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Research Article

The Impact of Weapon Systems on Structural Damage and Progressive Collapse: A Case Study of Belgorod Oblast

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Abstract: Structures are exposed to unexpected loads throughout their service life nowadays. This phenomenon, referred to as progressive collapse in the literature, has attracted the attention of researchers in recent years. This study examines the effects of firearms on buildings during wartime and their relationship with progressive collapse. Conducted using the example of Belgorod Oblast, a border city in Russia, the research evaluates the destructive impacts of various types of firearms and ammunition on residential buildings, commercial buildings, and historical structures. During the data collection phase, the data obtained daily was converted into weekly data. The research provides detailed data on the frequency of structures exposed in various villages and cities in the Belgorod region to different types of attacks and the types of damage caused by these attacks. In the analysis method, damages were classified from superficial damage to complete destruction, and the cause-effect relationship between firearm types and building damage was evaluated. The findings indicate that buildings suffer significant structural deterioration due to the types of damage sustained during wartime, and progressive collapse is rarely triggered. It is suggested that future studies focus on developing new design and construction techniques to enhance the durability of buildings, especially in the façade and roof, in light of these findings. The results of the study provide valuable information that will help us better understand the effects of firearms and modern warfare technologies on progressive collapse and the impacts of firearms on buildings.

Keywords: Blast loads, Progressive collapse, Russia-Ukraine war, UAV, Weapon systems

Silah Sistemlerinin Yapılar Üzerinde Yarattığı Tahribat ve Aşamalı Göçme Bağlantısı: Belgorod Oblastı Örneği

Öz: Günümüzde yapılar hizmet ömürleri süresince beklenmedik yüklere maruz kalmaktadırlar. Literatürde aşamalı göçme olarak adlandırılan bu durum son yıllarda araştırmacıların ilgisini çekmektedir. Bu çalışmada, savaş sırasında ateşli silahların yapı üzerindeki etkileri ve bu etkilerin aşamalı göçme ile ilişkisi incelenmiştir. Rusya'nın sınır kenti olan Belgorod Oblastı örneği üzerinden yürütülen araştırmada, farklı türde ateşli silahlar ve mühimmatların konutlar, ticari binalar ve tarihi yapılar üzerindeki yıkıcı etkileri değerlendirildi. Veri toplama aşamasında, günlük olarak elde edilen veriler haftalığa çevrilmiştir. Araştırma, Belgorod bölgesindeki çeşitli köy ve şehirlerdeki yapıların, farklı türde saldırılara maruz kalma sıklığı ve bu saldırıların neden olduğu hasar türleri üzerine ayrıntılı veri sağlamaktadır. Analiz yönteminde, hasarlar yüzeysel hasardan tamamen yıkılmaya kadar sınıflandırılmış ve ateşli silah türleri ile yapı hasarı arasındaki sebep-sonuç ilişkisi değerlendirilmiştir. Bulgular, yapıların savaş sırasında maruz kaldıkları hasar türlerine göre ciddi yapısal bozulmalara uğradığını ve aşamalı göçmenin nadiren de olsa tetiklendiğini göstermektedir. Gelecekteki çalışmaların, bu bulgular ışığında, yapıların özellikle cephe ve çatıda dayanıklılığını artıracak yeni tasarım ve inşaat tekniklerinin geliştirilmesine odaklanması önerilmektedir. Çalışmanın sonuçları, ateşli silahların ve modern savaş teknolojilerinin yapı üzerindeki aşamalı göçme etkilerini daha iyi anlamamıza ve ateşli silahların yapılar üzerindeki etkilerini anlamaya yardımcı olacak değerli bilgiler sunmaktadır.

Anahtar Kelimeler: Aşamalı göçme, İHA, Patlama yükleri, Rusya-Ukrayna savaşı, Silah sistemleri

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1. Introduction

Progressive collapse can be defined as a chain-reaction failure mechanism that can occur when structures are subjected to unexpected loads. These unexpected loads, which are not considered during the design phase, can arise for various reasons. The most significant of these is the impact of explosives or firearms. This situation typically occurs during terrorist attacks or on the battlefield. In war and conflict environments, the damage inflicted on structures and damage impact on structural integrity are of critical importance. It is known that this damage, which begins with the loss of a column, imposes additional loads on the rest of the system.

The first known example of progressive collapse occurred in 1968 at the 22-story Ronan Point apartment building. This structure was built using the large panel system (LPS) method with prefabricated concrete panels. A gas explosion on the 18th floor dislodged the exterior walls of the building, causing the upper floors to collapse sequentially in a domino effect. The collapse revealed significant deficiencies in the assembly of the prefabricated concrete panels and the safety of the gas installation, leading to major changes in building safety regulations in the United Kingdom. As a result of this incident, developed countries began to include explanations and criteria related to progressive collapse in their regulations, the 2001 terrorist attacks on the World Trade Center (WTC) (Kilicer, 2024).

Today, the United States Department of Defense's UFC 4-023-03 '*Design of Buildings to Resist Progressive Collapse*' is actively used in relation to progressive collapse. Design engineers can determine a structure's resistance to progressive collapse by using the analysis methods outlined in this guide. Although countries such as the United Kingdom, Canada, Russia, and others have included definitions and descriptions related to progressive collapse in their regulations, they have not provided clarity on the analysis methods. Therefore, the UFC 4-023-03 guide is used worldwide as a reference for progressive collapse analyses. While the UFC 4-023-03 guide does not generally address the specific events leading to progressive collapse, it examines the structural effects of potential column losses and offers various analysis methods. Events that could cause column loss include firearms and modern technological weapons.

This study examines the effects of firearms on structures and current research on progressive collapse. Studies such as those by Tahmilci (2007) and Francioli et al. (2021) address the behavior of structures under blast effects and the relationship between these effects and progressive collapse. Ozgan et al. (2023) examined the effect of ground influence on progressive collapse, while Abdelwahed (2019) aimed to provide design engineers with a broader perspective on minimizing the consequences of building progressive collapse following a column removal scenario. Byfield et al. (2014) addressed the challenges of frame modelling with steel connections and highlighted the advantages and disadvantages of some modelling procedures related to the treatment of connections. Stephen et al. (2019) proposed different alternative numerical approaches to simulate the sudden column removal in frame buildings and to investigate the effect of rise time on the structural response. Marjanishvili (2004) compared different modelling techniques used in progressive collapse analysis. He discussed the advantages and disadvantages of each method and concluded that the most effective analysis procedure for progressive collapse evaluation is a method that incorporates the advantageous parts of all four procedures. Kim & Kim (2009) investigated the progressive collapse-resisting capacity of steel moment-resisting frames using alternate path methods recommended in the GSA (2003) and DoD (2015) guidelines. They considered linear static and nonlinear dynamic analysis procedures for comparison. Compared to the linear analysis results, the nonlinear dynamic analysis provided larger structural responses, and the results varied more significantly depending on variables such as applied load, location of column removal, or number of building stories. Weng et al. (2016) examined nonlinear analysis methods for column removal scenarios in reinforced concrete buildings. Yuzbasi & Arslan (2019) conducted a comprehensive investigation into various methods used to model the progressive collapse mechanism of structures, as well as their application in simulating demolition processes. Building on this, Yuzbasi (2024) carried out experimental verification on the progressive collapse of a full-scale silo structure, specifically focusing on the effects of successive column removal. This study utilized the finite element method and incorporated blast load simulations to replicate the collapse sequence, offering valuable insights into the practical application of these methods. Fan et al. (2023) studied the Gurson-Tvergaard-Needleman (GTN) constitutive model, which describes the aggregate failure of metal voids, is selected as the constitutive relation to investigating the damage evolution and fracture of semi-rigid joints in steel structures during a progressive collapse.

Today, the rapid advancement of warfare technologies and the proliferation of firearms increase the risks structures face during war. Particularly, modern warfare techniques, such as UAV and FPV kamikaze drone attacks, raise questions about whether they cause significant structural damage and trigger progressive collapse. This situation raises curiosity about how the resilience of both civilian and military structures changes during warfare. Specifically, using the ongoing Russia-Ukraine war and the example of Belgorod, the destructive effects of different types of firearms and ammunition on residential buildings, commercial buildings, and historical structures will be evaluated. The primary objective of the research is to classify the types of damage structures encounter during war and examine the impact of this damage on structural integrity and progressive collapse. In this context, the cause-effect relationship between types of firearms and structural damage will be analyzed, and the potential for progressive collapse will be assessed. This research aims to contribute to the development of strategies for protecting structures under wartime conditions

This research examines in detail the frequency and types of damage caused by various attacks on structures across different villages and towns in the Belgorod region. The methodology of the study consists of three main stages: data collection, analysis, and presentation of results. Data were systematically collected from the Governor of Belgorod, official accounts, and the Russian Ministry of Emergency Situations. These data were supplemented with additional information such as photos and locations of the structures. The collected data were classified according to the types of damage, and the cause-effect relationship between types of firearms and structural damage was evaluated. Analysis results and key findings were reported, and recommendations were made to enhance the resilience of structures based on the types of damage they endure during wartime. The findings of the research indicate that structures undergo different structural deteriorations based on the types of damage they sustained during the war.

2. Material and Methods

The concept of progressive collapse has been increasingly observed in the literature since the 2000s, although it has always been present on battlefields and in structures exposed to unexpected loads. This study aims to explain the damage caused by firearms and modern weapon technologies on structures through real and contemporary examples. In this context, the Belgorod Oblast of Russia, which has been frequently subjected to attacks, has been considered. The types of modern and conventional attacks experienced by the oblast and its structures, including kamikaze drones, unmanned aerial vehicles, and classifications of structural damage, are explained under the following headings.

2.1. The Belgorod Oblast of Russia

Belgorod Oblast is a region in the southwestern part of Russia, bordering Ukraine. It has a total area of approximately 27.100 km² and a population of about 1.5 million people. Belgorod Oblast shares a border with Ukraine that is approximately 540 km long (Figure 1). This border holds significant importance, particularly in terms of military, security, and trade. Due to its strategic location, it is a region of great military importance for Russia. The region hosts various military structures, including air defense systems, logistics and support services, facilities, and bases. These bases play a strategic role in both protecting Russia's western borders and in its relations with Ukraine. The area is also equipped with air defense systems, which play a crucial role in protecting the oblast from threats posed by various firearms and aerial dangers. Given Belgorod Oblast's political significance and the ongoing Russia-Ukraine war, the locations of attacks by Ukrainian armed forces on Russia's Belgorod Oblast are provided using the map from Google Earth (2003) (Figure 1).

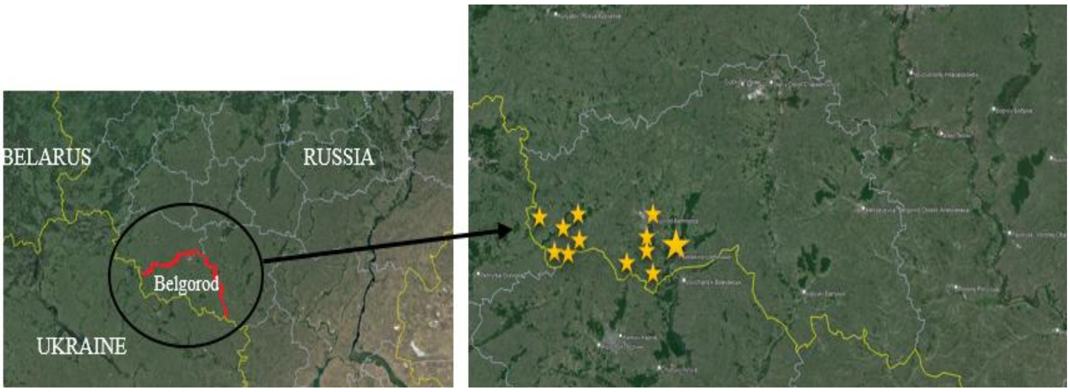

Figure 1. The location of Belgorod Oblast and the areas where the attacks.

Between May 6, 2024, and June 16, 2024, the structures most affected by attacks conducted by the Ukrainian Armed Forces on Russia's Belgorod Oblast were located in Shebekino (27 attacks), Murom (16 attacks), Belgorod city center (13 attacks), Novaya Tavolzhanka (10 attacks), Dubovoye (10 attacks), and Bezymeno (6 attacks).

Belgorod Oblast stands out as a border region due to its location. The buildings constructed in these areas are similar to those in the rest of Russia. It would be more accurate to evaluate the buildings in Russia based on the pre-1970 and post-1970 periods in terms of construction technology and material quality.

Ateş Can & Bakır (2021) discussed how residential architecture in the Soviet Union in the 1920s was approached to support the ideology, laying the foundations for communal housing in an ideological sense. These foundations were developed through studies conducted under Stroikom with state support, and the resulting housing designs were improved through analysis and optimizations in various categories, similar to the works in the West. Various competition proposals for new buildings that emerged during these years are presented in Figure 2 (Movilla Vega, 2020).

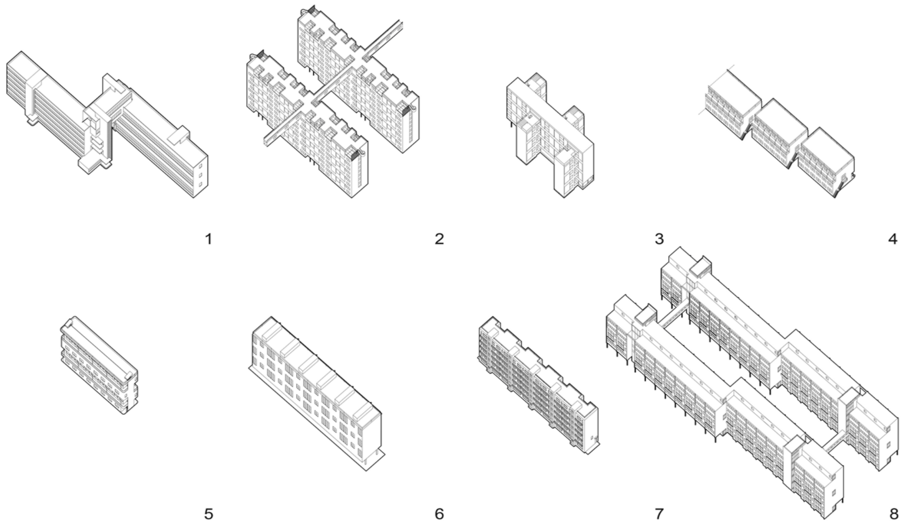

Figure 2. Axonometric views of the eight proposals submitted to the 1926 Comradely Competition: Ginzburg (1), Vegman (2), Vladimirov (3), Ol’ (4), Vorotyntseva and Polyak (5), Nikol’skiy (6), Pasternak (7) and Sobolev (8). Graphics by Daniel Movilla Vega (Movilla Vega, 2020).

Buildings constructed before 1970 bear the marks of the impacts of World War II and the political, economic, and socio-cultural differences that followed. The first of these is wooden architecture, the oldest type of architecture in Russia. The most importan t areas where wood was used as a construction material were Russian national houses and various facilities (Anlatilaninotesi, 2016).

Another example is Brutalism, which refers to the appearance resulting from the use of concrete in its raw, massive, imposing, and stark form on the building's exterior. This type of architecture typically featured materials like steel and glass over time, becoming essential elements of Brutalist architecture, which offers economical, simple, and ergonomic structures (Venni, 2024). In residential buildings, wooden structures and a series of five-story prefabricated buildings were constructed to quickly address the need for housing. Although many different types of buildings were constructed, especially in housing, the exterior walls consisted of large-sized expanded clay concrete blocks (40 cm), the interior walls were made of concrete blocks (39 cm), the inner walls were made of gypsum slag concrete panels (8 cm), and the floors were made of prefabricated hollow reinforced concrete slabs (22 cm) (Novostroev, 2019). Despite having thick exterior and interior walls, these structures cannot be said to be resistant to firearms and explosions that release greater energy.

After 1970, the way was paved for Russia to attract tourists and for local architecture to change by using modern, diversified, and different types of buildings and construction materials. At the same time, restoration work was carried out on buildings constructed in previous years (Sayer, 2020). Various building types were identified, and construction began, distributed across all regions of Russia. These buildings were constructed using different materials. The construction year, building materials, and purpose of some Russian buildings after 1970 are presented in Table 1.

Table 1. Characteristics of some types of Russian buildings after 1970 (Prawdom, 2024)

Building Type	Construction Year	Building Material	Purpose
111-96	1975-1996	Large Panel	Housing
111-97	1970	Large Panel	Housing
111-101 (P-101)	The Late 1970s	Panel	Military Housing
111-108	1970	Panel	Housing
111-121	1970	Panel	Housing
111-134	1975-1990	Large Panel	Housing
114-85	1974-2000	Brick	Housing
114-86	1975	Brick	Housing
1605	1958-1985	Panel	Industrial
90	1971	Large Panel	Housing
E-93	1970-2000	Brick	Housing
II-18/12	1967-1970	Panel	Housing
II-49	1965-1985	Multi-Unit Panel	Housing

The types of structures listed in Table 1, built throughout the Soviet Union, are mostly constructed of panel and brick. Some of these types of structures were built in the Belgorod region. The progressive collapse resistance of the structures subject to the study is particularly low in panel-type buildings. In structures built before 1970, the initiation of progressive collapse is simpler due to both poor material quality and technological deficiencies compared to the present day. Although buildings constructed throughout the Soviet Union after 1970 are seen as somewhat more resistant to progressive collapse, they were built with this deficiency as the structural analyses and designs did not take progressive collapse into account. In rural areas outside the city center, the quality and workmanship of the buildings are separate issues that need to be discussed. In the following sections, real-time examples and locations are provided to illustrate how munitions targeted at buildings can cause progressive collapse.

2.2. Kamikaze drones

FPV (First-Person View) kamikaze drones are remotely controlled unmanned aerial vehicles equipped with explosives. These drones are primarily used for military and security purposes and are usually designed for one-way missions. They are typically equipped with explosive payloads and complete their missions by crashing into targets or detonating at specific locations. High-resolution cameras and low-latency video transmission systems are used to allow the operator to control the drone with precision. These drones are generally equipped with some explosives and aim to cause damage by crashing into targets or detonating at predetermined locations. Drone operators can control them with high precision using special control devices or FPV goggles. Their applications include military operations, counter-terrorism, and security. They offer advantages such as high precision, flexibility, and low cost, while disadvantages include being single-use, the risk of signal interruption, and legal and ethical issues. Although there may not be a direct destructive effect on the structures, the fires initiated after the explosion can cause maximum damage to the building as they spread. Otherwise, localized explosions will only cause superficial damage.

Borsari & Davis (2023) describe various types of drones, including military-class medium-altitude long-endurance drones like the Turkish TB2, loitering munitions like the U.S. Switchblade, commercial DJI quadcopters, and homemade first-person view drones. Axe (2023) noted that in the later stages of the war, the use of FPV-piloted kamikaze drones to target both infantry and armored vehicles became widespread. This provided Ukraine with an incredibly cheap and effective attack alternative as well as a tool for psychological warfare. Rickli & Mantellassi (2024) noted that the quality of personnel is also reflected in the use of drones and is one of the most important factors in their effective utilization. Depending on the quality of the pilot, the success rate of an FPV drone flight can vary from 10% to 80%. An example of an FPV drone and its payload frequently used by the Ukrainian Army is shown in Figure 3.

(a) (b)

Figure 3. FPV Drones (Militarnyi, 2023) a) FPV Drone appearance b) FPV Drone with payload.

FPV drones play a significant role in modern battlefields and security operations. With technological advancements, the usage and effectiveness of these drones have also increased. However, in the context of progressive collapse, FPV drones do not seem to be successful. Although the impact at the target depends on many parameters, their effects on structures are quite limited. Even though drones can carry different amounts of TNT, Their carrying capacity is generally in the range of 1–5 kg (SavunmaTR, 2024). If these types of drones cause a fire after exploding, they can inflict maximum damage. Otherwise, they do not have the maneuverability and power to initiate a chain collapse mechanism in structures. They can cause regional damage at the point of explosion. Farcaş (2023) revealed that aside from structural damages, the most effective weapon in the Black Sea conflict was the drone. Many experts claim it is an artillery war, but they argue that they do not acknowledge. Also, the Chinese army, which has seen the intensive use of FPV drones in the Russia-Ukraine war, aims to expand the use of these drones; it conducts training and exercises for this purpose. For example, in a drill held in March 2024, Chinese army personnel used tanks and checkpoints (structural and non-structural elements) (Alpusam, 2024).

2.3. UAV (Unmanned Aerial Vehicle)

Unmanned Aerial Vehicles (UAVs) are aircraft that can be remotely controlled or autonomously programmed to perform various flight missions and tasks. UAVs, also defined as aircraft without human pilots onboard, can come in various sizes and shapes suitable for different types of missions. Nowadays, these vehicles are widely used across nearly every sector, primarily in military, civil, and commercial applications.

The history of UAVs began with the development of the Kettering Bug during World War I. However, the widespread adoption and advancement of this technology gained momentum with the use of radio-controlled target drones before and during World War II. Throughout the Cold War, the United States and the Soviet Union developed UAVs for espionage and intelligence-gathering purposes. In the 1970s, Israel laid the foundations of modern UAV technology by developing the Scout UAV. Throughout the 1990s and 2000s, the United States became a pioneer in this field by utilizing advanced UAVs such as the Global Hawk and Predator in military operations. Today, UAVs have a wide range of applications in both military and civilian fields, becoming more autonomous and versatile with technological advancements (Army Technology, 2021; Anderson, 2023; Wikipedia, 2024). Over the years, the evolution and transformation of technology, along with developments in military and political arenas, have influenced the current uses and development of UAVs. In recent years, UAVs have clearly demonstrated their ability to change the course of many conflicts. However, the impact of such new technological products on structures has not been fully explained. The damage that different types of UAVs can cause to structures and whether they can lead to structural collapse remains a subject of curiosity.

Many UAVs today are capable of carrying munitions and are actively used in wars for intelligence, surveillance, reconnaissance, assault, and special operations. Table 2 provides information on some UAVs in the inventory of the Ukrainian army and their missions during operations on Russian territory.

Table 2. Some UAVs in the inventory of the Ukrainian Army (Ukrspecexpor, 2024)

Name	Role	Country
Bayraktar TB2	Intelligence, Surveillance, Reconnaissance (ISR), Attack (Karar, 2023)	Türkiye
Leleka-100	ISR (Savunmasanayist, 2021a)	Ukraine
Punisher	ISR and operations (Crumley, 2022)	Ukraine
Spectator-M1	Surveillance and reconnaissance (Interfax, 2019)	Ukraine
PD-2	ISR, Attack (Savunmasanayist, 2021b)	Türkiye

From the table above, it can be assessed that the Leleka-100, Punisher, RQ-20 Puma, and Spectator-M1 UAVs, which are solely for ISR missions, are not capable of causing damage to structures. In contrast, the Bayraktar TB2 and PD-2 UAVs, which have attack roles, are capable of causing damage to structures. These UAVs, which carry munitions, sometimes target buildings and other elements. The Leleka-100, Punisher, and Spectator-M1 are manufactured by Ukraine, the RQ-20 Puma by the USA, and the Bayraktar TB-2 and PD-2 by Türkiye. The Bayraktar TB-2 is shown in Figure 4, and the PD-2 UAVs are shown in Figure 5.

Figure 4. Bayraktar TB-2 (Baykartech, 2024).

Figure 5. PD-2 (Ball, 2024).

The type and amount of munitions they carry are directly proportional to the damage they can inflict on structures. It is generally considered that these UAVs aim to target more practical and hard-to-reach areas rather than to demolish a building. In the following sections, the effects of the attacks carried out by the Ukrainian army using UAVs over Russia's Belgorod Oblast on structures are examined. Detailed information about traditional bombardment vehicles, rocket launchers, mortars, shrapnel, or MLRS used by the Ukrainian army is deemed unnecessary. These types of attack vehicles have been used worldwide for years and currently have no different designs or features. Particularly military unmanned aerial vehicles can damage structures due to the munitions they carry. Yiğit et al. (2018) stated that strategic and tactical UAVs are used for bombing, damage infliction, and assessment missions, while Erdil (2021) noted that UAVs are equipped with munitions and perform similar tasks to air force aircraft in many countries

2.4. Classification of structural damages

This study evaluates structural damages under six categories: no damage, minor damage, moderate damage, severe damage, total collapse and progressive collapse (Figure 6).

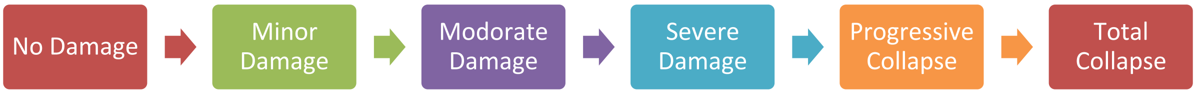

Figure 6. Classification of structural damages.

No damage: It is the condition where no structural or non-structural damage occurs in the building. In this case, the building maintains its full functionality without any compromise in safety or performance. Both the primary structural elements and secondary systems remain unaffected by external forces.

Minor damage includes superficial damages that do not affect the structure's overall integrity. It encompasses superficial damages such as small cracks, peeling plaster, flaking paint, removal of a facade or cladding material, and broken windows. The crack width should be less than 0.5 mm. It does not affect the load-bearing system of the structure and generally does not require repair or can be addressed with simple repairs. Minor cracks in interior and exterior walls, deterioration of roof covering materials, or small damages to floor coverings are also considered in this scope.

Moderate damage refers to noticeable damages in some parts of the structure that partially affect its usability. Examples include large cracks in the walls (limit 0.5 mm < w < 3.0 mm), cracks in columns or beams, jamming of doors and windows, and deformations in some parts of the structure. It can partially damage the load-bearing system, requiring repair, but does not cause the structure to completely collapse. Large cracks, issues with door and window closures, cracks in concrete elements, holes in the roof, and deteriorations in the ridge and rafters of the roof are evaluated within this category.

Severe damage involves significant damage to the load-bearing system of the structure, greatly endangering the safety and usability of the structure. Examples include serious cracks or breaks in columns and beams, large collapses in the walls, and complete collapse of some parts of the structure. The load-bearing system is severely damaged, potentially rendering the structure unusable. It requires either irreparable or very costly repairs. Breaking of columns, collapse of beams, falling of walls, and total collapse of some parts of the structure are included. These damage types are crucial criteria for evaluating structures after unexpected loads. Appropriate repair and strengthening works should be carried out for each type of damage.

Progressive collapse is a structural chain reaction in which damage that starts in any part of the structure spreads over time to other sections, causing a partial or total collapse of the structure. This type of collapse is triggered when initially small, localized damage (caused by various factors such as abnormal loads, terrorist attacks, construction errors, etc.) spreads to other parts of the structure. Typically, the building does not collapse suddenly but loses its stability over a period of time, eventually collapsing. The differences in this collapse process distinguish progressive collapse from total collapse. Figure 7 shows an image from SAP2000, where Kilicer (2024) determines the progressive collapse resistance of a reinforced concrete structure after the loss of a column. As can be seen, plastic hinges form in the beams, and the structure may start to collapse from a specific area due to the loss of load-bearing capacity in one or more elements. In this study, the difference between total collapse and progressive collapse were identified by the fact that the structure does not collapse all at once but experiences a chain reaction mechanism triggered by the loss of elements.

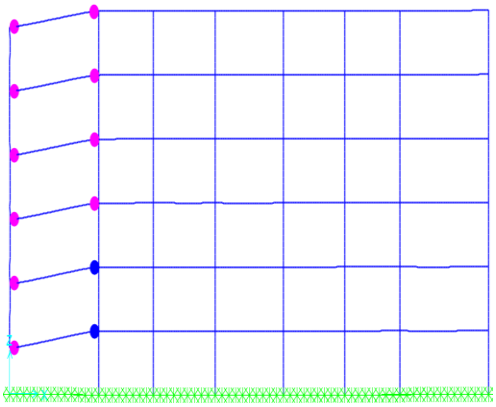

Figure 7. A view of a progressive collapse analysis in the SAP2000 program (Kilicer, 2024).

Total collapse is a failure in buildings where the entire structure or a significant portion suddenly and completely collapses. It typically occurs due to severe weaknesses in the load-bearing elements, sudden overloading, material fatigue, or external factors such as earthquakes, explosions, or high winds (Figure 8). The difference from progressive collapse is that total collapse happens suddenly, rendering a large portion of the structure unusable at once, whereas progressive collapse starts in one section of the structure and spreads to other areas over time. Total collapse events occur when the supporting and load-bearing components fail to perform their functions, leading to the structure becoming entirely unusable. Such a collapse can result in both significant financial loss and serious casualties.

(a) (b)

Figure 8. A view of a total collapse a) before collapse b) Total collapse (Kim et al., 2019).

3. Results

The research and investigations conducted in the Belgorod Oblast of Russia include a comprehensive weekly and regional examination of the damage structures sustained during the war, with a specific focus on progressive collapse. In these investigations, the destructive effects of different types of firearms and ammunition on residential, commercial, and historical buildings have been analyzed in detail, taking into account the data officially presented by the Governor of Belgorod Region, Mr Vyacheslav Vladimirovich Gladkov, and the Belgorod Region Operational Headquarters. During the data collection phase of the research, photographs of damaged structures, damage assessment reports, and other supplementary information obtained weekly have been systematically gathered. This data has been sourced from the Belgorod Regional Government and official accounts, as well as the Russian Ministry of Emergency Situations**.**

A comprehensive review of the existing literature on progressive collapse and war damage has been conducted and supported by data obtained from Russia. The analysis methods are based on classifying the various levels of damage to structures, ranging from superficial damage to progressive collapse. This classification covers a wide spectrum, from minor cracks to the complete collapse of buildings. Additionally, the cause-and-effect relationship between types of firearms, ammunition, and structural damage has been thoroughly evaluated. The primary aim is to determine how much of the damage caused to structures within a specific timeframe during the war can lead to progressive collapse or identify which type of attack triggers the chain-collapse mechanism.

In some cases, attacks occur near structures without causing any damage. Many such attacks have been recorded. Explosions around infrastructure facilities, auxiliary buildings (barns, outbuildings), wildfires, various equipment, motor vehicles, and military vehicles have been disregarded unless they caused damage to structures. Two images of such incidents are provided in Figure 9.

Figure 9. An example of attacks that did not cause structural damage (Governor of Belgorod, 2024).

In light of the information provided above, Table 3 has been prepared considering the attacks by Ukrainian armed forces on Russia's Belgorod Oblast between May 6, 2024, and June 16, 2024. Only cases of window breakage have been excluded; all other attacks that have been officially recorded are considered under the headings No Damage, Minor Damage, Moderate Damage, Severe Damage, Total Collapse, and Progressive Collapse**.**

Table 3. Types and distribution of structural damage sustained

Date	No Damage	Minor Damage	Moderate Damage	Severe Damage	Total Collapse	Progressive Collapse
06.05/12.05		16	10			1
13.05/19.05		19	13	4	3	
20.05/26.05		17	10	6	1	
27.05/02.06	1	23	6	2	1	
03.06/09.06		18	6	2		
10.06/16.06	1	7	1	1		1

The table shows the types of damage sustained by structures and their numerical distribution according to damage levels as a result of attacks in the Belgorod region during specific dates. Between May 6 and May 12, a significant number of superficial and moderate damage cases were observed, with one case of progressive collapse. During the period from May 13 to May 19, in addition to superficial and moderate damage, the presence of severe damage and total collapse incidents is noteworthy. In the week of May 20 to May 26, there are high amounts of superficial and moderate damage, along with severe damage and total collapse cases. The week of May 27 to June 2 saw the highest number of superficial damage cases. In the week of June 3 to June 9, the severe damage cases relatively decreased, while superficial and moderate damages continued. In the week of June 10 to June 16, there was a general decrease in the types of damage, but still, one case of progressive collapse was recorded. It is thought that the increase in attacks at the end of May and the beginning of June is due to improved weather conditions. Overall, the data shows that structures in the Belgorod region have sustained various levels of damage as a result of the attacks. Progressive collapse cases have been recorded on specific dates, indicating serious structural failures. According to the given data, the percentage of progressive collapse cases in total damage incidents is approximately 1.18%, while total collapse cases account for about 2.92 %. These percentages show that progressive collapse is rare among all damages, whereas total collapse represents a more serious condition. This situation highlights the severity of risks faced by structures in the region during the war and the need to enhance their resilience.

Structures in the Belgorod region suffer various damages during the war. The intensity of attacks and the targeted areas affect the degree of damage to the structures. Examples of superficial damage, the lowest degree of damage, which can sometimes be repaired with low budgets or may not require any repair at all, are shown in Figure 10.

(a) (b) (c)

(d) (e) (f)

Figure 10. Examples of Minor Damage: a) exterior wall damage, b) roof puncture, c) facade damage, d) roof damage, e) porch damage, and f) facade damage (Governor of Belgorod, 2024).

The images show superficial damages such as small damages and deformations on the exterior walls of residential buildings, punctures and deteriorations on roofs, window damages, facade cladding damages, peeling paint, and falling plaster. Additionally, cladding damage on commercial buildings, cracks, and peeling on the exterior walls of apartment buildings are noticeable. These superficial damages are cosmetic in nature, do not affect structural integrity, and usually require simple repairs. These damages, caused directly by the war, can negatively impact the usability limits of the structures.

Previously, it was explained that moderate damage refers to a situation where a structure or object has suffered a certain degree of damage but has not become completely unusable. This type of damage is typically characterized by the preservation of structural integrity to a large extent but with significant damage to some non-load-bearing walls, roofs, or other components. The structure or object may partially lose its function; for example, some rooms in a building may become unusable while other parts remain functional. Visible cracks, fractures, or deformations may be present, but severe situations like the collapse of the structure are not in question. Moderate damage, although requiring significant repairs, can be restored to a usable condition through these repairs.

Structures in the Belgorod region do not always sustain the same level of damage during the war. The intensity of the attacks and the targeted areas affect the degree of damage to the structures. Moderate damage represents the middle level of damage, with noticeable damages in some parts of the structure, partially affecting its usability. Examples of Moderate Damage are shown in Figure 11.

(a) (b)

Figure 11. Examples of Moderate Damage are a) Collapse of non-load-bearing wall and roof damage and b) Damage to facade, windows, and doors along with porch and mechanical systems damage (Governor of Belgorod, 2024).

The figure shows two buildings from the Belgorod region in Russia, both moderately damaged due to the attacks. The image on the left (a) depicts a house that has sustained significant structural damage. Part of the roof has collapsed, and there are visible cracks in the walls caused by external forces or a catastrophic event. The image on the right (b) shows a commercial building with a damaged ground floor. The storefront is severely damaged, with debris scattered around. This damage likely resulted from an explosion or a similar impact.

Structures in the Belgorod region sometimes sustained severe damage during the war. One of the most adverse levels of damage is severe damage, where some parts of the structure have damage to the load-bearing system and the building is rendered unusable without repairs. Examples of Severe Damage are shown in Figure 12.

(a) (b)

Figure 12. Examples of Severe Damage are a) Severe exterior damage to the structure and b) Severe interior damage to the structure (Governor of Belgorod, 2024).

Figure 12 shows examples of two different structures that have sustained severe damage. The heavily damaged buildings are presented as a result of the attacks in the Belgorod oblast. The image on the left (a) depicts a building that has suffered significant structural damage, with most of the roof completely collapsed and the walls of the building largely destroyed; such damage renders the structure unusable and requires extensive repairs. The image on the right (b) shows severe interior damage, with the ceiling and walls of the room largely collapsed and the interior completely ruined; windows and other structural elements are significantly damaged. Such damage typically renders the structure completely unusable and requires extensive repairs or rebuilding.

Another type of structural damage is the concept of progressive collapse, which differs from total collapse and initial damage. Progressive collapse starts with the loss of a column and can lead to the collapse of a portion of the structure or even the entire structure. Examples of progressive collapse encountered during incidents investigated in the Belgorod region of Russia over specific dates are shown in Figure 13.

Figure 13. Examples of Progressive Collapse (Governor of Belgorod, 2024).

Figure 13 shows examples of progressive collapse in buildings located in the Belgorod region of Russia. The top two photos and the bottom two photos depict the same structure. Such collapses can occur due to structural failures and may be exacerbated by external factors or internal weaknesses. These incidents highlight the importance of engineering and regular maintenance. The visible damage and smoke indicate significant structural weaknesses and emergency response efforts. The initial damage during the dates examined was caused by bombardment and MLRS (Multiple Launch Rocket System). Damage to one or several load-bearing elements disrupts the balance of the structural system, resulting in the collapse of a portion. This type of collapse, compared to other structural failures, is characterized by casualties, injuries, and socio-cultural and political consequences.

While the types of damage can vary, they are caused by various firearms and modern equipment. Two such examples are FVP drones and Unmanned Aerial Vehicles (UAVs). Traditional means include bombardment, rocket launchers, mortars, multiple launch rocket systems (MLRS), and fragments of attack munitions shattered in the air by air defense systems (shrapnel). The frequency of these types of attacks occurring in the Belgorod oblast of Russia over a specific time period is provided in Table 4.

Table 4. Weekly distribution of attacks on structures during the war in the Belgorod region

Date	FVP	Bombardment	UAV	Rocket Launcher	Mortar	MLRS	Shrapnel Fragments	Unknown
06.05/12.05	1	8	2	6		1	7	2
13.05/19.05	8	4	3	7		1	13	4
20.05/26.05	10	5	3	4	1	1	7	3
27.05/02.06	13	6	7		2		5	
03.06/09.06	8	2	7				6	2
10.06/16.06	6	3	1			1		1

According to the data in the table, FVP drones are the most frequently used weapon type, accounting for 26.90% of attacks, with a total of 46 instances. Shrapnel fragments come in second at 22.22%, used 38 attacks. Rocket launchers were used 17 attacks, making up 9.94%, while bombardments were recorded 28 attacks, accounting for 16.37%. UAVs were used 23 attacks, constituting 13.45% of the attacks. Mortars were used three attacks, making up 1.75%, and multiple launch rocket systems (MLRS) were used four attacks, accounting for 2.35%. The "unknown" category was recorded 12 attacks, making up 7.02%. These data indicate that FVP drones and shrapnel fragments are particularly prominent in the conflicts.

On a weekly basis, FVP drones and shrapnel fragments have been the most frequently used weapons. During the period from 06.05 to 12.05, bombardments and shrapnel fragments were heavily used, while from 13.05 to 19.05, the use of FVP drones and rocket launchers increased. In the period from 20.05 to 26.05, FVP drones were the most used weapon. From 27.05 to 02.06, the use of FVP drones and rocket launchers peaked. From 03.06 to 09.06, there was an increase in the use of UAVs and rocket launchers, while other categories saw a decrease. In the period from 10.06 to 16.06, there was a general decrease in all categories.

FVP drones are reflected in the statistics as one of the most frequently used types of attacks. Although their direct damage capability to structures is limited, they can significantly increase damage by causing fires in the areas where they crash and explode. Figure 14 shows the increase in damage and fire on the roof of a commercial building in the Belgorod region as a result of an FVP drone attack.

Figure 14. Damage to the structure caused by FVP (Governor of Belgorod, 2024).

Such attacks are frequently encountered in modern warfare; however, there are no recorded instances of FPV drones causing progressive collapse in structures. While they can cause significant damage, this can only happen indirectly. Drones cannot cause severe damage to structures built with non-combustible roof and facade materials. This type of attack can only be useful in specific and sensitive locations and does not have an impact strong enough to initiate a progressive collapse mechanism in buildings. Another type of modern attack is the use of UAVs. Although various UAVs are manufactured, Table 5 provides details on the types of UAVs used, their missions, and whether they can cause progressive collapse in the attacks conducted in the Belgorod region.

Table 5. UAV missions and progressive collapse risk in Belgorod Region

Name	**Mission**	**Progressive Collapse Risk**
Bayraktar TB2	Intelligence, surveillance, reconnaissance (ISR), attack (Karar, 2023)	Yes
Leleka-100	ISR (Savunmasanayist, 2021a)	No
Punisher	ISR and precision operations (Wikipedia, 2024)	No
Spectator-M1	Surveillance and reconnaissance (Crumley, 2022)	No
PD-2	ISR, attack (Savunmasanayist, 2021b)	Yes

The table shows the missions and progressive collapse risk of unmanned aerial vehicles (UAVs) used in the Belgorod region. The Turkish-made Bayraktar TB2 and PD-2 models undertake intelligence, surveillance, reconnaissance (ISR), and attack missions, and both carry a progressive collapse risk. The Leleka-100 is solely involved in ISR missions and does not carry this risk. The Punisher is used for ISR and precision operations, while the Spectator-M1 is only used for surveillance and reconnaissance; neither model has a migration risk. This information is important for assessing the operational capacities and potential structural impacts of UAVs. An example of the damage UAVs have caused to structures in the Belgorod region is shown in Figure 15.

Figure 15. Example of damage caused by UAV to structures (Governor of Belgorod, 2024).

Figure 15 shows an example of damage caused by unmanned aerial vehicles (UAVs) to a structure. The impact of UAVs has resulted in noticeable damage to the structure. Such attacks can create structural weaknesses and collapse risks in the upper parts of the structure. Particularly, historical and architecturally valuable buildings become more vulnerable to such damage, increasing the need for repairs. The visual clearly demonstrates the potential destructive effects of military and strategic UAV uses on civilian structures. Additionally, the destructive impact of UAVs can vary depending on the type of attack and the amount of ammunition carried. UAVs generally have more destructive effects than compared to drones; however, in terms of progressive collapse, they currently have limited capability to initiate a chain collapse mechanism like drones. On the other hand, shrapnel fragments, which may not be a direct attack type but an indirect effect of an attack, have been observed to cause unexpected damage to structures. Figure 16 shows the damage caused to a structure by elements neutralized by air defense systems.

Figure 16. Example of the effects caused by attack elements neutralized by the air defense system (Governor of Belgorod, 2024).

Air defense systems are critical military elements designed to detect and intercept enemy aircraft or missiles. These systems play a vital role in protecting strategic facilities and defending civilian settlements. However, as shown in Figure 16, the debris from neutralized elements can fall onto structures, sometimes destroying parts of residential buildings. This is a rare occurrence even with drones and UAVs. The damage to a structure, despite the prevention of an air attack, indicates that some physical impacts are inevitable. Additionally, the intervention of emergency teams and the containment of damage are crucial in such situations. These incidents highlight the capacity of air defense systems to protect civilian areas. They also lead to confusion between the concepts of regional collapses and complete collapses through progressive collapse in structures.

In previous sections, the damage caused by different types of attacks was discussed. The study examined these types of damage and evaluated the impacts of various forms of attacks. Table 6 below details the distribution of damage according to these attack types, providing a comparative view of the damage levels caused by factors such as bombardment, drone attacks, and shrapnel.

Table 6. Damage distribution according to different types of attacks

	No Damage	Roof Damage	Facade Damage	Fire	Total Collapse	Progressive Collapse
Bombardment		17	15	5	3	1
FVP Drone	1	24	19	6		
UAV	1	14	11	3		
Rocket Launcher		12	9	2	1	
Mortar		1	2			
MLRS		3	4			1
Shrapnel		30	20	4	2	
Unknown Attack	1	7	8	1		

Table 6 summarizes the types of damage caused by various attack methods. Different types of damage such as no damage, roof damage, facade damage, fire, total collapse, and progressive collapse are listed according to bombardment, FPV drone, UAV, rocket launcher, mortar, multiple launch rocket system (MLRS), shrapnel, and unknown attack types. For instance, bombardment resulted in roof damage 7.45% of the time (17 instances), while causing facade damage 6.58% of the time (15 instances). FPV drones caused roof damage 10.53% of the time (24 instances) and facade damage 8.33% of the time (19 instances). UAVs caused facade damage 4.82% of the time (11 instances), whereas rocket launchers left roof damage 5.26% of the time (12 instances). Mortars caused facade damage 0.89% of the time (2 instances). MLRS caused roof damage 1.32% of the time (3 instances) and facade damage 1.75% of the time (4 instances). Shrapnel left roof damage 13.16% of the time (30 instances) and caused facade damage 38.77% of the time (20 instances). Unknown attack types caused roof damage 3.07% of the time (7 instances), facade damage 3.51% of the time (8 instances), and progressive collapse was most commonly observed (1 instance) in both bombardment and multiple launch rocket systems. This indicates that structures subjected to these types of attacks experienced progressive collapse. The least frequent attack was by mortars, occurring only twice, causing facade damage. The most frequent attack was by FPV drones, causing roof damage 24 times and facade damage 19 times.

The analysis of different levels of damage caused by various types of attacks on structures examines the impacts of different attack forms. The varying levels of damage to structures based on these attack types are presented comparatively in Table 7. This table helps us understand the varying impacts of attacks of different intensities and the resistance levels of structures.

Table 7. Damage levels according to different types of attacks

	No Damage	Minor Damage	Moderate Damage	Severe Damage	Total Collapse	Progressive Collapse
Bombardment		13	5	2	3	1
FVP Drone	1	31	9	5		
UAV	1	14	6	2		
Rocket Launcher		3	9	3	1	
Mortar		2	1			
MLRS		1	1	1		1
Shrapnel		21	15	2	1	
Unknown Attack	1	9	2			

Table 7 details the damage levels caused by different types of attacks. FVP drone attacks result in 18.56% superficial damage overall, while shrapnel effects cause 8.98% moderate damage and 1.20%

severe damage. Bombardment is associated with severe impacts such as 1.80% complete destruction and 0.60% total collapse. MLRS systems can also lead to 0.60% moderate damage and complete destruction. Rocket launcher attacks have caused 5.40% moderate damage, 1.80% severe damage, and 0.60% complete destruction. The least frequent types of attacks are mortar and MLRS systems, each causing only a few instances of damage. The most frequent type of attack is by FVP drones, which cause 18.56% superficial damage, making them more impactful compared to other attack types. The least common type of damage is progressive collapse, occurring at a rate of 1.20%, while the most common type of damage is superficial damage at 56.29%. Progressive collapse indicates a reduction in the structure's durability and poses a risk of complete collapse over time. This situation is a threat to the long-term safety of the structures. Overall, the table shows the effects of different types of attacks on structures at various damage levels.

4. Discussion and Conclusion

This study conducted in the Belgorod Oblast of Russia provides a comprehensive assessment of the types of damage structures faced during the war and the concept of progressive collapse. The research shows that bombardment and MLRS attacks seriously threaten the structural integrity of buildings and can trigger progressive collapse. In this context, it is evident that measures to enhance structural resilience must be taken. The study reveals that the war has caused significant structural degradation and occasional progressive collapse in buildings. In particular, bombardment and FPV drones, although indirect, have a high potential for damage, posing a direct threat to structures. Buildings are at great risk from such attacks, highlighting the need to improve their resilience, particularly in roofs and facades. Additionally, different types of attacks (rocket launcher, mortar, MLRS) have varying impacts on the damage levels of buildings. The frequency and intensity of the attacks increase the risks faced by structures, underscoring the importance of structural resilience.

Supported by concrete data, this study offers crucial insights into the need to strengthen structural resilience. From May 6 to June 16, 2024, damage types in Belgorod Oblast were meticulously classified. Minor damage was observed in 16 to 31 structures, while moderate damage affected between 1 to 6 structures. Moreover, severe damage and total collapse were rare but recorded in 1 to 3 cases. Progressive collapse, while accounting for only 1.18% of total damage, presents a serious long-term risk to structural integrity. These findings highlight the significant risks buildings face during war and the critical, though infrequent, nature of progressive collapse as a structural failure. Abdelwahed (2019) provides a comprehensive review of studies on progressive collapse and, similar to this study, discusses methods to enhance buildings' resistance to progressive collapse. Studies such as Byfield et al. (2014) and Marjanishvili (2004) also discuss the significance of progressive collapse in civil engineering, while similarly addressing the weaknesses in structures, as highlighted in this study.

The study emphasizes the importance of enhancing the resistance of buildings to modern warfare technologies. Current building materials and design methods are inadequate to prevent progressive collapse. Therefore, developing new materials and construction techniques will play a critical role in improving building safety. Future research should focus particularly on this area. The effective intervention of emergency teams is crucial for protecting structures and preventing loss of life after a war. Enhancing the training and equipment of these teams will facilitate quick response and repair of buildings. Additionally, such interventions will boost the sense of security in the community.

Informing the community about threats to buildings during wartime, increasing awareness, and ensuring individuals are prepared is of great importance. This will not only enhance personal safety but also contribute to preventing structural damage. Structural reinforcement efforts should be prioritized. Buildings should be constructed to withstand bombardment and drone attacks more effectively. This includes encouraging the strengthening of existing buildings and the construction of new ones using new materials and technologies. Building designs should consider features that prevent progressive collapse and develop solutions to increase load-bearing capacity.

The integration of modern defense systems is critically important. Developing effective defense mechanisms against unmanned aerial vehicles and drones will play a significant role in minimizing structural damage. These systems should be enhanced to protect both civilian and military structures. Extensive research and development should be conducted. Scientific studies should be increased to better understand the effects of firearms and modern warfare technologies and to develop strategies to minimize these effects. Such research can provide innovative solutions to minimize the risks structures face during war.

Collaborations should be encouraged at both local and international levels to enhance the protectability of buildings. Joint strategies should be developed to protect structures in war zones. These efforts are crucial for ensuring the safety of both the buildings and their occupants. In summary, this research outlines the impacts of war on structures and the measures needed to minimize these effects in detail. Structural reinforcement, integration of defense systems, and advanced research and development activities are critical to improving building safety. Future studies should follow these recommendations and develop innovative solutions to enhance the durability of structures under war conditions. These steps provide a strategic approach to minimizing the risks buildings face during war. While military structures require more protection measures, similar resilience standards must be established for civilian structures. This is essential for the protection of both the buildings and the people within them

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