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Blast Proofing the College Hall in the American University of Beirut

Rany Abbas, Mohammed Abdul Nabi, Ali Karaki, Bassam Ramadan, and Farah Said

Department of Civil and Environmental Engineering, American University of Beirut, Bliss Street, Beirut

Abstract: The aim of this paper is to blast-proof the College Hall at the American University of Beirut. The paper starts with a risk assessment analysis for the college hall building in order to assign a certain worst-case scenario. Based on the assigned scenario, blast calculations are going to be conducted and the corresponding structural analysis will be carried out.Several structural and non-structural materials that can contribute in the enhancement of the performance of the building in a blast event are reviewed. The building is also assessed according to sustainable standard measures and scales. The theme of this paper is System and Data Analysis.

Key words: Blast-proofing, blast loading, structural analysis, CFRP, building retrofitting

1. Introduction

College Hall is one of the oldest and most important buildings at the American university of Beirut. It was subjected to an act of terrorism that leveled it back in 1991. Therefore, the aim of the paper is mainly to retrofit the College Hall against blast loading. Studies on explosive-resistant materials are going to be reviewed and incorporated in the retrofitted building in order to enhance the performance of the building against any potential explosive. The design will also be done according to different sustainability measures that will decrease energy consumption and maintain a sustainable and eco-friendly building. In this paper, the focus is on the calculation of the blast loads and the factors that affect their intensity and pattern. A structural analysis model of the structure is developed and analyzed accordingly using ETABS. Also, different explosive-resistant materials are selected based on researches and previously done experiments. Sustainability status is evaluated and represented according to certain scaled measures and guidelines.

2. literature Review

The knowledge on blast loads and their impact on structures is fairly recent, accumulated over the past 50 years, prompted by both acts of terrorism and accidental explosions. Considering the complexity of their analysis, the low probability of an explosion incident near residential or commercial buildings, and the added cost of construction, most structural designs do not account for blast loads, and therefore, they are susceptible to damages from explosions given that the blast loads are much larger than the conventional design loads [9].

An explosion is defined as a large sudden release of massive energy over a short period of time that lasts for a few milliseconds, causing very high temperatures and pressures. At the time of detonation, the resulting hot gases expand and occupy the near surroundings, leading to wave propagation through space in a spherical direction through unconfined areas. This is known as a blast wave or shock front. As the shock wave expands, its strength and velocity decay due to spherical convergence. Of the released chemical energy of the blast, only a third is released upon detonation, the rest of the energy is released slowly in smaller air explosions after the explosive products mix with air and burn. Yet, these have a minor effect on the blast

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Corresponding author: Mohamad Abdul Nabi, Ph.D., research fields: construction management and engineering.

wave since they occur at a significantly larger period of time [8].

2.1 Pressure Time History

Fig. 1 displays the pressure profile in relation with time of a blast wave as described in [7]. At t = 0, the pressure of the element (structure) is equal to the ambient pressure P_0, at $t = t_A$, the time of arrival from the detonation point to the element, the pressure increases instantaneously to P_{so}, the peak pressure, also referred to as the peak overpressure. The time of increase to the peak pressure is infinitesimal, and therefore is considered to be zero for design purposes. The pressure then decays exponentially until it reaches P_0 for a time period of t_o, which is also the duration of the positive phase. The pressure continues to decrease below P_0, until it reaches a minimum value of P_{so}^-, and then it returns to the ambient pressure P_0. The negative phase has a duration of t_o^-, which is larger than t_o. However, P_{so}^- is much smaller than P_{so}, thus, it has a small impact on the structural integrity. During the negative phase, the structure undergoes suction forces, which explains the presence of shattered glass and debris on the exterior of the building.

For an explosion that occurs near the ground, the initial shock wave encounters a rigid surface and is therefore refracted, and increased by reflection from the ground. The reflected wave and initial wave merge together to form a single wave, thus amplifying the peak overpressure. The reflected wave is often several times larger than the incident pressure.

3. Scope and Methodology

3.1 Scope

The scope of this paper is mainly to retrofit the College Hall, at the American University of Beirut, against blast loading taking into consideration high sustainable features and measures. First, a risk assessment is carried out to estimate the level of risk College Hall is exposed to. The blast loads are calculated based on the factors that influence these loads such as explosive materials used, explosive weight, and standoff distance. A structural analysis of the building under these loads is then carried out using ETABS. Different materials are analyzed based on their ability to resist blast loadings. Finally, a sustainability evaluation is to conducted and analyzed based on different measures and criteria.

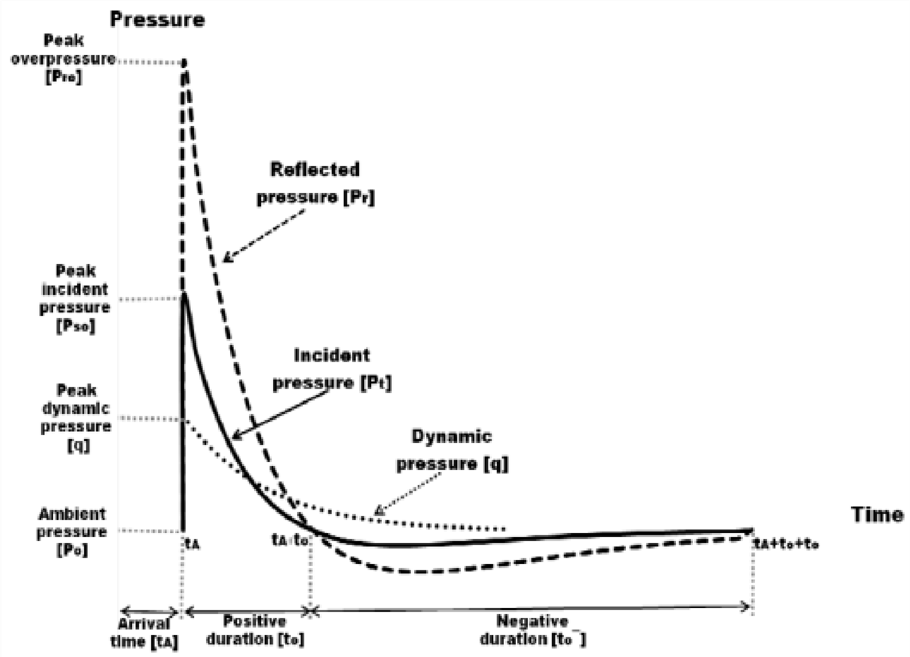

Fig. 1 Pressure Time History of Incident and Reflected Peak Pressure.

3.2 Methodology

3.2.1 Blast Loads

Based on existing literature blast loads are calculated based on a risk assessment analysis where the worst-case scenario is taken into consideration. The main blast load parameters, such as the peak pressure and duration of the positive phase, depend on the weight of the explosives and standoff distance.

3.2.2 Risk Assessment

Risk assessment of the College Hall is conducted based on the layout of AUB maps, in particular the location of the building with respect to the university access points. With the help of the security department at AUB, different scenarios are identified. Historical evidence and are also taken into consideration to estimate a worst case likely scenario.

3.3 Materials

Different materials that may be used in the retrofitting and retrofitting of College Hall are considered. The materials can be used for either structural or non-structural elements such as blast-proof glass and carbon fiber reinforced polymers. The maximum strength capacities and characteristics of different materials are investigated based on the purpose of their usage.

3.4 Structural Analysis

The College Hall building is modeled on ETABS based on the architectural and structural layout provided by the FPDU. The structural model is subjected to the calculated blast loads. The results of the structural analysis are used to design the structure and examine if any elements are overstressed.

3.5 Sustainability

To evaluate the sustainability standards in college hall, several things were done. First, a meeting was carried out with different people from the Physical Plant Department which is responsible for managing the different electrical, mechanical, electromechanical things in the AUB buildings. FPDU provided the information regarding the energy consumption، , water consumption, building management system, water fittings, lighting system, waste audits, safety regulations, ventilation system, and accessibility for the disabled. After analyzing the information gathered, different recommendations will be provided to meet sustainability in the college hall.

4. Risk Assessment

College Hall is located in front of the AUB Main Gate at an approximate distance of 30 meters. Reviewing the layout of the map of AUB, and consulting with security guards, it was concluded that the only way a vehicle can target college hall is by parking near the Main Gate on Bliss. On the other hand, the building can be easily accessed in person, given that people are rarely fully inspected at the gates.

Historically in Lebanon, large explosions have been used, with thousands of Kilograms of TNT equivalent. In 2005, Rafik Harriri was assassinated by a massive explosion with an estimated 1800 Kg of TNT equivalent [12]. Also, in 1983, two large trucks with an estimated 9525 Kg of TNT equivalent were used in the barracks bombing against the building housing the Multinational Force in Lebanon, killing 241 US and 58 French peacekeepers.

For the purposes of the College hall design, the blast load of two scenarios are analyzed. The first is a truck carrying approximately 5000 Kg of TNT, detonating his explosives at the main gate, which is approximately 30 meters from the building. The second scenario is that of a suicide bomber carrying an estimated 20 Kg in his vest, detonating his explosives inside the College Hall Building, at a close distance to the structural elements. A 20% safety factor of the explosive mass is used for load calculations.

5. Blast Load Calculation

To quantify the explosive wave, scaling is introduced for simplification, where the idea is that two different explosions, of the same type of explosives, at the same scaled distance, with the same geometry but different mass, have a similar blast waves under the same conditions. According to Hopkinson-Cranz law, a dimensional scaled distance is introduced as described by Equation (1) [7].

$$Z = \frac{R}{\sqrt[3]{W_e}} \tag{1}$$

Where,

- R = Distance from the Detonation point to the Structure element.
- W_e = Mass of explosives in Kilograms of TNT

Using the above data, and the Value of Z, the peak pressure (P_{so}) in bars can be calculated using equation (2)[3].

$$P_{so} = \frac{6.7}{Z^3} + 1 \ldots\ldots\ldots for P_{so} > 10\ bars \tag{2}$$

$$P_{so} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \ldots for P_{so} < 10\ bars$$

The dynamic pressure q_s is given by equation (3) [8].

$$q_s = \frac{5P_{so}^2}{2(P_{so} + 7P_0)} \text{in bars} \tag{3}$$

Where

P_0 = Ambient pressure.

Due to the reflection of the blast wave, the Pressure is amplified and is given by equation (4)[10].

$$P_r = 2P_{so}\left(\frac{7P_0 + 4P_{so}}{7P_0 + P_{so}}\right) \tag{4}$$

Where,

P_r = Reflected pressure.

The pressure on the side walls, rear and roof is given by equation (5). [7]

$$P = P_{so} + C_d q_s \tag{5}$$

Where,

C_d = Drag Coefficient.

Finally, the duration τ of the positive phase is estimated using equation (6) [7].

$$\tau = 1.2\sqrt[6]{W_e} \times \sqrt{R} \text{in ms} \tag{6}$$

- Load Calculations of Scenario 1: Truck

Table 2 represents the calculated peak overpressures on the surfaces of college Hall due to 5000 Kg of TNT detonated near the main gate.

- Load Calculations of Scenario 2: Suicide Vest

Table 3 represents the calculated peak overpressures due to a suicide vest at several standoff distances from point of detonation. These are the values of pressure an element is subjected to at that distance.

5.1 Blast Load Modeling

The response of a structure under a blast load depends on several factors other than the shape of the structure and its distance from the blast. The natural period of the structure and its relation to the positive phase duration of an excitation plays a fundamental role on determining its behavior. If the duration of the excitation is longer than the natural period Tn of the structure, then its maximum deflection takes place before the excitation ceases, and dynamic analysis should be used, as often is the case for earthquake loading. If the duration of the positive phase of the excitation is a lot shorter than the natural period $(< Tn/4)$, then the structure deals with an impulsive loading [7].

Table 1 Drag coefficients.

Loaded Surface	C_D
Front	0.8-1.6
Rear	0.25-0.5
Side and Roof (Depending pressure, KN/m^2)	
0-172	-0.4
172-345	-0.3
345-896	-0.2

Table 2 Blast loads of scenario 1.

Surface	Load (Bars)
Front	8.5
Side	1.53
Roof	1.53
Rear	3.1

Table 3 Blast loads of scenario 2.

Distance (m)	Load (Bars)
1	1254
2	153
2.5	64.4
3	48
4	19.5
5	7.1
6	4.33
7	2.88

A blast wave only lasts for a few milliseconds. Since the College Hall building is comprised of 5 floors, its natural period is approximately 0.5 seconds, much larger than the duration of the positive phase. Therefore, it is safe to assume that the elements will barely experience a deflection before the complete passage of the blast wave. Thus they are loaded according to the impulse value of the wave's time history. The exact natural period of the structure can be calculated accurately using the ETABS software.

The pressure time history of the blast wave experiences the peak pressure instantaneously, then it undergoes an exponential decrease to the ambient pressure.

However, practically, the load can be assumed to decrease linearly, and hence be modeled as a triangular load.

6. Structural Analysis

The response of the structure was analyzed using the ETABS software. The architectural and structural plans of College Hall were acquired from the FPDU.

The different sections were defined and drawn. An $f'_c = 45$ MPA was assumed for columns and walls. An $f'_c = 35$ MPA was assumed for the slabs.

The usual load patterns were defined, along with the load cases and load combinations.

In addition to the dead load, superimposed dead load, live load, and seismic loads in both directions, the blast loads were added for this particular analysis.

To define the blast load, a time history function was defined as a triangular function with instantaneous increase to the peak, and linear decrease to 0 over a span of 28 ms. The load pattern was defined as a Blast load.

The settings defined in ETABS to define the load case are as follows. The load case was defined as a time history, calculated using non-linear direct integration. The load case type was defined as a Load Pattern (i.e., not acceleration), and the function called was the previously defined Blast time history function.

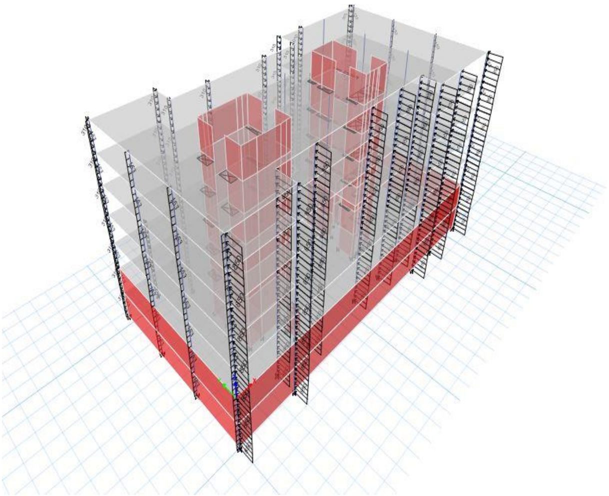

Fig. 2 Model of college hall with the assigned loads.

For design purposes, load combinations are defined according to the likely combinations of loads to occur simultaneously. The load combinations of most interest based on the ACI and UFC codes are the following:

- 1.2Dead + 1.6Live
- 1.2Dead + 0.5Live + or – EQ
- 1.2Dead + 0.5Live + Blast

The blast loads were assigned to the frames of the front façade, to the side surfaces, to the rear façade, and to the roof of the building. The loads calculated for the first scenario are displayed in Fig. 2.

Note that the natural period was evaluated to be 0.601 seconds.

After running the analysis, and checking for the concrete design of the frames, the results obtained are displayed in Fig. 3.

The concrete frames highlighted in red are the overstressed members. Most of the overstressed members are located in the front façade, which bears most of the loads. Only the element with largest section in the front façade is not overstressed. As for the side surfaces, the loads are considerably lower and therefore the elements are not overstressed. However, the members on the top floor are overstressed due to the presence of the blast load on the roof. To avoid collapse, the sections of the overstressed elements need to be redesigned.

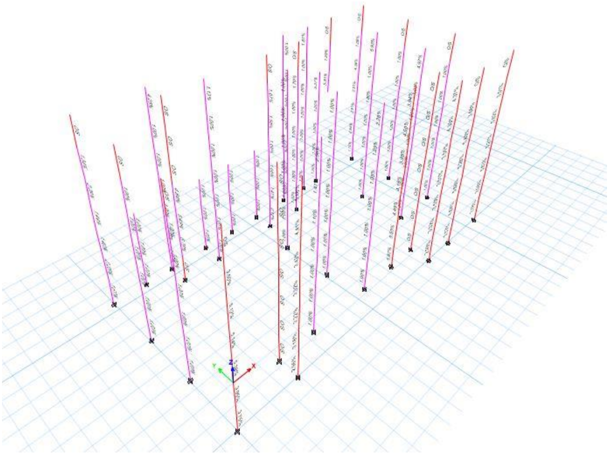

Fig. 3 Analysis results of concrete frames.

As for the second scenario that involves suicide vest, the loads are significantly higher, by order of 10 to 100 times higher, depending on the distance between the structural member and the point of detonation. Therefore, failure of the corresponding elements is a sure thing. And considering that the suicide bomber is able to move freely, all the elements may be subjected to the blast in a different plausible scenario.

A remedy for that situation would be to install a metal detector prior to entering College Hall to eliminate that particular threat, which would be more practical, time saving, and economical.

7. Retrofitting Materials

The following materials were used in the retrofitting of College Hall.

7.1 Carbon Fiber Reinforced Polymer

Unreinforced masonry walls (URM) do not provide a good protection against air blasts. When they are subjected to a relatively huge load, the wall will fail and the interior of the structure will be receiving the debris. For blast protection requirements, this type of wall has been prohibited.

The solution for this case lies in using sprayed-on polymer coating to retrofit unreinforced masonry walls and increase resistance to air blast [4]. The polymer material has the ability to permit deformation and dissipate blast energy while containing the wall fragments. The coating will contain the debris and remain intact. The most known polymer is Carbon Fiber Reinforced Polymer (CFRP) for protecting building against blast loads. It is a very durable and lightweight composite material, and it resembles wallpaper, it adheres easily to most surfaces and shapes [5]. CFRP is nearly three times stronger than steel. FRP do not deal with the building foundation so the entire application can be done in fewer than 75 days without interrupting any other operations for an occupied building. The point here focuses on humans' safety even if the building may not be usable after the event.

FRP has risen in the structural engineering community, and by time it is gaining the acceptance in its field especially when the needs are being satisfied. Briefly, the process consists of weaving the fibers into a fabric (saturated with epoxy resin) and then applying it to the component's surface that requires blast proofing [6]. After the resin cures, a tensile reinforcement/confinement is added to the material.

After an explosion, the building (target) will be subjected to an impulse load. Every structural component of the building will be having a specific degree of blast resistance which can be established by modelling loads in different directions on walls, floor slab, ceiling slab and columns. FRP strips come as a solution when a negative bending effect is present in regions where there is insufficient steel reinforcement. The danger lies when debris is transformed into high speed projectiles leading to destruction and human casualties.

Experiments have led to several conclusions about CFRP. The most important one lies when considering the worst-case scenario (no reinforcement), CFRP had the ability to avoid effectively the URM wall's collapse and all debris were contained, thus, 100% rate of human survival and minimum damage.

The CFRP layer/membrane is a very thin one (less than 1/8 inch usually) can be installed in a clever way hiding it architectural finishes. With a large increase in strength but a moderate increase in stiffness (10%), it consists of materials with strong ultimate tensile strength (3000 MPa). The guide for the design and construction of FRP systems is fully detailed in ACI-440.2R-08.

The Slabs and masonry walls in College Hall will be coated with the CFRP material. This will limit the projectile debris from harming individuals. Also, in case of Slab failure, the debris not fall lower slabs and cause extra loads on it, which helps to avoid a progressive collapse.

7.2 Anti-shatter Film

Anti-shatter film (ASF), also commonly known as "shatter-resistant window film" (SRWF) or "security film", is a laminate used to improve post-failure performance of existing windows. Applied to the interior face of glass, anti-shatter film holds the fragments of broken glass together in one sheet, thus reducing the projectile hazard of flying glass fragments. A more appropriate name for anti-shatter film would be "fragment reduction" film, since the methodology behind this hazard mitigation technique is focused upon retaining glass fragments resulting from blast overpressures.

8. Sustainability Standards Check

Before considering any upgrade in the building to meet sustainable measures, it is important to understand its status. The standards reference used in the evaluation is "Existing Building Retrofit" guidebook, published by Centre for Sustainable Buildings and Construction, Building and Construction Authority.

Energy consumption was audited for electricity consumption by reviewing energy bills, and was found to be 2,966,784 KWh in 2016, which is considered high.

Water consumption was reviewed and found to be six m^3 per day.

The water fittings in College Hall are labeled under the Water Efficiency Labeling Scheme (WELS) and are sensor activated.

The lighting system (lamps, luminaires, and ballasts) was checked and found to be activated by motion sensors in corridors and in office.

The Building Management System (BMS) is a computer-based control system that monitors, controls and optimizes the mechanical and electrical equipment in the building, to identify its weaknesses.

In the college hall, fire alarms are installed and the Protection Office Control Room manages them and they comply with the Fire Code Regulations.

College hall is found to be accessible to the disabled through its main entrance. The disabled can access the Registrar or the Cashiers desk from the inside doors.

The ventilation system is will be checked to see whether natural ventilation is a feasible alternative. Based on the information provided by Miss Lilian, air cooled chillers are used. There are two units that provide college hall and their capacity is 200 Tons.

Table 4 Building performance assessment.

Performance Grade	Excellent	Good	Poor
Thermal Comfort	+ 0.5 MPV (Predicted mean vote)		
Energy Consumption		40th Percentile	
Water Consumption	WELS Excellent & Very Good Fittings		
Mechanical System	100% planned availability and meeting current functional demands - No standing alarms, no losses or events- Fully meets design functionality.		
Electrical/IT/ Comms Sys.	100% availability- No event reports due to equipment unreliability		
Staff Satisfaction	Few complaints - Below average absenteeism.		
Flexible Floor Plate	Very flexible- Multiple exits, no internal columns or obstructions, easily sub leased.		
% of Net Lettable Area with 2.5% Daylight		30-60%	

The level of refurbishment needed is level 1, Which means minor refurbishment need to be made to College Hall to make it competitive with a new office building. Minor refurbishment requires for example installing modern blinds, revising layout to improve daylight and flexibility, repainting interior and other things.

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