO SHOCK WAVE OF 4.0 KG OF PBX [17].

Stand-off distance (m)	*Scaled distance "Z" ($m/kg^{1/3}$)*	*Observed damages*	*Inference of structures condition after visual assessment*
3.0	1.77	Small cracks on the upper and lower face	Compromise of the building's load capacity
1.5	0.88	Breaking of the concrete section, keeping the reinforcements in the original position	Slab rupture
0.0	0.08*	Complete destruction	Collapse of the structure

* Considering that the center of mass of the explosive would be the distance from the charge to the face of the slab.

C. Classification of damage to structures and materials

A classification system was developed to compare the damage to tested structures based on various studies and sources. This system consists of four levels of damage to concrete structures, aiming to encompass the potential consequences that may occur in such structures [18]. Table III presents this classification.

TABLE III. DAMAGE LEVEL CLASSIFICATION [18].

Level	*Damage description*
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, rupture of the concrete section was observed, with the reinforcement preserved, but the structural element presented curvature
IV	Collapse of the concrete structural element, characterized by its collapse and rupture of the concrete and steel reinforcement

III. METHODOLOGY

Through a literature review of open-source documents, articles, studies, dissertations, theses, and manufacturers' manuals, this study aimed to evaluate the lethality of loitering munitions against buildings by analyzing the effects of the shock wave (blast effect) on various reinforced concrete structures resulting from the detonation of an explosive, thereby excluding the effects of fragmentation and penetration.

To this end, initial research was conducted to gain a deeper understanding of this emerging technology, its concepts, characteristics, and capabilities. Particular emphasis was

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placed on identifying the warhead mass of these munitions, as this is a critical parameter for the execution of this study.

To analyze the behavior of structures subjected to the detonation of an explosive charge, experimental field tests were reviewed, which involved reinforced concrete structures of varying dimensions and compositions exposed to an explosion. These tests provided data correlating the damage to different structures with different scaled distances "Z."

The damage classification for structures and materials, ranging from Level I to IV as outlined in [18], was employed to quantify the results from various sources and studies reviewed.

Using the data on warhead masses from different LM models listed in Table I, combined with the results of experiments involving explosions near various structures, it was possible to compile these data into tables for comparison. This enabled an estimation of the destructive capacity of the researched LM models against the analyzed structures.

IV. RESULTS AND DISCUSSION

To estimate the destructive capacity of the LM listed in Table I, their respective scaled distances (Z) were calculated and compiled in Table IV. The "Z" value was determined using TNT as the standard explosive for all LM, and a distance of 5 cm was considered, corresponding to the distance between the LM's warhead and the target at the moment of impact.

TABLE IV. "Z" VALUES OF LM CONSIDERING TNT AS AN EXPLOSIVE, AT A DISTANCE OF 5 CENTIMETERS.

Country	***Name***	***WH Mass (kg)***	***Scaled distance Z ($m/kg^{1/3}$)***
Belarus	*Burevestnik* MB	10	0.023
China	CH-901	2.7	0.036
South Korea	*Devil Killer*	2	0.039
USA	*Switchblade* 300	0.3	0.075
	Switchblade 600	1.5	0.044
	Cutlass	1.4	0.045
	Terminator	0.4	0.068
	Coyote	0.9	0.052
	Battlehawk	0.4	0.068
	Hero-20	0.2	0.086
	Hero-30	0.5	0.063
	Hero-70	1.2	0.047
	Hero-120	3.5	0.033
	Hero-120NG	4.5	0.030
	Hero-250	5	0.029
	Hero-400	8	0.025
	Hero-400EC	10	0.023
	Hero-900	20	0.018
	Hero-1250	30	0.016
Europe	*Fire Shadow*	22	0.018
Yemen	*Samad*-2	18	0.019
	Samad-3	18	0.019
Indonesia	*Enrol Pilot*	0.8	0.054
Iran	*Qasef*-1/*Ababil*-2t	30	0.016
Israel	*Orbiter* 1 K	2.6	0.036
	Sky Striker	5 – 10	0.029-0.023
	Green Dragon	3	0.035
	Harop	23	0.018
	Harpy	32	0.016
	Harpy NG	16	0.019
	Mini Harpy	8	0.025
	Rotem	1.2	0.047
	Spike Firefly	0.35	0.071
Poland	*Warmate*	1.4	0.045
	Warmate 2	3	0.035
Russia	KYB-UAV	3	0.035
	Lantset 1	1	0.050
	Lantset 3	*3*	0.035
Türkiye	Kargu	1.4	0.045
	Kargu-2	1.4	0.045
Ukraine	RAM	2 – 4	0.039-0.032

Among the LM listed in Table IV, it is observed that the Israeli Harpy model has the highest warhead payload capacity, at 32 kg, while the American Hero-20 has the lowest, at 0.2 kg, corresponding to scaled distances "Z" of 0.016 and 0.086 $m/kg^{(1/3)}$, respectively.

The data from experimental tests of explosives against structures, gathered from the literature review, were compiled and are presented in Tables V and VI. All analyzed structures were reinforced concrete slabs. Among the characteristics of the tested specimens are the scaled distance "Z" values and the corresponding observed damage levels.

TABLE V. EXPERIMENTS NUMERATION

Author	**N**
Mendonça et al. 2021	1
Zhao e Chen 2013	2
Castedo et al. 2015	3
	4
	5
	6
Li et al. 2016	7
	8
	9
	10
	11
Tanapornraweekit, Haritos e Mendis 2011	12
	13
	14
	15

TABLE VI. DAMAGE LEVEL FOR EACH EXPERIMENT.

Experiment Number	***Thickness (mm)***	***Compressive stress (MPa)***	***Scaled distance ($m/kg^{1/3}$)***	***Damage level***
1	100	32.6	0.08	IV
2	40	39.5	0.52	II
3	150	25	0.20	III
4	150	25	0.20	III
5	150	44.16	0.20	III
6	150	43.33	0.20	III
7	120	40	0.03*	III
8	120	145	0.03*	III
9	100	145	0.03*	III
10	150	145	0.03*	III
11	120	145	0.03*	III
12	75	32	0.52	III
13	75	32	0.52	I
14	75	32	0.65	I
15	75	32	0.65	I

* Considering distance of 3 centimeters

The structures numbered 7 to 11 did not have available "Z" values in the article, necessitating their calculation. Based on the data from Tables IV, V, and VI, it is possible to compare the "Z" values of the LM with the "Z" values of the structures and their respective damage levels, thereby estimating the lethality of the LM listed in Table IV against the different experiments in Table VI, as illustrated in Fig. 6.

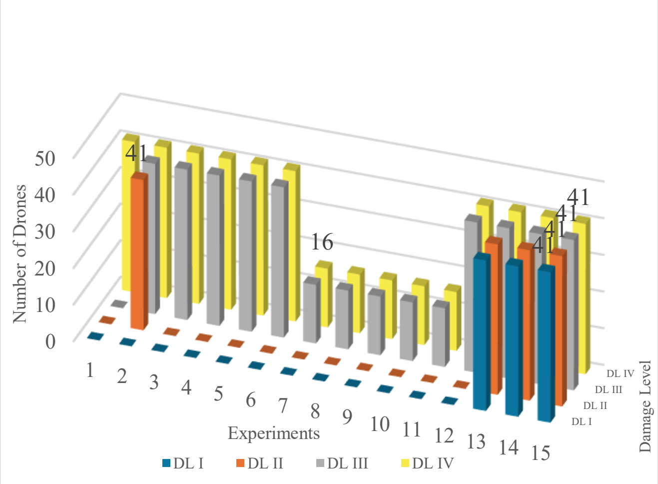

Fig. 6. Amount of LM that can cause a level of damage to one of the evaluated structures.

Analyzing the obtained values, it can be stated that virtually all the explosive devices (LM) listed in Table IV would cause total destruction (damage level IV) to a structure with the specifications of Structure 1, as all have a value approximately less than or equal to the "Z" value of Structure 1, which is 0.08 m/kg$^{(1/3)}$.

Structure 2 exhibited a damage level II for a "Z" value of 0.52 m/kg$^{(1/3)}$; however, the maximum "Z" value of the LM is 0.086 m/kg$^{(1/3)}$ for the Hero-20. Therefore, it can be inferred that the damage level caused by the LM in Table IV against a structure with the specifications of Structure 2 ranges from II to IV, leaning more toward total destruction of the component when compared to the damage level inflicted on Structures 1 and 6.

For Structures 3 to 6, the LMs in Table IV would cause damage ranging from level III to IV.

Among the observed LM, 16 with values less than or equal to 0.03 m/kg$^{(1/3)}$ would cause damage ranging from level III to IV in structures with the specifications of Structures 7 to 11.

Structure 12 would experience a damage level of III to IV for all LM in Table IV.

Among the structures reinforced with fiber polymers, Structure 13 presented a "Z" value of 0.52 m/kg$^{(1/3)}$, while Structures 14 and 15 demonstrated a "Z" value of 0.65 m/kg$^{(1/3)}$. Thus, it can be inferred that virtually all LM in Table IV would cause a damage level ranging from I to IV, tending toward more severe damage.

The damage level as a function of "Z" can be visualized in Fig. 7. Analyzing its values, it is observed that lower "Z" values resulted in more severe damage, corresponding to the gray area. Conversely, "Z" values above 0.52 m/kg$^{(1/3)}$ led to lighter damage, corresponding to the yellow area. The observed damage values at Z = 0.52 m/kg$^{(1/3)}$ varied due to the significant differences among the reference structures, indicating that structures with higher load-bearing capacity are capable of withstanding greater effects.

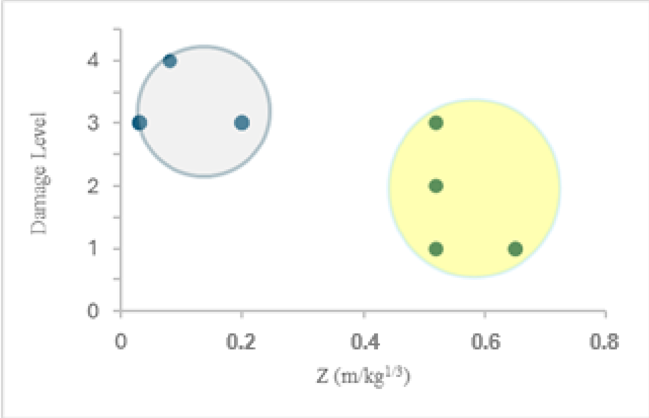

Fig. 7. Graphical representation of damage level as a function of "Z".

V. CONCLUSION

This study aimed to assess the lethality of loitering munitions (LM) against buildings, focusing on the effects of the shock wave (blast effect) resulting from the detonation of an LM upon impact with reinforced concrete structures of varying dimensions and compositions. The evaluation was conducted through a literature review of recent academic publications on the subject.

By comparing the capabilities of warheads from various LM models with the results obtained from field experimental tests that evaluated the detonation of an explosive in proximity to a reinforced concrete structure, it was observed that this emerging technology possesses significant destructive potential against such structures, which exhibit characteristics commonly found in military target buildings. The observed damage ranged from Level III to Level IV.

The findings were derived, within the established boundary conditions, from comparisons and inferences based on the analyzed experimental tests, some of which involved scaled distance values (Z) greater than the range typically associated with LM. The research remains ongoing, with plans to conduct field tests to subject high-strength structures to the scaled distance (Z) range of LM, aiming to evaluate their behavior under blast-induced stresses.

Future studies are recommended, employing field experiments to investigate the fragmentation effects caused by warheads.

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