ANALYSIS OF BLAST LOADS ON STRUCTURES WITH FACADE OPENINGS USING UFC 3-340-02

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Abstract

Designing blast-resistant structures with openings presents a significant challenge due to the complex propagation and interaction of shock waves with internal structural components. While international design codes have been established to address this issue, engineering practice in Vietnam primarily relies on empirical methods for assessing external blast loads on simple rectangular geometries, often neglecting internal pressure effects due to a lack of experimental data. As an alternative to computationally intensive CFD simulations, this article presents a comprehensive approach utilizing UFC 3-340-02 to determine blast loads acting on both exterior and interior structural surfaces. An automated calculation method is introduced to estimate the determination of these loads and rapidly generate a robust loading database. This study provides Vietnamese engineers with a practical blast loading assessment tool and a new approach to accurately analyze structural components, thereby enhancing the survivability and resilience of structures against explosive events.

Keywords: *Blast load; shock wave; incident pressure; UFC 3-340-02.*

1. Introduction

Designing structures to resist blast loading is a specialized field of engineering that requires a deep understanding of blast loading, impact loading, and the behavior of structures under the effect of high-rate strains. When a high explosive detonates, it releases a tremendous amount of energy rapidly, creating a shock wave that propagates through the surrounding area. The interaction of this wave with a structure imposes extreme loads that can cause catastrophic failure if not adequately accounted for in the design. Openings, such as windows and doors, on a structure's facade fundamentally alter this interaction, creating a complex loading that includes both external and subsequent internal pressures. Thus, for the engineering design of structures to resist blast loading from terrorist attacks and accidental events, numerous analytical and empirical methods and design codes are employed internationally [1]-[8]. In Vietnam, experimental curves are mainly used to predict a structure's external blast load from a ground explosion, specifically for rectangular-shaped buildings [2]. However, due to a lack of experimental

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data, analytical blast loading neglects the phenomenon of blast waves propagating into and interacting with the structure's interiors.

To assess internal blast loadings, some authors have focused on calculating them to estimate the level of human damage. A. Malhotra *et al.* [9] calculated "Accidental explosion and effect leakage into structures" and showed that blast waves penetrate buildings through openings such as windows and doors, causing increased internal pressure and affecting people. The maximum pressure results are used to analyse the reflection of waves inside and the potential for damage to the lungs, eardrums, etc.

K. B. Holm employed numerical simulation methods on the ANSYS platform to calculate the blast pressure on the structure and assess the impact of the blast pressure on the injury level of people inside the structure [10]. During the calculation process, the author conducted experiments to measure the blast pressure waves inside the front walls, side walls, and ceiling, and compared the results with those from the simulation.

Z. Koccaz *et al.* [11] focus on architectural and structural design to withstand explosive loads, including internal wave reflections within the structure. A. Eytan *et al.* [12] calculated the interactive blast loads on structures using UFC 3-340-02 and compared them with Kaplan's method. The results of this study emphasize the importance of using techniques to calculate the internal blast loads. These results can be used to assess damage and injury to people and equipment inside structures in some detailed scenarios.

In addition to addressing the problems above, the solution utilizes CFD and ALE simulations on platforms such as Autodyn and LS-DYNA, which have been continually developed and refined over time. C. Neto *et al.* [13], enable the investigation of complex propagation and interaction processes. However, calculations based on CFD simulation platforms are very time-consuming, require significant software investment, and are only suitable for overall problem verification, rather than for researching general design calculation processes. To simplify calculations for standard rectangular structures subjected to single explosions on the ground or in the air, UFC 3-340-02 provides a safe and effective method for experimental calculations. Despite widespread use of UFC 3-340-02 worldwide, research and application of UFC 3-340-02 in calculating blast-resistant structures and civil defense systems in Vietnam remain scarce. Therefore, to address the gap, this article aims to provide an overview of utilizing UFC 3-340-02 in predicting blast loads on the exterior and interior walls and ceilings of structures. Furthermore, the method for automatically calculating these loads is also described. The program generated a blast loading database to analyze the safety and survival of windows, doors, internal curtains, and the entire structure subjected to blast loadings, as well as external blast loadings on above-ground rectangular structures with openings.

2. Overview of blast loads propagation into structures

2.1. General

Calculations of blast loads acting on structures often neglect the pressure of shock waves propagating into the structures. Although structures with openings are shielded or protected on the external surfaces, blast waves can destroy the openings, penetrate and cause injury to people inside the structure, or blast pressure can affect the internal walls and roof.

The most common case is when openings only appear on the front of the structure, while the other surfaces have no openings. This is the most likely scenario because internal partitions and walls will limit the flow of blast waves into the structure. The internal blast load increases due to the reflection of the blast wave on internal components. Another case, including holes appearing in the structure's front, rear, or side walls, is not considered, as it is less dangerous.

The pressure will be amplified rapidly when an incident wave impacts the front wall. Windows and doors may be destroyed almost immediately (within a millisecond) unless they are designed to withstand the loads. As a result, the blast pressure will pour into the structure's interior through these openings. The sudden release of high pressure will form an internal shock wave inside each opening. Each shock wave will propagate and combine into a single shock wave, which will then continue to propagate throughout the interior of the structure.

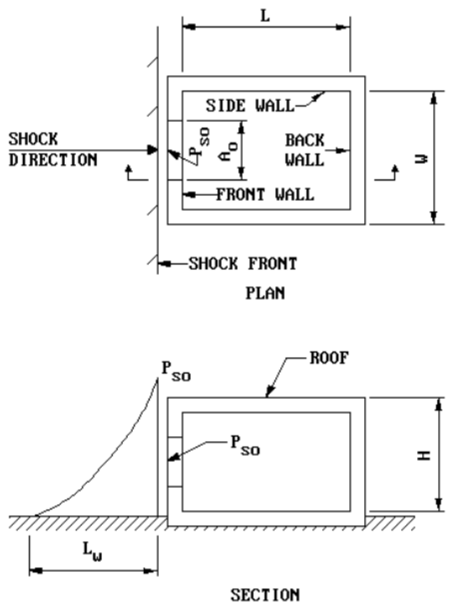


Fig. 1. Idealised structure configuration for interior blast loads [8].

In Fig. 1, when the shock wave hits the structure's front wall, the pressure is P_{so} and the wavelength is L_w. As the shock wave sweeps through the structure, the blast pressure enters the building through the opening in the front wall with an area of A_o. The areas of multiple openings are summed to form a single hypothetical opening located at the center of the front wall. The blast pressure entering the building first impacts the inner surface of the front wall, then interacts with the inner surfaces of the side walls, the roof, and the rear wall. The idealized time-dependent load diagrams for these surfaces are presented in Fig. 2.

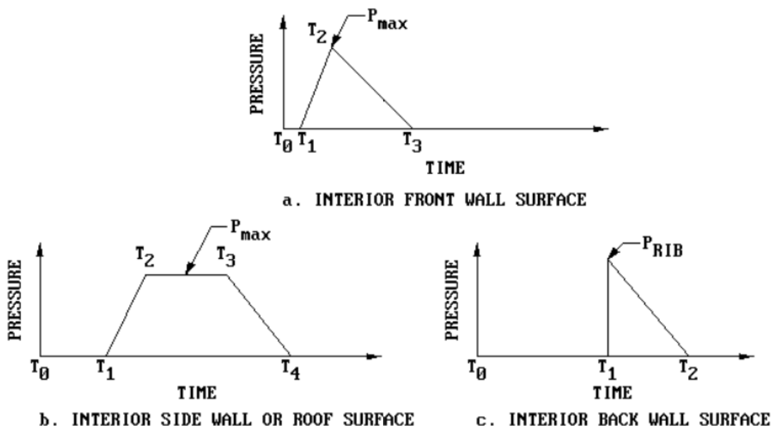


Fig. 2. Idealized interior blast loads [8], [14].

Blast loads acting on the structure's exterior, except for the front wall, are calculated as if there were no openings and have also been calculated and introduced in UFC 3-340-02.

For simplicity and safety, UFC 3-340-02 only considers the most hazardous case, where the shock wave is perpendicular to the front wall and causes the most severe internal shock wave effects [12], [15].

The load calculation results are used to determine the maximum outward displacement of the wall. The calculated load values for interior walls are also used to design partition and wave-absorbing walls, as well as to assess the safety level and the impact of blast waves on personnel.

2.2. Exterior front wall loads

Due to the clearing time effect, blast wave clearing significantly reduces the maximum pressure acting on the wall. Depending on the overall size of the wall and the openings, the clearing time of the reflected pressure can be significantly reduced.

The pressure-time relationship of the blast load acting on the front wall of a structure with openings is like that of a solid front wall, except that the clearing time is shortened. The value S' is incorporated into the calculation to evaluate this time clearing

[8], [16]. This value is the weighted average distance the expansion wave must travel to cover the entire wall if the arrival shock wave can enter the structure immediately. If fragile shielding panels (such as windows, doors,...) are not destroyed immediately, the clearing time will not be shortened.

To calculate this load, UFC 3-340-02 proposes dividing the front elevation into elements with area δ_n based on the boundary and the location of the vent.

- For each cell, determine the cell type (1, 2, 3, 4), then assess δ_n.

Tab. 1. Table for determining the value of δ_n

Area	δ_n	Number of clearing sides
1	1.0	Two adjacent sides
2	0.5	Two opposite sides
3	1.0	One side
4	1.0	None

The weighted average clearing distance *S'* is expressed as:

$$S' = \frac{\sum \delta_n h_n A_n}{A_f} \leq S \quad (1)$$

where S' is the weighted average clearing distance with openings, δ_n is clearing factor, h_n is average clearing distance for individual areas as follows:

Area 1 - width or height of the area, whichever is smaller;

Area 2 - distance between opposite sides where clearing occurs;

Area 3 - distance between the side where clearing occurs and the opposite side;

Area 4 - same as Area 1.

A_n is the area of individual wall subdivision, A_f is the area of the wall excluding openings

The clearing time $t'_c = \dfrac{4S'}{(1+R)C_r}$

The parameters of the incident wave pressure include the peak average pressure P_{max}, the peak positive reflected pressure $P_{r\alpha}$, fictitious duration of the reflected pressure t_{rf}, fictitious positive phase duration t_{of}, and clearing time t_c will be calculated based on the database to determine the wave pressure on the front wall, similar to a closed structure on the ground.

The pressure-time relationship is shown in Fig. 3 where P_r is peak reflected pressure, P_{so} is peak incident overpressure, I_r is reflected impulse, C_D is drag coefficient, P_s is stagnation pressure, t_o is positive phase duration, t_{rf} is reflected time.

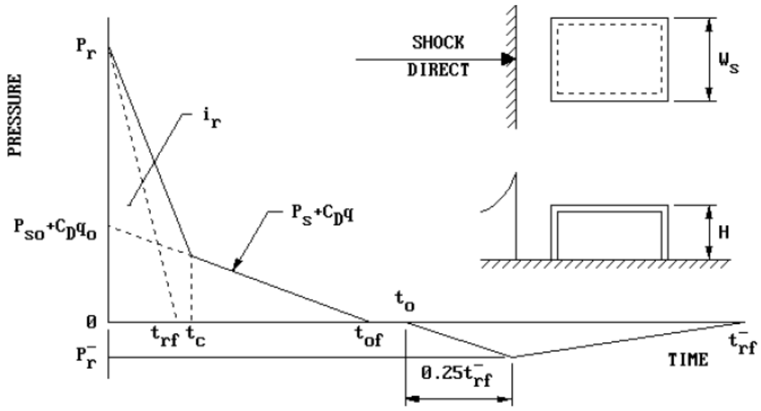


Fig. 3. Pressure diagram on the exterior of the front wall [8].

2.3. Interior blast loadings

2.3.1. Pressure-time blast load on interior front wall

The blast load time history acting on the interior face of the front wall is shown in Fig. 4. The time when the shock wave reaches the exterior surface of the front wall is taken as zero ($T_0 = 0$). The blast load acting on the inner front wall begins at T_1. This time represents the time required for the shock wave to enter the structure through the opening of A_o. The pressure increases linearly from time T_1 to the maximum pressure P_{max} at time T_2 and then decreases linearly to zero at time T_3.

The peak average pressure, P_{max}, acting on the inner surface of the front wall varies as a function of the incident pressure, P_{so}, and the corresponding wavelength, L_w, for that pressure, as well as the shape of the wall.

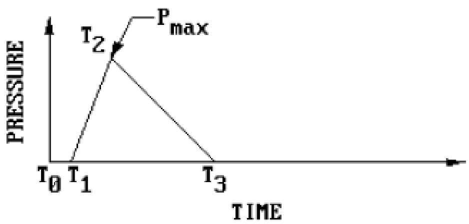


Fig. 4. Pressure diagram on the front wall (inside) [8].

The maximum average pressure value P_{max} is shown in the dplot data of Fig. 2-203 to Fig. 2-206 in UFC 3-340-02, corresponding to the width-to-height ratio w

and height *W/H,* respectively equal to 3/4, 3/2, 3, and 6 [8], [15]. Other values must be assessed using 2D interpolation.

The idealized times T_1, T_2, and T_3 are also taken from the database, and the following instruction:

T_1 value (ms) is determined based on the values of P_{so}, *W/H,* and A_o/A_w by interpolating the data in Tables 2-207 and 2-208 of UFC 3-340-02.

T_2-T_1 (ms) is determined based on the values of P_{so}, *W/H,* and L_w/H by interpolating the data in Tables 2-209 and 2-210 of UFC 3-340-02.

T_3-T_1 (ms) is determined based on the values of P_{so}, *W/H,* and L_w/H by interpolating the data in Tables 2-211 and 2-212 of UFC 3-340-02.

2.3.2. Pressure-time blast load on interior side wall

The blast pressure entering the building through the gaps in the front wall must travel along the interior of the front wall before reaching the side wall. The incident pressure reaching the side wall is increased due to reflection from the wall itself. The front wave expands and travels across the side wall until it reaches the rear wall.

The length of the side wall affected by this reflected wave is a function of the wavelength L_w. The time-dependent blast load, idealized as pressure, acting on the inner surface of the side wall is shown in Fig. 5.

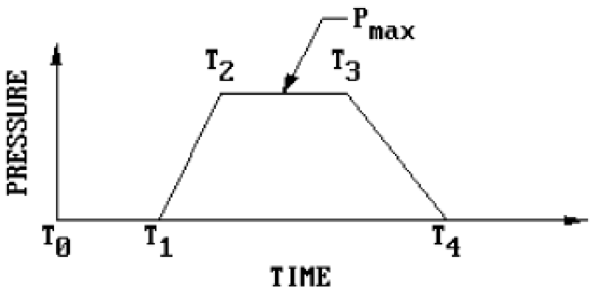


Fig. 5. Pressure-time diagram on the inner face of the side wall [8].

The time at which the shock wave reaches the exterior face of the front wall is considered zero (T_o = 0). The time T_1 represents the time it takes for the shock wave to travel from the openings to the inner side wall. The pressure increases linearly from time T_1 to the maximum pressure P_{max} at time T_2, remains constant until time T_3, and decreases linearly to zero at time T_4. This idealized curve applies to both side walls and roofs. The peak pressure and time point can be calculated by:

The peak pressure $P_{max} = \frac{KL}{L_w}$ (psi).

T_1 and T_2 (ms) values are determined based on the values of P_{so}, *W/H* by interpolating the data in Tables 2-213 of UFC 3-340-02.

T_3 and T_4 (ms) value is determined based on the values of P_{so}, *W/H, L/H,* L_w/L by interpolating the data in Tables 2-214 to Table 2-229 of UFC 3-340-02.

2.3.3. Pressure-time blast load on interior roof

The calculation process for the roof is similar to that for the side wall, except that the initial parameter values are swapped between W and H for calculation and showed in Fig. 6.

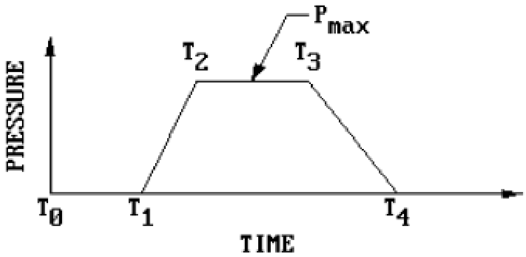


Fig. 6. Pressure-time diagram on the interior face of the roof [8].

2.3.4. Pressure-time blast load to interior back wall

The pressure reaching the rear wall is essentially uniform across the whole wall. This pressure immediately increased to the normal reflected pressure when it hits the back wall. The idealized pressure-time acting on the inner face of the back wall is shown in Fig. 7.

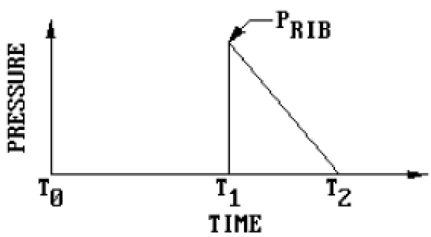


Fig. 7. Pressure diagram on the rear wall (inside) [8].

The time at which the shock wave reaches the exterior of the front wall is taken to zero (T_0 = 0). Time T_1 represents the time required for the front face of the shock wave to travel from the gap to the back wall. The pressure increases instantaneously to P_{RIB} due to the normal reflection of the shock wave's front face and then decreases to zero at time T_2. The values of peak pressure and time points are calculated according to the following cycle:

P_{RIB}/P_{so} (psi) is determined based on the values of P_{so}, L/H, A_0/A_w by interpolating the data in Tables 2-230 and Table 2-231. The peak pressure $P_{max} = (P_{RIB}/P_{so})P_{so}$ (psi).

T_1 (ms) is determined based on the values of P_{so}, W/H, and A_o/A_w by interpolating the data in Tables 2-232 and 2-233 of UFC 3-340-02.

T_2-T_1 (ms) is determined based on the values of P_{so} and A_o/A_w by interpolating the data in Tables 2-234.

2.4. Calculation procedure

Although UFC 3-340-02 introduces a method to calculate all types of blast and structural behavior under blast loading, the routine is tough and inconvenient for users. To simplify the process and create an automatic method for estimating blast loadings, the mini tool has been developed with a diagram of the calculation steps in Fig. 8:

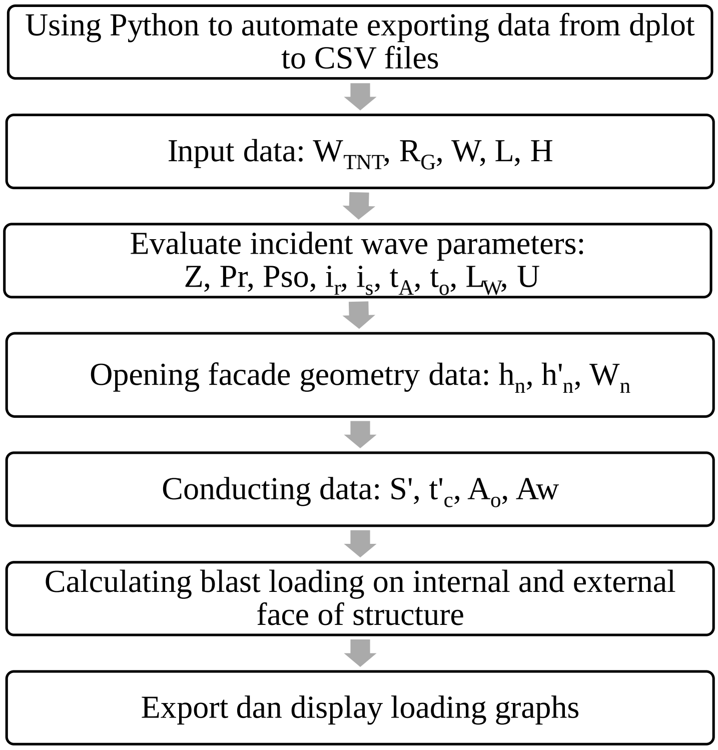


Fig. 8. Blast-loading calculator diagram.

3. Scenario surveillance

In this section, two case studies are introduced to test and calculate blast loads in the structure.

3.1. 250 lbs of blast loading impact on a structure

Determining the blast load parameters subject to a structure with the location and dimensions in Fig. 9 and Fig. 10:

Input parameters:

Distance from the explosion to the front face R = 50 m (164 ft)

The structure has dimensions: 7 m × 10 m × 5 m (23 ft × 33 ft × 16.4 ft)

The explosive charge has a mass W = 250 lbs of TNT;

Safety factor 20%.

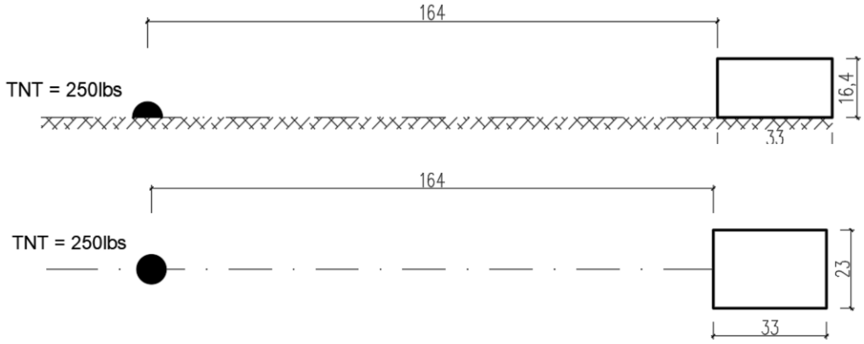


Fig. 9. Plan and elevation of the structure (unit ft).

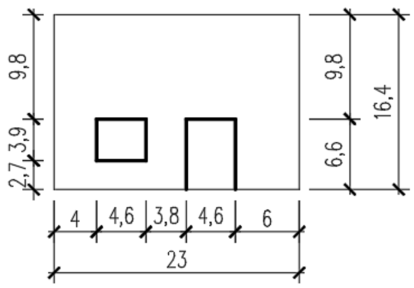


Fig. 10. The front wall of the structure is subjected to blast waves (unit ft).

3.1.1. Determine the incident pressure and reflected pressure parameters

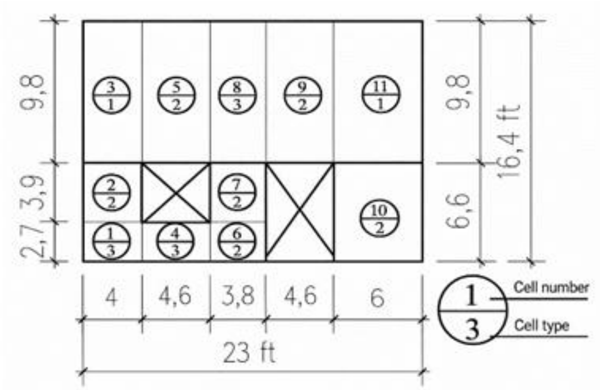
The incident pressure and reflected pressure parameters acting on the front wall of the structure are also calculated automatically based on the same procedure. The results are shown in Tab. 2.

Tab. 2. Incident and reflected pressure parameters

Weight (lbs)	Z (ft/lb$^{1/3}$)	P_r (psi)	P_{so} (psi)	t_A (ms)	U (ft/ms)	t_0 (ms)	L_w (ft)	i_s (psi-ms)	C_{ra} (ft)
250	24.5	4.77	2.23	107.31	1.19	24.37	24.23	23.76	2.11
P_{ra} (psi)	C_r (ft/s)	S (ft)	G (ft)	t_c (ms)	t_{of} (ms)	q_0 (psi)	C_D	P_{max} (psi)	t_{rf} (ms)
4.71	1.15	11.48	16.40	23.49	21.31	0.12	1	2.35	16.06

3.1.2. Determine exterior blast load on front wall

Determine $\Sigma\delta_n h'_n A_n$ by dividing the front wall and openings into small sections.



Front wall partition table with ventilation holes							
No.	**Panel Type**	**δ_n**	**h'_n (ft)**	**h_n (ft)**	**W_n (ft^2)**	**A_n (ft^2)**	**$\delta_n h'_n A_n$ (ft^3)**
1	3	1	4	2.7	4	10.8	43.2
2	2	0.5	4	3.9	4	15.6	31.2
3	1	1	4	9.8	4	39.2	156.8
4	3	1	2.7	2.7	4.6	12.42	33,534
5	2	0.5	9.4	9.8	4.6	45.08	211,876
6	3	1	3.8	2.7	3.8	10.26	38,988
7	2	0.5	3.8	3.9	3.8	14.82	28,158
8	3	1	9.4	9.8	3.8	37.24	350,056
9	2	0.5	9.4	9.8	4.6	45.08	211,876
10	2	0.5	6	6.6	6	39.6	118.8
11	1	1	6	9.8	6	58.8	352.8
TOTAL							**1,577.29**

Then, the parameters of the shock wave impact on the exterior front wave were determined and illustrated in Fig. 11:

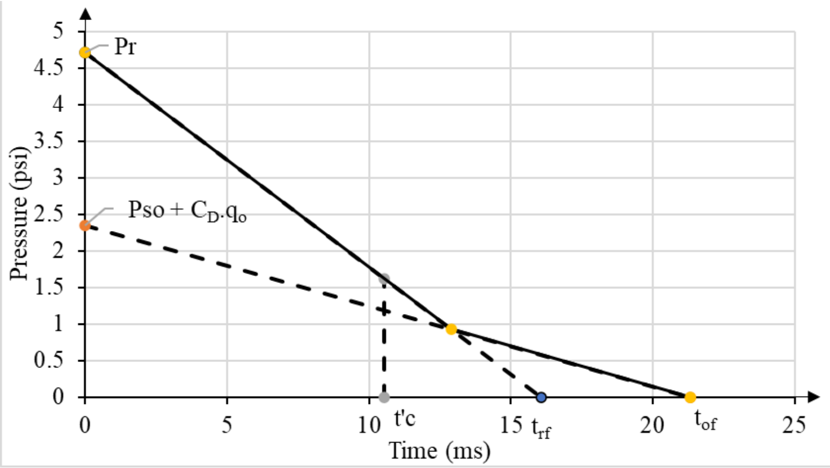


Fig. 11. Pressure – time diagram on the exterior front wall.

3.1.3. Interior pressure – time blast loads

Using the calculation procedure and the database of UFC 3-340-02, the pressure – time relationship for blast loading acting on the internal wall and roof is introduced in Fig. 12:

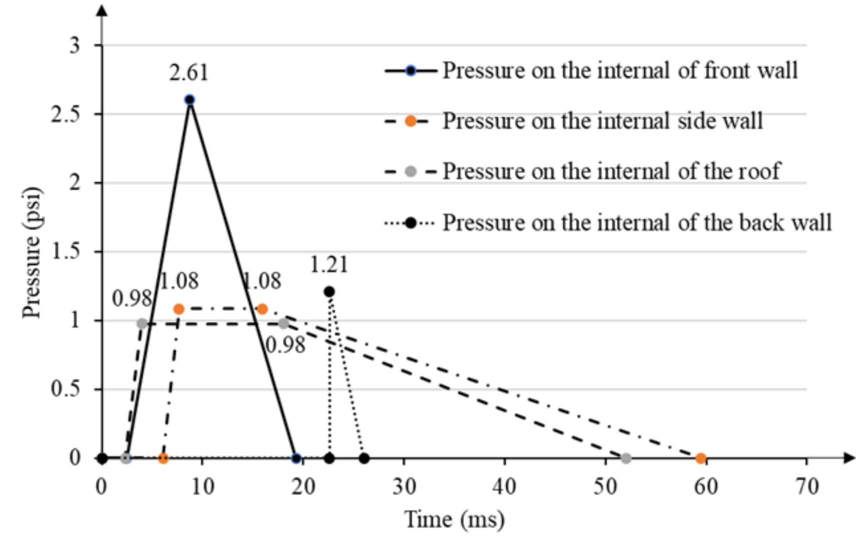


Fig. 12. Pressure – time diagram on the internal faces.

3.2. The relationship between maximum average pressures vs charge weights

Surveying in the case of a ratio between the length and the width that is approximate, it can be observed that the peak pressure on the inner face of the side walls, roof, and back wall is similar (Fig. 13). However, the pressure on the exterior and interior of the front wall is significantly higher. These pressure effects cannot be neglected in structural calculations. They are fully capable of causing harm to individuals inside the structure and generating sufficient force to blow off the roof or side walls under a large explosive load.

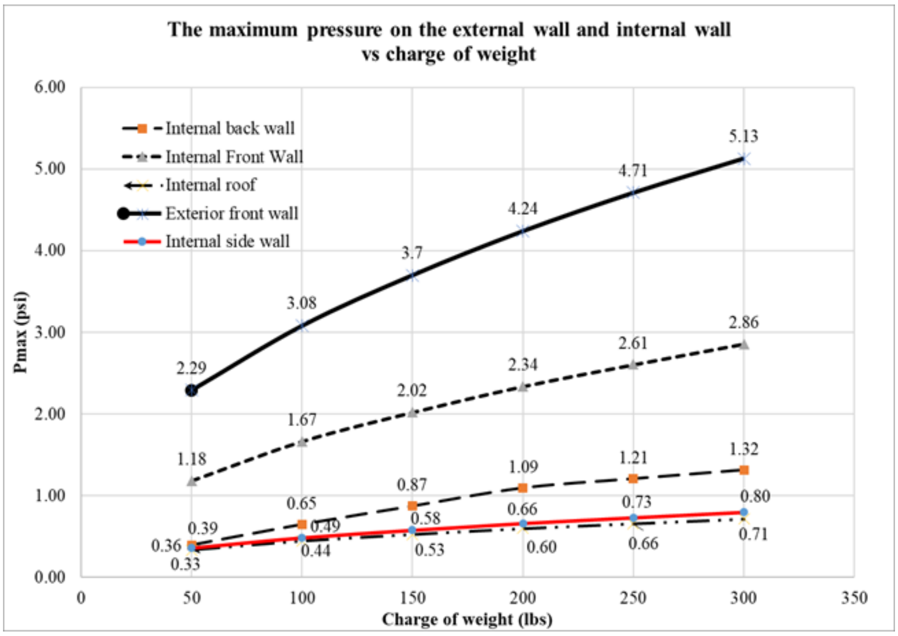


Fig. 13. The maximum pressure on the exterior face of walls and the interior roof vs equivalent charge weights.

These load values must be estimated and incorporated into structural design calculations, including strength checks for the building, doors, and windows, as well as assessments of potential damage to the structure.

Although the dynamic of blast loadings on the structure pressure is affected by the opening scale, the maximum pressures also likely follow the Hopkinson-Cranz Scaling Law – the explosive charge scales with equivalent distance.

4. Conclusion

The article presents a comprehensive methodology for calculating both external and internal blast loads on structures with openings, as outlined in UFC 3-340-02. Our analysis addresses a significant deficiency in current Vietnamese engineering practices, which often neglect the critical effects of internal pressure propagation, potentially leading to underestimations of total structural loads and catastrophic failures.

The results clearly illustrate that for structures with facade openings, the internal blast pressures are substantial and cannot be disregarded. While the exterior front wall experiences the highest peak pressure, the pressures generated on the interior surfaces, including the front, side, back walls, and roof, are significant enough to cause severe damage to non-load-bearing components, equipment, and personnel within the structure. This finding underscores the necessity of incorporating internal load calculations into the standard design process for blast-resistant structures.

While advanced computational methods, such as CFD, offer detailed simulations, they are often computationally expensive and impractical for routine design verification. In contrast, the empirical approach of UFC 3-340-02 provides a reliable, safe, and efficient tool for engineers. The development of an automated calculation tool based on this standard, as presented in this study, further enhances its practical value by enabling engineers to rapidly generate a blast loading database for comprehensive structural analysis and safety assessment.

This research serves as a foundational step. To build upon these findings, future work should prioritize the experimental validation of these calculation results to understand the physical phenomena better and refine the application of the UFC 3-340-02 standard within the local context. Furthermore, developing calibrated CFD models, verified against these experiments, would enable the investigation of more complex geometries and scenarios beyond the current standard's scope, ultimately contributing to the development of more robust guidelines for protective structures in Vietnam. By integrating this established international standard, this work provides a direct path toward enhancing the safety and survivability of critical infrastructure against explosive events.

Acknowledgement

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Tóm tắt: Thiết kế kháng nổ cho các kết cấu có lỗ thoáng là một thách thức lớn do sự phức tạp của quá trình lan truyền và tương tác của sóng nổ với cấu kiện bên trong công trình. Trong khi các tiêu chuẩn thiết kế quốc tế đã được phát triển để giải quyết vấn đề này, Việt Nam chủ yếu dựa vào các phương pháp thực nghiệm để đánh giá tải trọng nổ bên ngoài trên các tòa nhà hình chữ nhật đơn giản và bỏ qua các hiệu ứng áp lực bên trong do thiếu dữ liệu thực nghiệm. Thay vì phụ thuộc vào các mô phỏng CFD phức tạp, bài báo này trình bày một phương pháp tiếp cận toàn diện sử dụng tiêu chuẩn UFC 3-340-02 để tính toán tải trọng nổ tác động cả lên mặt ngoài và mặt trong cấu kiện công trình. Một phương pháp tính toán tự động được giới thiệu để tự động tính toán các tải trọng trên và tạo ra các cơ sở dữ liệu tải trọng nhanh chóng. Nghiên cứu này cung cấp cho các kỹ sư Việt Nam một công cụ tính toán tải trọng nổ thực tế và một cách tiếp cận mới để phân tích chính xác các cấu kiện và nâng cao khả năng kháng lực của công trình với tải trọng nổ.

Từ khóa: *Tải trọng nổ; sóng nổ; áp lực sóng tới; UFC 3-340-02.*

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