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Numerical Study on the Dynamic Behavior of Masonry Walls Subjected to Blast Load

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Abstract- Hazardous blast loads pose significant structural challenges to buildings and infrastructure. Masonry walls, widely used in commercial, manufacturing, and residential constructions are susceptible to blast loads due to their rigidity and limited energy dissipation capacity. Understanding the effects of blast loads on masonry walls is essential for designing structures capable of withstanding such forces, thereby minimizing structural damage and ensuring occupant safety. This study investigates the impact of explosive loading on masonry walls, encompassing failure mechanisms, and strategies to evaluate and mitigate blast damage. ABAQUS/Explicit 2017 was used for a numerical evolution to assess eight masonry wall cases, comparing the performance of clay- brick masonry walls including as well as without a core made of reinforced concrete under blast loads and to figure out the importance of lateral wall support. The outcomes demonstrated that the resistance throughout clay-brick masonry walls to explosions decreases in terms of maximum displacement, stresses, and damage patterns as wall thickness increases. Conversely, walls with thicker RC cores demonstrated significantly improved performance by absorbing most of the energy from the air blast. Furthermore, side-supported walls outperformed free-standing walls in terms of displacement, stress distribution, and overall damage resistance, with the latter experiencing total collapse in several scenarios.

Keywords- *Explosion, TNT, Brick Wall, Rc Core, ABAQUS, URM.*

Abbreviation

URM: Unreinforced masonry walls.
CFRP: Carbon fiber-reinforced polymer.
DIF: Dynamic increase factor.
P_O: Atmospheric pressure.
P_{op}: Maximum pressure.
t_A: The arrival time of the shock wave.
ψ: Decay coefficient.

I. INTRODUCTION

A A masonry wall is a systematic arrangement of units interconnected by mortar joints. Masonry is used in monuments, arches, and economical structures because of its durability, visual appeal, and sustainability. The study of blast-loaded masonry walls is essential due to increasing security threats and catastrophic events. Structures may sustain damage from high-pressure waves and debris resulting from accidental or intended explosions. The poor tensile strength of masonry or mortar joints could restrict the response of these structural systems to significant in-plane and out-of-plane lateral forces. Numerous variables influence the reaction of a URM wall during blast loads imposed orthogonally towards its surface; the parameters include boundary conditions, slenderness ratios, and masonry wall shear, compressive, and tensile strengths [1]. Under blast effect, masonry walls fail primarily as follows: Outward Deflection and Debonding: The unexpected blast pressure can deflect the wall outward, causing mortar joints to fall apart or masonry units to separate, Cracking: Masonry walls can crack under unexpected loads, particularly at weaker joints such as mortar joints, Spalling and Ejection: Greater blast loads can spall masonry and blow debris, Pancaking: Masonry units can fail under repeated blast load, causing collapse. Thickness, material properties (like compressive strength and elasticity), mortar joint quality, and boundary conditions (e.g., restricted or free to deflect) affect masonry wall response. The way masonry walls behave to blast loads depends on several variables: Blast Wave Description: Blast wave magnitude, duration, and type determine wall pressure intensity, Distance from the Blast Source: Masonry walls near explosions have a higher blast load. The law of inverse square says that blast intensity diminishes with distance, Masonry walls that are thicker, higher, and strengthened exhibit superior resilience to blast loads. Nevertheless, excessive thickness could raise the risk of rupture and failure due to energy transmission through the wall. The material property of construction units (such as concrete block, brick, and stone) and mortar (e.g., compressive strength, bond strength) significantly influence the capacity of the wall to absorb and dissipate blast energy, Reinforced masonry walls, incorporating embedded steel bars or mesh, provide superior performance under blast loads, as masonry wall is a systematic arrangement of units interconnected by mortar joints. Masonry is used in monuments, arches, and economical structures because of its durability, visual appeal, and sustainability. The study of blast-loaded masonry walls is essential due to increasing security threats and catastrophic events. Structures may sustain damage from high-pressure waves and debris resulting from accidental or intended explosions. The poor tensile strength of masonry or mortar joints could restrict the response of these structural systems to significant in-plane and out-of-plane lateral forces. Numerous variables influence the reaction of a URM wall during blast loads imposed orthogonally towards its surface; the parameters include boundary conditions, slenderness ratios, and masonry wall shear, compressive, and tensile strengths [1]. Under blast effect, masonry walls fail primarily as follows: Outward Deflection and Debonding: The unexpected blast pressure can deflect the wall outward, causing mortar joints to fall apart or masonry units to separate, Cracking: Masonry walls can crack under unexpected loads, particularly at weaker joints such as mortar joints, Spalling and Ejection: Greater blast loads can spall masonry and blow debris, Pancaking: Masonry units can fail under repeated blast load, causing collapse. Thickness, material properties (like compressive strength and elasticity), mortar joint quality, and boundary conditions (e.g., restricted or free to deflect) affect masonry wall response. The way masonry walls behave to blast loads depends on several variables: Blast Wave Description: Blast wave magnitude, duration, and type determine wall pressure intensity, Distance from the Blast Source: Masonry walls near explosions have a higher blast load. The law of

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reinforcement mitigates cracking and diminishes the risk of wall failure, and Pre-existing Conditions: Any decline or damage of the masonry may amplify the impact of explosion. Engineers commonly employ a combination of analytical models and actual data to comprehend the behavior of masonry walls against blast pressure. The main analysis steps are: Calculating Blast Load: Size, location, and environmental factors can be used to compute the pressure-time history of blast load using models like the Friedlander curve or software like CONWEP (U.S. Army Corps of Engineers' explosive load analysis technique), FEA (Finite Element Analysis): FEA models can simulate blast-loaded masonry wall stress distribution, displacement, and failure modes. This form of research enables extensive wall response assessment, including localized damage and potential collapse. Design Codes for Blast Resistance: UFC 3-340-02 (the United States. Department of Defense) and ASCE 59-11 are blast-resistant structure codes. A multitude of numerical and experimental investigations have been carried out to find out the consequences of blast impacts on walls constructed from masonry. Ehsani et al. [2] carried out a test on two non- bearing URM walls with sizes 11 ft x 8 ft x 8 inch each, CFRP was retrofitted onto one URM wall on both sides, a 200-pound (90.8-kilogram) TNT charged explosion was used to demolish the walls from a 30-feet standoff distance, based on the research, the effective implementation of CFRP retrofitting prevented the URM wall from collapsing as well as retained what of the masonry detritus within the CFRP, the CFRP retrofitting enables non-bearing URM walls to resist major damage, such as the compressive fail of the masonry, with no collapsing. Shamim et al. [3] assessed a RC-framed wall with dimensions of 3000 X 3000 X 230 mm that was infilled in masonry. The RC frame had a cross-section of 230X 235mm, and the wall contained a 1000X 1000 mm opening at the center, a 100 kg TNT charge was used to explode the wall at various standoff distances that was 20 m, 30 m, as well as 40 m, the findings of the inquiry showed that that; a decrease via standoff distance is linked with an increase in wall displacement, applicable to both walls with as well as with no openings, furthermore, the RC framed masonry wall with opening demonstrates greater peak displacement compared to a wall free of an opening. Anas et al. [4] performed a numerical study on 6000x2500x350 mm brick URM wall subjected to blast loads of 3.6 and also 7.2 kg-TNT equivalents at a constant distance of 3.5 m from the wall, an improved blast performance of the wall was achieved by using a 230 mm thickness reinforced concrete wall including a 70 mm wide cavity and reinforced concrete walls containing bricks and sand as soft fillings within the cavity, the 230 mm thickness RC walls containing soft fillings (bricks and sand), in particular bricks in the cavity exposed to blast load, illustrate that the majority of the energy from the air-blast has been absorbed by softcore materials resulting in reduced displacement, reduced damage dissipation energy, and observable cracking in 350 mm thick walls and the 230 mm thickness reinforced concrete wall without infill materials. Anas et al. [5] analyzed the blast behavior of free-standing compounded unreinforced masonry (URM) walls commonly utilized in Afghanistan using the ABAQUS/Explicit program, explosive charge of 7.20 kilogram of TNT with a stand-off distance equal 3.50 m, a 2 mm thick high-strength CFRP laminate is used just to the front side or to both sides of the wall to enhance its performance, results from numerical investigations indicate that; the utilized CFRP sheet mainly absorbs explosive energy through in-plane plastic deformation, the wall absorbs remaining energy, so improving its efficiency, furthermore, it has been clarified that; a thicker wall is unnecessary, as the performance of walls measuring 220 mm and 330 mm in thickness is comparable when the sheet is applied to both surfaces during the examination of the maximum overpressure. Thango et al. [6] executed a numerical analysis to conduct the structural behavior of two masonry walls exposed to explosive loads using ABAQUS program, one wall had no opening, while the other included an opening, this analysis contained parametric studies to assess the effects of variations in charge weight and the spacing between the explosion origin to the structure, and static load on the responses of the walls, The results indicate that the typical in-plane cracking diagonally fail mechanism might prevail under blast conditions, influenced by explosive weight and stand-off distance, particularly when the wall is also subjected to in-plane static loads, moreover, the impact from explosion may be considerably minimized if there is an opening within the wall.

II. AIM OF STUDY

In the current study, a numerical investigation using ABAQUS/Explicit 2017 program for eight cases of masonry walls was conducted to compare the response for clay-brick masonry walls and other clay brick masonry walls containing a reinforced concrete core under blast load and to know the importance of side support of walls. This investigation includes variations in wall thicknesses of 320 mm and 370 mm, in addition to various boundary conditions of the walls (free-standing system, three side support system).

III. BLAST LOADING

An explosion is an extreme release of energy that causes gas expansion, high temperatures, powerful pressure waves, and debris or fragments. An explosion releases energy quickly, creating a shock wave that destroys nearby items and buildings. The positive phase starts when the explosive wave hits the structure (Figure (1), point B). The pressure quickly peaks and then steadily descends to atmospheric pressure during the positive phase. Decreasing relative to atmospheric pressure provides a negative or suction condition (point C in Figure (1)). Overpressure in the positive phase is greater than in the negative phase, and reverse pressure effects in the negative phase are thought to be minimal apart from lightweight constructions [7], [8], [9], and [10].

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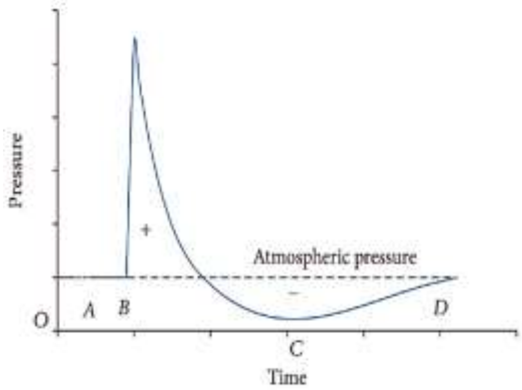

Figure (1): Pressure time history for free explosion [7].

The empirical model mentioned in [10] and [11] may clarify the path of the blast pressure wave, as demonstrated in Eq. (1).

$$P(t)=\begin{cases} P_O, (0 \le t \le t_A) \\ P_O + P_{OP}\left(\frac{t}{t1}\right), (t_A \le t \le t1) \\ P_O + P_{OP}\left(1-\frac{t-t1}{t2}\right).\exp\left(-\frac{\psi(t-t1)}{t2}\right), (t1 \le t) \end{cases} \quad (1)$$

Here, $P(t)$ = explosion pressure during time; P_O = atmospheric pressure; P_{OP}= Peak pressure; t_A = The arrival time of the shock wave; $t1$ = increasing time duration; $t2$ = reducing time duration; ψ = decay coefficient.

IV. CASE STUDY

The research used ABAQUS/Explicit 2017, a computational software, to evaluate the blast reaction of a clay brick-constructed wall of 4000 mm in length and 2500 mm in height with 320 mm and 370 mm thickness. The dimensions of the bricks are specified as 230 mm (length) × 110 mm (width) × 71 mm (thickness). The mortar joints are 20 mm in thickness. The walls are either free-standing or supported with a side support system that prevents side wall movement.

Eight cases of masonry wall was studied as follows: the first and fifth cases have a 320 mm thickness of clay bricks, the second and sixth cases have a 370 mm thickness of clay bricks, the third and seventh cases are content of two wythes of masonry walls, each measuring 110 mm in thickness, and the 100 mm core in between made of reinforced concrete which is reinforced by steel rebars placed at a distant of 100 mm center-to-center in the two horizontal and vertical directions, and finally the fourth and eighth cases are content of two wythes of masonry walls, each measuring 110 mm in thickness, and the 150 mm core in between made from reinforced concrete which is reinforced by steel rebars placed at a spacing of 100 mm center-to-center in the two horizontal and vertical directions, as shown in Table (1), Table (2), and Figure (2). The explosion in consideration is a surface unconfined air explosion with a 5 kg-TNT charge at a standoff distance of 2 m. The charge was positioned within 1 meter above the ground.

Table (1): Model ID

	Model no.	Wall ID	Model no.	Wall ID
Brick models	M1	B-320	M5	B-320-S
	M2	B-370	M6	B-370-S
Brick with reinforced concrete core models	M3	BR-100	M7	BR-100-S
	M4	BR-150	M8	BR-150-S

Table (2): Model Description

Model no.	Dimension (L × H× t) (mm)	Boundary condition
M1	4000× 2500× 320 (solid)	Free standing
M2	4000× 2500× 370 (solid)	Free standing
M3	4000× 2500× 320 (RC core)	Free standing
M4	4000× 2500× 370 (RC core)	Free standing
M5	4000× 2500× 320 (solid)	Free standing with side support
M6	4000× 2500× 370 (solid)	Free standing with side support
M7	4000× 2500× 320 (RC core)	Free standing with side support
M8	4000× 2500× 370 (RC core)	Free standing with side support

In this arrangement, the first English alphabet indicates the type of model, if it is ‘‘B” the model consists of bricks and mortar only, and if it is ‘‘BR” the model composed of a pair wythes of masonry walls and RC core. The second numeric denotes either the thickness of the wall in the context of brick models or the thickness of the core (mm); the third English alphabet ‘‘S” indicates that the model has side support.

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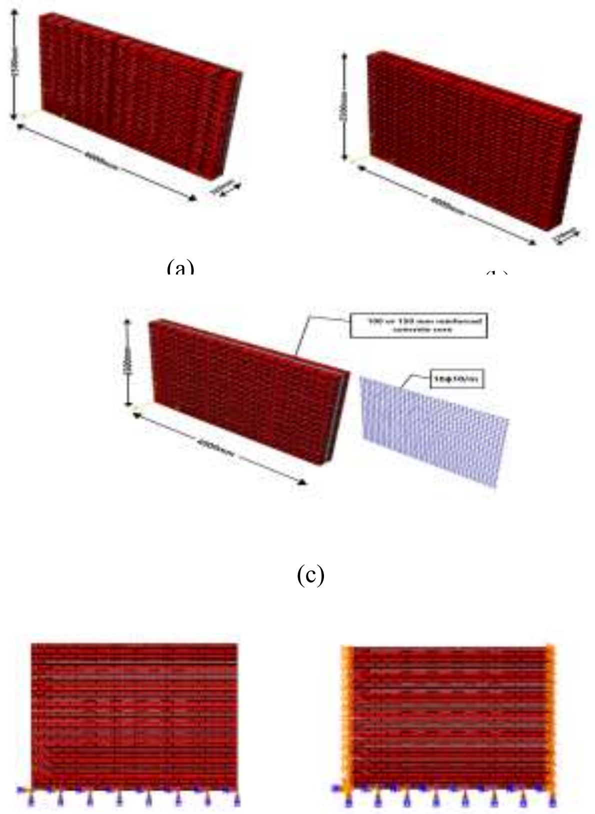
strength, tensile strength, and elastic modulus 30 Mpa, 3 Mpa, and 26.6 Gpa, respectively, according to [14], while the steel rebars have a yield strength of 400 MPa in accordance with ECP 203-2020. The tensile and compressive strengths of brick and mortar have a DIF of 3, whereas the DIF for Young's modulus is 2 [15]. A DIF is 3.0 for compressive strength, 6.0 for tensile strength and elastic modulus was applied for reinforced concrete core in accordance with the CEB FIB CODE 2010. A DIF equal 1.25 is used for reinforcing steel, as cited in UFC 3-340-02 [9] and TM 5-1300, 1990 [8].



(d) (e)

Figure (2): Finite element models: (a), (b) Brick models; (c) RC core model; (d), (e) Boundary conditions of the walls (fixed bottom -fixed bottom with hinge sides).

VI. MASONRY WALLS MODELLING

Three procedures exist for modeling masonry; first technique is a detailed micro-modelling, where units, mortar, as well unit-mortar interaction can be represented individually, second technique is a simplified micro-modelling, in which units as well mortar in the joint spaces are modeled with continuous elements, meanwhile the unit-mortar connection is characterized by discontinued elements, and finally the third technique is a macro-modelling that treats units, mortar joints, and also the contact among the unit with mortar represent an uniform continuum [16] and [17]. To find accurate findings, a detailed micro-modelling approach used for the numerical modelling mentioned in this paper. Using ABAQUS/Explicit 2017, a C3D8R element is employed to distinguish the brick unit, joint mortar, and concrete. The steel rebars are discretized using T3D2 elements, while their mesh is integrated into the concrete with the EMBEDDED_REGION constraint command. The wall is fixed to a stationary surface and hinged from the sides. The GENERAL_CONTACT_INTERACT keycard employs "hard", "friction", and "cohesion" contacting models, together with the penalty contact approach, to characterize the connection among the wall and an arbitrary surface [18] and [19]. The required input parameters for either contact interaction models affected by out-of-plane loads can be found in [20], where the coefficient of friction is 0.75 in the case of unit-mortar interaction.

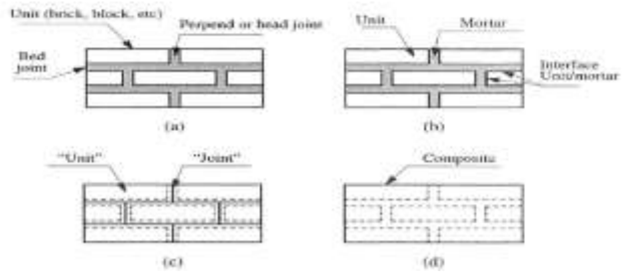


Figure (3): Modeling of masonry arrangements: (a) Masonry specimen; (b) Detailed micro-modelling; (c) Simplified Micro-modelling; (d) Macro-modelling [17].

VII. RESULTS AND DISCUSION

This section discusses how masonry walls behave against blast load in terms of Von-Mises stresses, displacement, and wall damage.

- For free standing walls, the peak displacement of the clay-brick URM walls, which are 320 mm thick (M1) was found to be 1073.21 mm. When the wall's thickness was increased to 370 mm, the maximum displacement of the clay-brick URM walls (M2) was 959.561 mm, representing a 10.6% decrease relative to max displacements of M1 (Figure (4) and Figure (9)), but in both cases, a collapse occurs, and there was a separation of bricks and mortar at the same height as the height of the bomb.

In M3, the use of 100 mm RC core led to the collapse in the wall from above on the front wall opposite to bomb and collapsing from the right side on the back of the wall. However, with the use of 150 mm of RC core in the M4, some of the bricks

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- and mortar fly out slightly from the sides, certainly better than M3.
- The peak displacement for the 100mm reinforced concrete core in the wall was determined 104.3 mm, meaning that it decreased by about 90% in contrast to 320 mm thickness clay brick URM walls (M1) while the max displacement for the 150mm reinforced core in the wall was determined 58.6 mm, meaning that it decreased by 43.8% in comparison to the wall with 100mm core (M3) and by about 93.8% in comparison to 370 mm thick clay brick URM walls (M2).
- For side supported walls, as a result of the brick walls exposed to the explosion, the maximum response occurred in the middle and no collapse occurred because of their side supported. In the case of the concrete core in the middle, nothing happened to it or to the front wall. The response only occurred in the upper part of the back wall because of the tensile stresses resulting from the blast wave.
- For fixed bottom and hinged sides walls , the maximum displacement of a 320 mm thick clay brick URM walls (M5) is 16.6mm. However, the maximum displacement of M6 is 15.3 mm, a 7.8% decrease from M5 (Figure (4) and Figure (10)).
- The peak displacement of the 100 mm reinforced concrete core (M7) is 46.65 mm while for 150 mm reinforced concrete core (M8) is 33.4 mm, meaning it decreased by 28.4% relative to max displacements of M7 (Figure (4) and Figure (10)).
- It is found that, increasing the wall thickness (core & brick) gives better controls the damage patterns derived from the masonry CDP model. (Figure (6) and Figure (7)).
- The wall's displacement is managed by the RC core located inside it (Figure (4)) . Additionally, it considerably lowers the maximum level of stress, splitting on the rear side of wall and decreasing the max displacements to 96. 9% better than M1 (Figure (7)).
- Comparing the cases of free-standing walls and the walls that supported from the side in the case of the URM walls, it was found that the collapse occurred in free standing walls and the side supported walls are much better in terms of displacement, stresses, and damage pattern.
- In comparing the cases of free -standing walls and laterally supported walls in unreinforced masonry (URM) with a reinforced concrete (RC) core, it was observed that the free -standing wall with a 100 mm RC core experienced partial failure, whereas the laterally supported walls exhibited superior performance regarding displacement, stress distribution, and damage patterns.

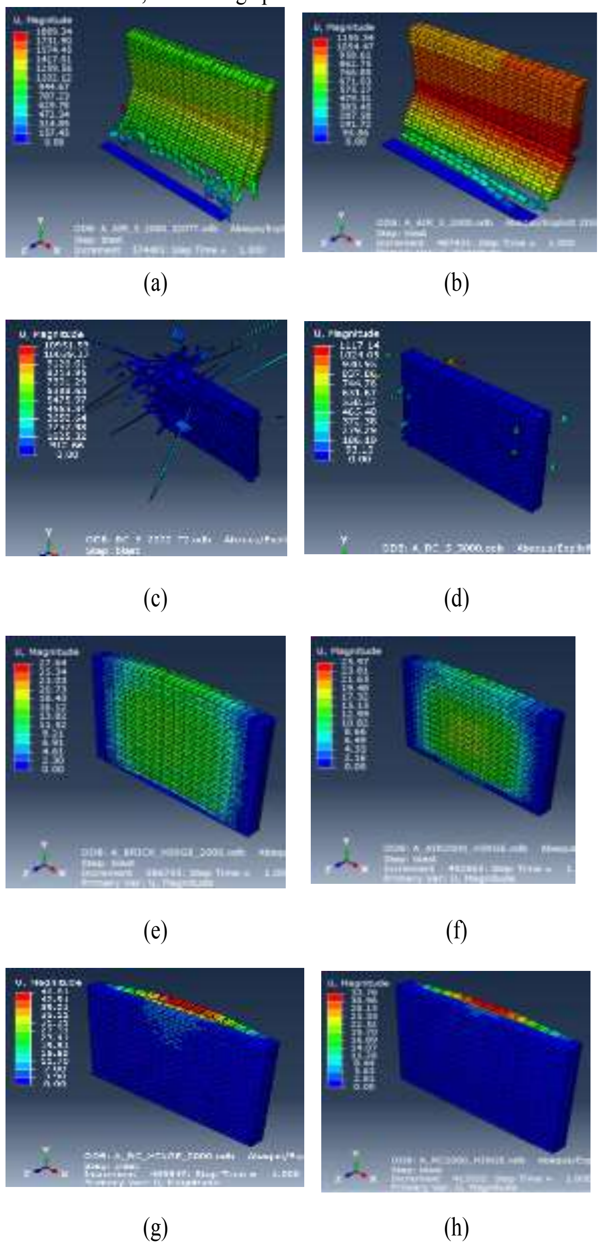

Figure (4): Displacement distribution (mm): (a) M1; (b) M2; (c) M3; (d) M4; (e) M5; (f) M6; (g) M7; (h) M8.

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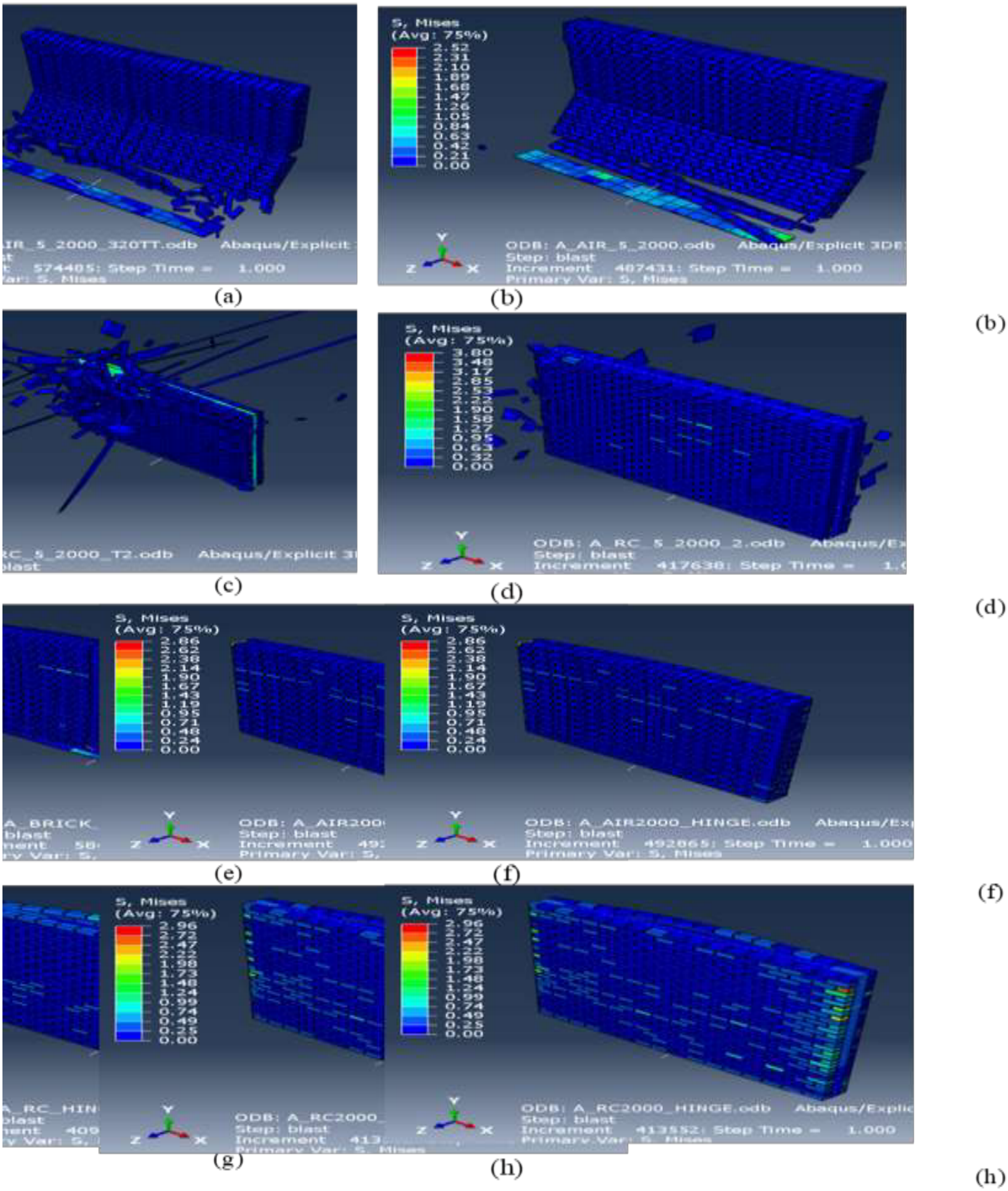

Figure (5): Distribution of Von mises stress (MPa):
(a) M1; (b) M2; (c) M3; (d) M4; (e) M5; (f) M6; (g) M7; (h) M8.

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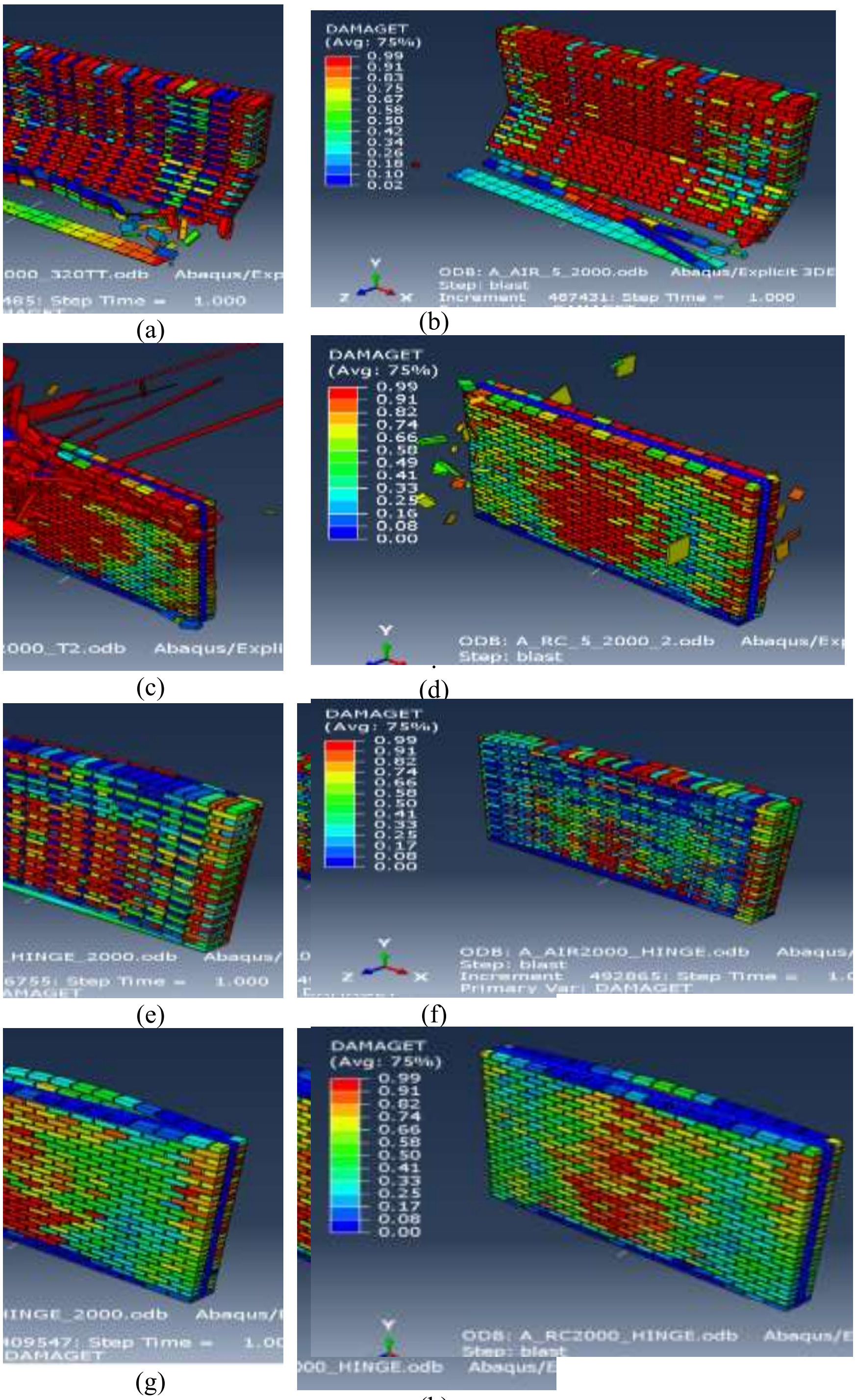

(b)

(d)

(f)

(h)

Figure (6): Damage pattern on the explosion side of walls:
(a) M1; (b) M2; (c) M3; (d) M4; (e) M5; (f) M6; (g) M7; (h) M8.

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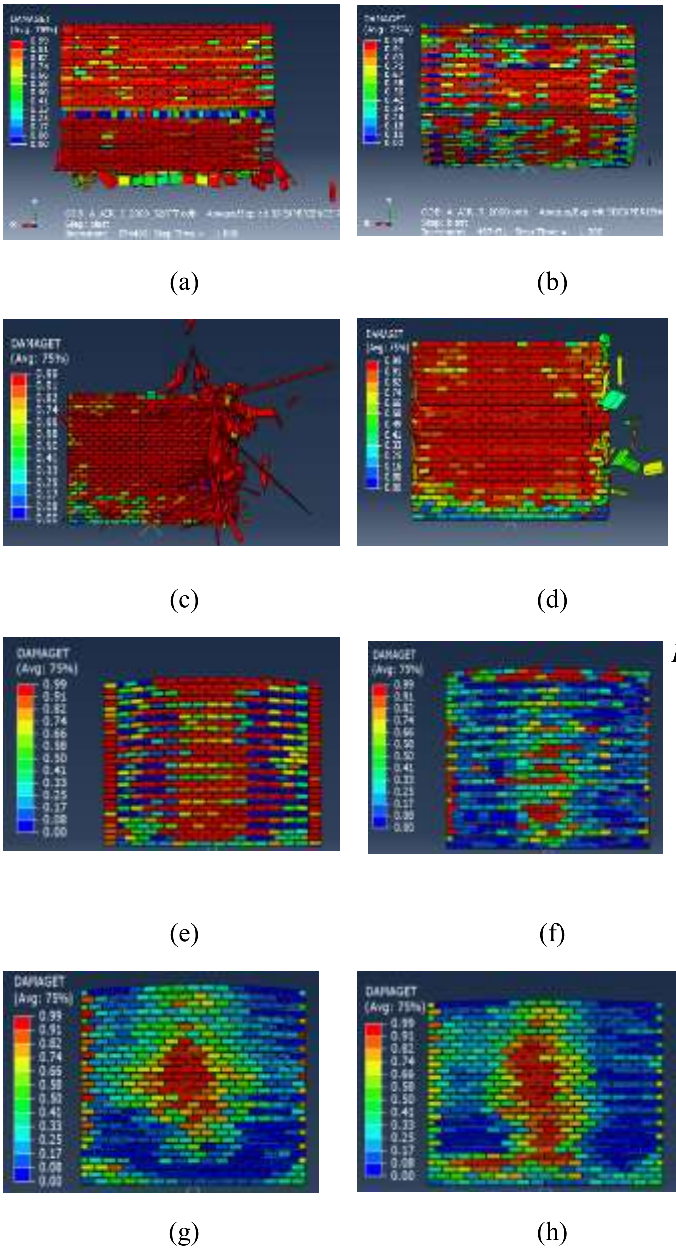

Figure (7): Damage pattern across rear side of walls: (a) M1; (b) M2; (c) M3; (d) M4; (e) M5; (f) M6; (g) M7; (h) M8.

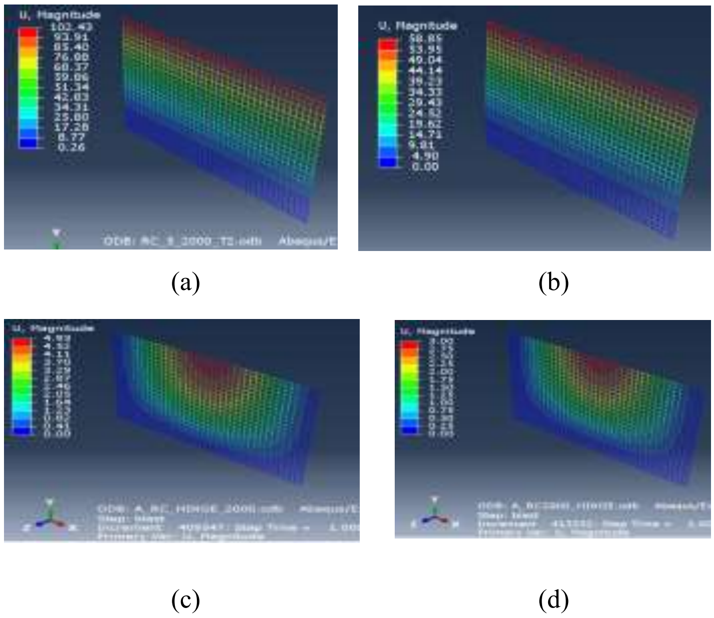

Figure (8): Distribution of displacement of reinforcement (mm): (a) M3; (b) M4; (c) M7; (d) M8.

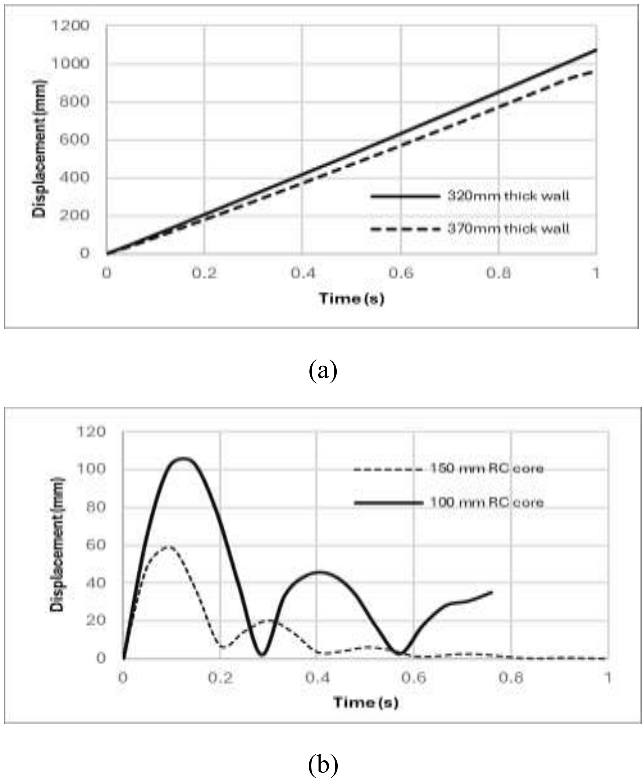

Figure (9): Comparison between the maximum displacement of clay-brick masonry walls either with or with no RC core: (a) M1, M2; (b) M3, M4.

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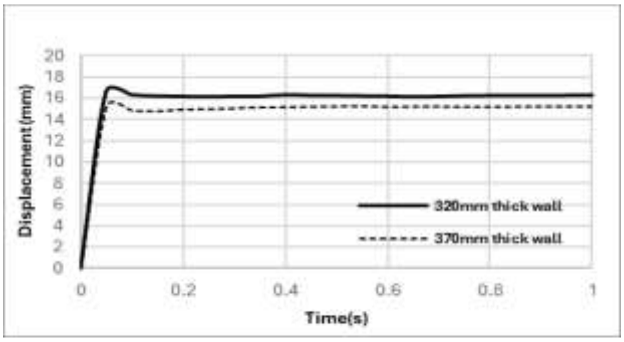
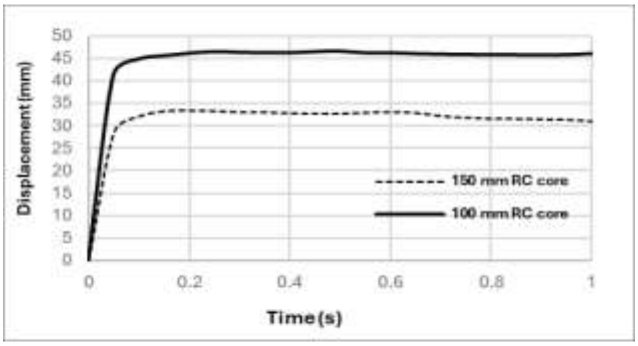


(a)



(b)

Figure (10): Comparison between the maximum displacement of clay-brick masonry walls either with or with no RC core: (a) M5, M6; (b) M7, M8.

VIII. CONCLUSION

Blast loading is a crucial consideration in the construction of masonry walls for structures situated in regions susceptible to explosions. Masonry walls, owing to their comparatively brittle characteristics, are subjected to damage from high-intensity blast impacts. Nevertheless, knowing the factors that affect their response and implementing suitable design strategies, such as reinforcing and energy-absorbing materials, can markedly improve their blast resistance. Advancing research and development of blast-resistant design methodologies is crucial for enhancing the safety of structures exposed to explosive hazards. The out-of-plane behavior of clay-brick masonry walls of 4000 mm length × 2500 mm height x 320 mm and 370mm thickness (with and without RC core) exposed to a 5.0 kilogram-TNT load with scaled distance of 1.169 m/kg$^{1/3}$ have been analyzed by ABAQUS/Explicit, 2017, a high-precision qualified program. The explosion occurs one meter above the ground. For this objective, eight FE models had been developed: Four cases of clay-brick masonry walls with varied thicknesses of 320 mm and 370 mm and four masonry walls consist of two wythes of walls having a thickness of 110 mm sandwiching RC core wall with grade M30 that is 100 mm and 150 mm thick. The following conclusions have been made based on the outcome of the FE simulation:

1- The resistance throughout clay-brick masonry walls to explosion declines in terms of maximum displacement, stresses, and damage patterns as wall thickness increases.
2- The maximum central displacement, stresses, and damage are much reduced when the thickness of RC core is increased because it absorbs the majority of the energy generated by the air burst.
3- For free standing walls, the application of 100mm RC core within the wall decreases the peak displacement of by about 90% compared to 320 mm thick clay brick URM walls while the application of 150mm RC core within the wall lowers the peak displacement by about 93.8% relative to 370 mm thick clay brick URM walls.
4- M8 decreases the max displacements to 96.9% better than M1.
5- Comparing the cases of free-standing walls and the walls that supported from the side in the case of the URM walls and URM walls with RC core, it was found that the collapse occurred in free standing walls an d the side supported walls are much better in terms of displacement, stresses, and damage pattern.

IX. RECOMMENDATION

The scope of the current study was focused on examining the performance of clay-brick masonry walls as well as other clay-brick masonry walls containing reinforced concrete core under blast load. It is suggested that research be conducted on Masonry wall under blast load behavior in to identify: -

1- The influence of Concrete strength of core
2- Effect of different Steel mesh of core
3- Effect of Different standoff distance of blast Charge
4- Blast Charge affect
5- **Enhanced Material Testing:** Further investigation is required about the performance of new masonry materials under blast loading to assess their suitability for blast-resistant applications.
6- **Improved Modeling:** Innovations in numerical modeling, including non-linear dynamic modeling, can yield more precise estimations of wall performance in complex blast situations.

Real-World Testing: Comprehensive blast testing of masonry walls, incorporating varying

1- reinforcement methods, is essential to verify theoretical models and enhance design standards.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Salma Ashraf Afify: Writing – original draft, Investigation, Data curation, Conceptualization. ***Ibrahim A. El-Azab***: Writing – review & editing, Supervision, Investigation, Conceptualization. ***Amr R. El-Gamal***: Writing – review & editing, Validation, Software, Methodology, Data curation, Conceptualization. ***Ibrahim M. El-shenawy***: Writing – review & editing, Supervision, Investigation. ***Hala Mohamed Refaat***: Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

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The manuscript has all the necessary data.

DECLARATIONS AND COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest Regarding the paper, the authors declare that they have no conflicts of interest.

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