Numerical Analysis of Compound Walls of Brick Masonry, Strengthened with C-FRP Laminate under Explosive Detonations - Afghanistan Scenario

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Abstract. Afghanistan, a nation plagued by wars, terrorism, and counter-terrorism, has borne the brunt of these conflicts. The common people of Afghanistan are weary of the continuous cycle of attacks and counter-attacks by warlords. Even places of worship and those who gather there are not spared from these acts of violence. For years, explosive blasts have targeted the compound walls surrounding these religious structures. In this research, we investigate the impact of such blasts on free-standing URM walls commonly used in Afghanistan. Using ABAQUS/Explicit code, we conduct nonlinear analysis to examine the blast performance of these walls. Additionally, we retrofit the walls with a high-strength C-FRP laminate. To optimize computational time, we employ a macro strategy. The results show that the strengthened walls exhibit comparable blast performance. Importantly, when the laminate is applied to both faces, there is no longer a need for increased wall thickness in the masonry construction.

1. Introduction

In ancient cities, particularly, there is a greater abundance of masonry structures compared to reinforced cement concrete (RCC) buildings [1-3]. Many of these structures hold historical significance, with their artistic architecture contributing to the country's heritage. Given the current circumstances in Afghanistan, building structures face a significant threat from extreme impact and explosive loads [4]. The presence of a freestanding masonry compound wall surrounding the building perimeter serves as a critical crash barrier in mitigating the effects of explosive-induced loads on the building [5]. In recent years, several researchers have adopted retrofitting and strengthening strategies for existing masonry buildings to enhance their resilience against blast loading, utilizing high-strength composite polymers [2,5-7]. Among these polymers, GFRP and CFRP are the most commonly employed composites. The current study focuses on the use of C-FRP, which exhibits both strength and ductility, in the form of laminated sheets [8].
Numerous research studies have been carried out to examine the response of walls when exposed to explosive forces [1, 7-14]. A proposed method, outlined in reference [12], utilizes the concepts of continuum damage mechanics and cracking development mechanics to predict the behavior of these walls under such conditions. The results revealed that when subjected to a blast load at a reduced scaled distance, the wall generated smaller fragments. [8] conducted a computational analysis to investigate how masonry walls respond to blast loads. A homogenized orthotropic masonry material model with strain rate effect was developed to simulate the damage to the masonry material. The results showed that when the scaled distance was less than 4 m/kg$^{1/3}$, the masonry wall was entirely destroyed. Conversely, when the scaled distance exceeded 7 m/kg$^{1/3}$, no cracks appeared on the wall. A study was conducted on brick masonry walls that were subjected to blast loads at different distances. The researchers discovered that the time delay was affected not just by the distance, but also by the speed at which the waves traveled through the air and the site. [7] focused on investigating the behavior of masonry infill walls to explosive product detonations. They used underwater

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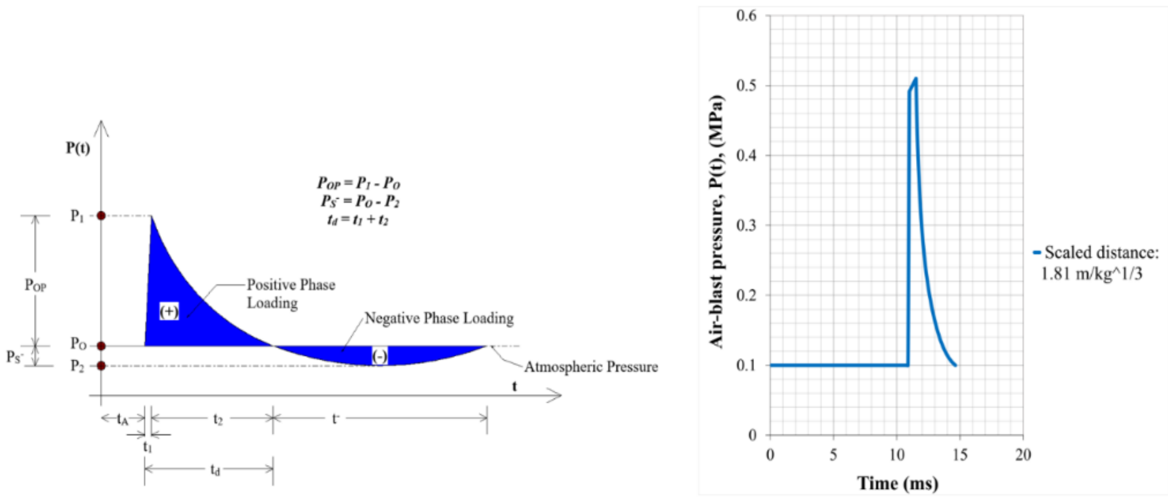
simulators (called WBWG) to simulate the conditions and calibrate a numerical model using ABAQUS Explicit dynamics software. [11] explored the use of rigid block and spring homogenized models (HRBSM) to analyze masonry walls under impact and blast loadings. Their research employed a dependable method of homogenization, utilizing a model that incorporates both a rigid body and a spring. This approach took into consideration the impact of high strain rates. The results showed good agreement with experimental findings for both impact and blast cases. The study also calculated the total duration of time required for impact and blast loads, which were determined to be 12.38 minutes and 3.35 minutes respectively. Schneider and colleagues [10] conducted a research study aimed at examining the characterization of debris projection from masonry walls when subjected to blast loads. The test recorded peak overpressures ranging from 100 to 150 Kips. Moreover, the velocity increased in correlation with the peak overpressures and corresponding impulses. As the load increased, it was expected that launch angles would have less horizontal and vertical dispersion. In a separate study, [13] investigated the effects of blast loading on masonry infill walls through experimental analysis. The results derived from this research were subsequently employed to fine-tune a computational model employing Abaqus. In a scholarly investigation conducted by [14], the effects of unorthodox, curvilinear masonry configurations, such as vaults, under the influence of explosive forces were scrutinized. The scholars then proceeded to evaluate the behavior of a curved masonry edifice when exposed to blast loading. Through the discovery, it was determined that masonry joints lacking dilatancies, and thus demonstrating non-associative plastic behavior, had a direct correlation to decreased membrane forces. As a consequence, this ultimately caused a notable 14% disparity in the out-of-plane deflections of the structure when compared to the associative scenario. Another study by [9] focused on investigating the effectiveness of various protective solutions used on brick masonry walls when exposed to blast loads. The numerical models were compared to field test results conducted at full scale. The comparison was made based on criteria such as pressure, acceleration, and permanent displacement.

The current study examines the explosive performance of compound masonry walls with varying thicknesses. The walls, constructed using red clay bricks measuring 220mm x 110mm x 70mm, were analyzed using the advanced software ABAQUS/CAE through a non-linear analysis approach. Two wall thicknesses were considered: 225mm and 335mm. Additionally, the walls were studied with the inclusion of a 2mm thick CFRP sheet or laminate, either solely on the explosion face or on both the explosion and remote faces of the wall.



(a) (b)

Fig. 1. (a) A fictionalized account of a chemical explosion's history, and (b) a projected timeline

2. Numerical Modeling

- **Blast loading**

The proposed pressure waveform of the air-blast wave, as presented by [15], is depicted in Figure 1(a). Broadly speaking, the blast-induced load can be categorized into two distinct phases: the negative pressure phase and the positive pressure phase. It is important to note that the magnitude of peak overpressure is comparatively smaller during the negative phase as compared to the positive phase. In this particular framework, P_i symbolizes the maximum overpressure, t_A represents the time the shock wave arrives, t_1 signifies the time it takes for the pressure to rise, t_2 indicates the time it takes for the pressure to decrease, t_d denotes the positive time, P_o represents the air pressure

(0.1MPa), and t^- refers to the negative time [16-24]. The existing design guidelines, such as IS 4991 [16] and TM-5 [17], recommend neglecting the negative phase during blast analysis and design. Instead, they suggest focusing solely on the positive pressure phase. The assumption is made that the negative pressure phase is significantly weaker and does not affect the structural damage response [2, 3, 4, 5, 6]. Hence, the impact of the phase characterized by negative pressure has been overlooked [3]. The blast wave properties have been computed utilizing empirical equations recommended by [15] for varying scaled distances. The values of t_A, t_1, t_2, and the overall duration (t) have been determined based on empirical correlations. A dedicated solver within Abaqus [18] was employed to simulate the explosive event. The resulting blast time profiles are depicted in Figure 1(b).

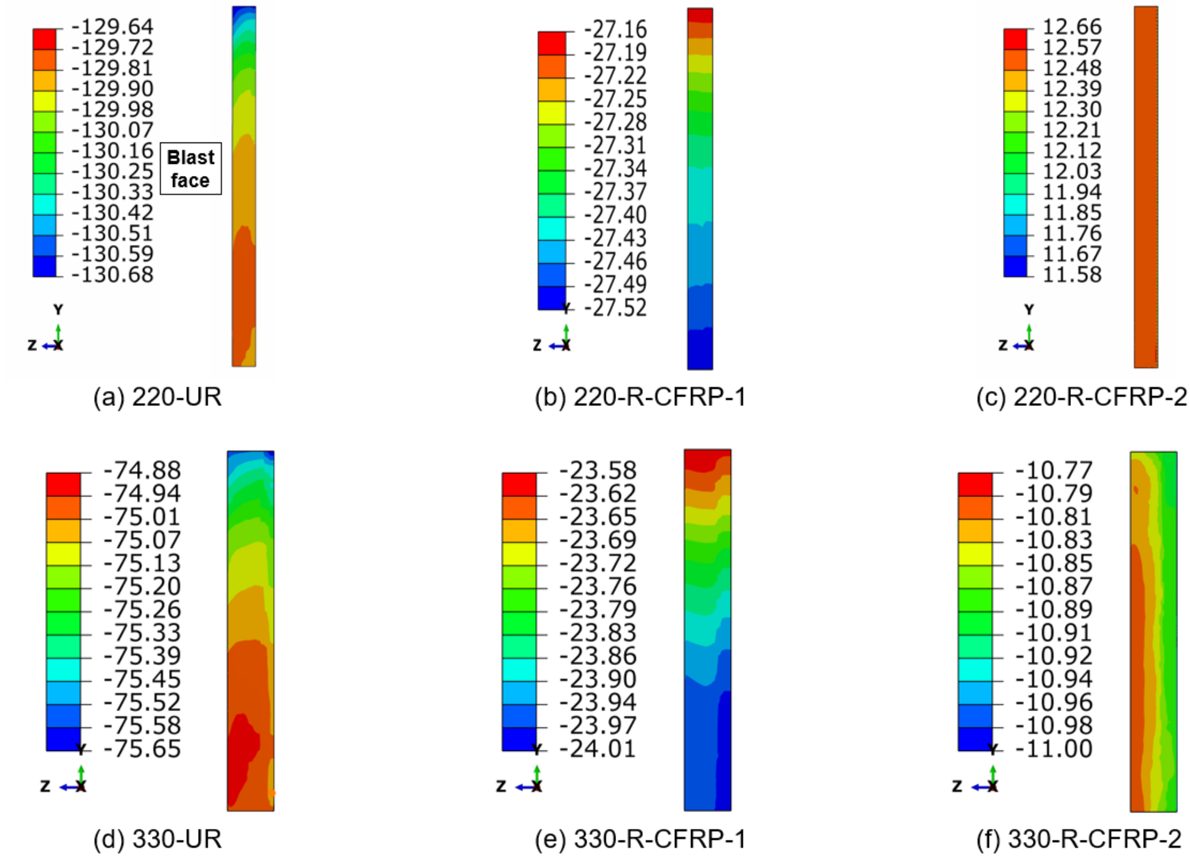


Fig. 2. Z-displacement (mm) profile of the walls

- **Masonry Modelling**

In the present research, the concrete damaged plasticity (CDP) model integrated into ABAQUS/CAE offers a broad range of possibilities for simulating masonry and other materials with quasi-brittle characteristics [5, 6]. The CDP model is specifically designed to account for both tension-induced cracking and compression-induced crushing as potential failure mechanisms in masonry structures [25-26]. In the context of this model, damaged variables are utilized, which span from a value of 0, indicating intact material, to a value of 1, indicating material that is completely damaged. [3-6]. In the analysis of the yield or failure surface governed by two hardening parameters, specifically compressive equivalent plastic strain ($\varepsilon_c^{pl,h}$) and tensile equivalent plastic strain ($\varepsilon_t^{pl,h}$) [18], The plastic deformation under compression is of utmost importance when it comes to understanding the relationship between the compressive strength of masonry and the parameters that indicate damage [36]. The relationship between these two variables is interconnected in terms of the failure mechanisms observed under both compression and tension loads. It is postulated that the stress-strain curves observed in uniaxial conditions can be replaced with curves plotting stress against inelastic strain. This conversion process is automated through the use of Abaqus, which utilizes stress versus plastic-strain data provided by the uSER [16-22]. The parameter values for the CDP model of brick masonry are sourced from Valente and Milani's research in 2016 [23]. Other research works conducted by the author Kanaan M. H. G. are of the interest to the readers in the concerned research area, sources: [27-31].

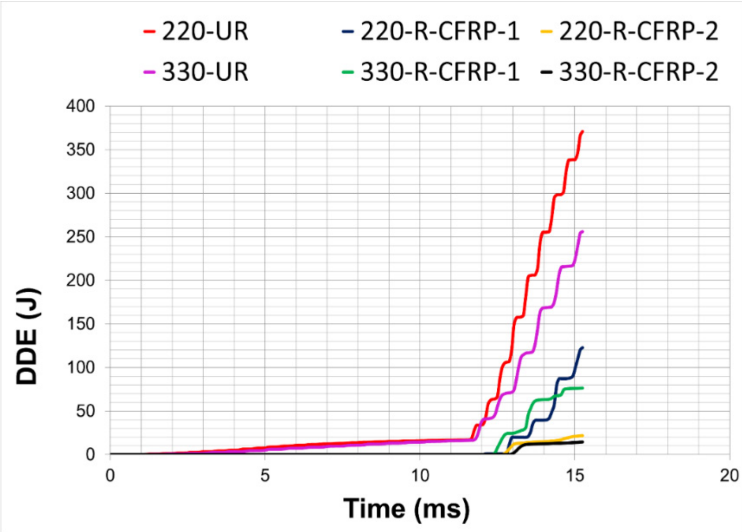


Fig. 3. DDE profile of the walls

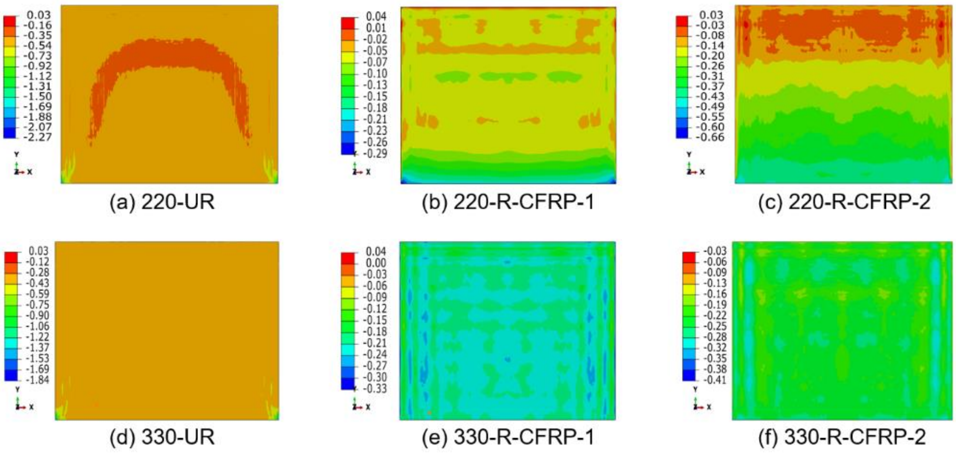


Fig. 4. Normal stress (MPa) contour on the walls' blast face

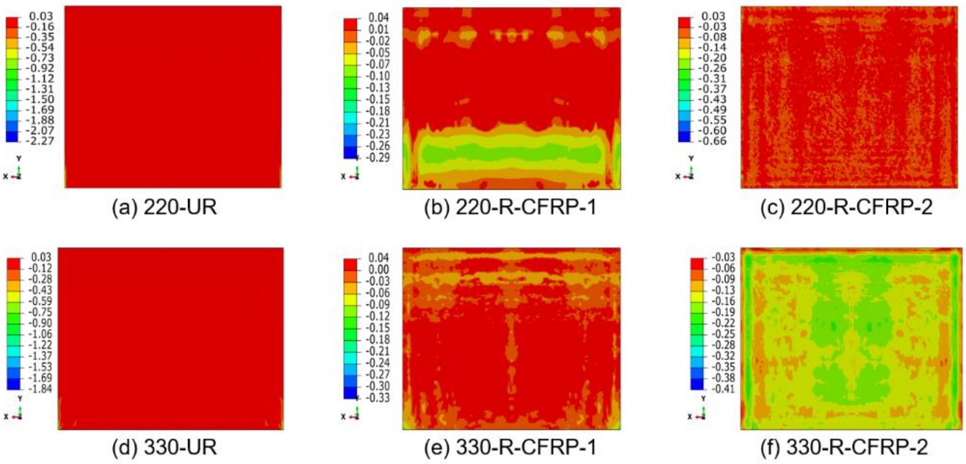


Fig. 5. Normal stress (MPa) contour on the walls' remote face

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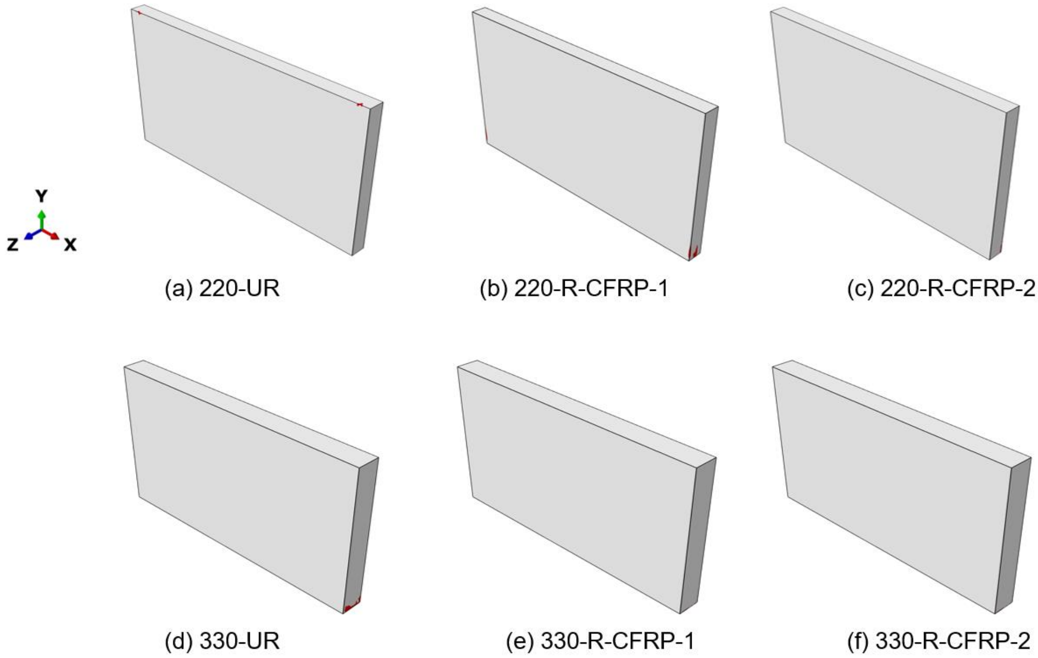

Fig. 6. Compression damage profiles

3. Results

After conducting dynamic analyses, several noteworthy observations have been made:

- The maximum displacement for URM walls of 220mm and 330mm is found to be 130.68mm and 75.65mm, respectively. The corresponding damage (DDE) values are 370.95J and 255.76J, as shown in Table 1 and Figure 2 to Figure 5.
- No significant crushing of the masonry has been observed, as depicted in Figure 6.
- A considerable amount of cracks, both horizontal and vertical, have emerged on the distant side adjacent to the unattached edges of the both walls. The average crack depths measure 155mm and 132mm, respectively, as shown in Figure 7.
- The URM walls, with thicknesses of 220mm and 330mm, experience maximum compressive stresses of 0.54MPa and 0.43MPa, respectively. These values are below the permissible compressive stress of 1.10MPa, as stated in IS 1905:1987, Table 1.
- By applying a CFRP sheet with a tensile strength of 2050MPa and a thickness of 2mm to the explosion face of the 220mm thick URM wall, the deformation, damage, and cracking depth are reduced by 79%, 67%, and 74% respectively, compared to an un-retrofitted URM wall of the same thickness, as shown in Table 1. Similarly, the percentage reductions for these parameters in the 330mm thick CFRP retrofitted wall are 68%, 76%, and 70% respectively, compared to a 330mm thick un-retrofitted wall, as indicated in Table 1. However, it should be noted that using a CFRP laminate on the explosion face alone is not highly effective in reducing cracking on the tension side of the walls, as depicted in Figure 7.
- The utilization sheets on both sides has a substantial impact on minimizing the maximum displacement, damage, and cracking, as indicated in Table 1.
- In order to achieve the greatest level of performance in terms of maximum displacement and cracking, it has been found that retrofitting a wall with a thickness of 330mm and a sheet on both sides is the most effective solution.
- The effectiveness of walls with laminate is greater when applied to the explosion face only, compared to the rear face. This holds true for both walls, as shown in Table 1. Nevertheless, applying laminate to both faces significantly enhances their ability to withstand blasts.
- The findings indicate that the utilization of sheet on both sides eliminates the need for a thicker wall. The performance of walls measuring 220mm and 330mm in thickness is equivalent to those with sheet on both sides, given the specified explosive weight and standoff distance (refer to Table 1).

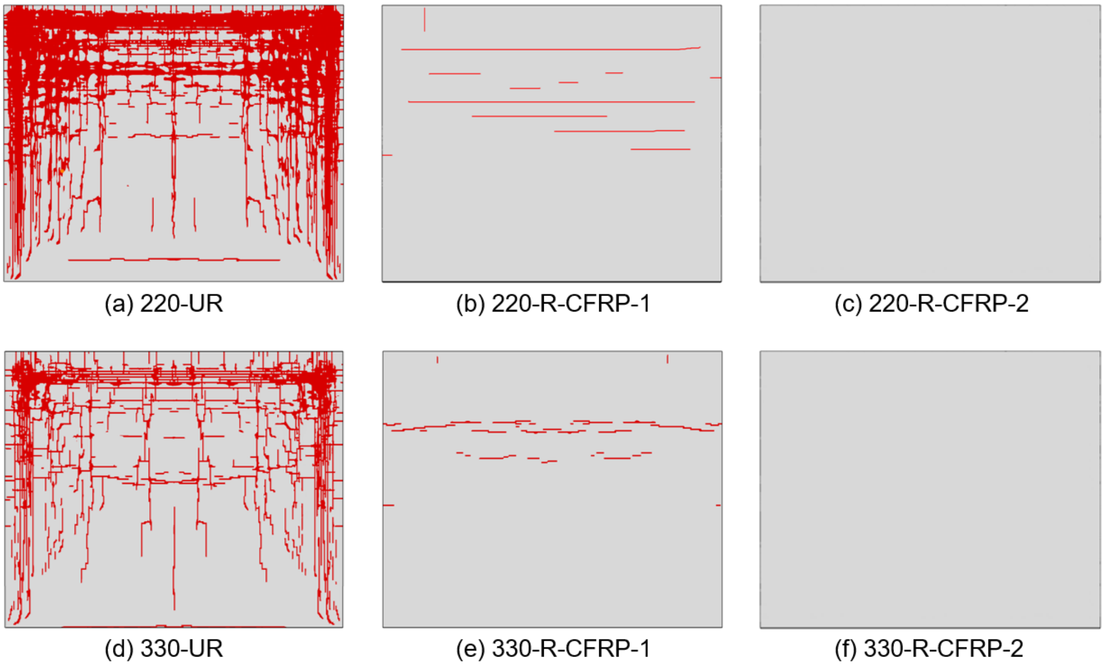

Fig. 7. Tension damage profiles

Load-carrying mechanism:

- By exclusively employing CFRP sheeting on the side facing the explosion, the sheet is tasked with absorbing and dispersing the bulk of the explosive force through its in-plane mechanism. Consequently, a smaller portion of the blast energy is transmitted to the masonry wall, resulting in diminished displacement and considerably reduced harm when compared to an unreinforced wall.
- The incorporation of CFRP sheeting on both the front and back surfaces of the masonry wall greatly enhances its resistance to explosions. The sheeting on the back surface functions as a partial restraint, effectively dispersing energy and fortifying the wall's capacity to withstand blasts.

Table 1. Predicted responses

Wall No.	**Maximum transverse Z-displacement (mm)**	**Maximum principal stresses (MPa)**	**Average flexural crack depth (mm)**	**Maxm. *DDE (J)**
220-UR	130.68	+0.03; -0.54	155	370.95
220-S-CFRP-1	27.52 ([a]79)	+0.04; -0.23	40 ([a]74)	122.63 ([a]67)
220-S-CFRP-2	11.58 ([a]91)	+0.03; -0.14	No cracking	21.86 ([a]94)
330-UR	75.65	+0.03; -0.43	132	255.76
330-S-CFRP-1	24.01 ([b]68)	+0.04; -0.18	32 ([b]76)	76.38 ([b]70)
330-S-CFRP-2	10.81 ([b]86)	+0.03; -0.13	No cracking	14.35 ([b]94)

*[*a] %age reduce w.r.t. 220-UR;*
*[*b] %age reduce w.r.t. 330-UR*

4. Conclusions

The objective of this research is to perform numerical simulations on masonry walls with different thicknesses, namely 220mm and 330mm. The objective is to test the walls' ability to withstand explosive loads, specifically a quantity of 7.20kg of TNT, positioned at a safe distance of 3.50m and at a height of 1.50m from the ground. To enhance the walls' response to such explosions, a C-FRP sheet is applied to the side that will be directly exposed to the blast, as well as to both faces of the walls. Predictions indicate that the C-FRP sheet effectively dissipates a significant portion of the explosive energy by undergoing plastic deformation within the plane. The energy that remains is subsequently transmitted to the wall, leading to a comprehensive enhancement in performance. When the sheet is only applied to the face exposed to the explosion, it successfully reduces displacement, but does not effectively mitigate cracking on the opposite face. However, when the sheet is applied to both faces of the walls, it greatly enhances both cracking resistance and displacement response. Furthermore, the study reveals that there is no need for thicker walls, as walls with thicknesses of 220mm and 330mm perform equally well when equipped with the C-FRP sheet on both faces under the considered peak overpressure. The results underscore the efficacy of employing C-FRP sheets to enhance the performance and safety of compound masonry walls when exposed to explosive loads. The use of such sheets can help mitigate potential damage and ensure the integrity of infrastructure in similar scenarios.

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