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RESPONSE OF NON-ENGINEERED RESIDENTIAL UNITS SUBJECTED TO INTERNAL BLAST LOADING

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Abstract. *A large number of residential units in the cities and the countryside regions of Sindh were constructed without considering any design provision and are constructed either using brick masonry made up of burnt clay which are usually plastered using either cement sand mortar or mud or lime mortar Over few years back, due to the shortage of natural gas, people started keeping portable fuel gas cylinders at their homes, which may produce serious consequences in these non-engineered residential units. Therefore, the proposed study aimed to investigate the behaviour of the typical residential units exposed to indoor confined blast loading resulted as an action of blasting of an LNG cylinder. The well-known commercially available finite element software has a CONWEP model that was used for blast analysis in modelling to evaluate the result of blast on those walls of residential units. Based on the initial analysis, weak zones were identified and strengthened with locally available Textile Reinforced Mortars to study the post blast behaviour of the strengthened units under static loading. Strengthening schemes were beneficial in restoring to bearing load capacities that damaged elements and units.*

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1 INTRODUCTION

Masonry is among the oldest and most prevalent structural materials, utilized historically and presently for many construction applications. Numerical modeling is frequently necessary for the design of nonstandard masonry structures or the evaluation of existing ones to comprehend their structural behavior under diverse loading circumstances[1]. Walls, as critical load-bearing components, are especially vulnerable to external blast pressures, hence gathering the interest of structural engineers about their blast resistance properties. In the occurrence of an explosion, substantial quantities of debris are generated by the compromised masonry wall. This presents a significant risk to the building's occupants and is a primary contributor to injuries, fatalities, and property damage. Consequently, there is an increasing demand for upgrading unreinforced walls that may be subjected to blast stresses. Despite the widespread adoption of concrete and steel in contemporary construction, Unreinforced Masonry (URM) structures remain extensively employed in rural regions owing to their beneficial attributes, such as superior durability, economic efficiency, material accessibility, and enhanced thermal insulation performance [2].

In a conventional URM building, the walls undergo two-way action when exposed to out-of-plane forces, with lateral support from transverse walls and vertical support from floors or the roof at the top and bottom. The magnitude of damage resulting from the explosion is conditional on the particular support conditions. The failure of a free-standing cantilever wall is dependent upon several parameters, including the yield of the explosive, its standoff distance, the height of the explosive charge, and the explosion's position along the wall's length. The development of vertical cracks is affected by the wall's thickness and the ratio of its length to height. Nonetheless, walls that extend in both directions predominantly fail by exhibiting diagonal cracking, accompanied by infrequent vertical cracks near the supporting edges [3] .

Numerous studies [4-7] have been conducted to understand the effect of blast forces along with the strengthening of an unreinforced masonry wall with varying composites and TRM. Carney *et al*. [9] performed an analytical study to assess the response of URM walls to out-of-plane forces under static and air-blast loads. The walls were reinforced with strips and rods composed of glass fiber reinforced polymer (GFRP). The study's findings indicated that walls reinforced with GFRP sheets had enhanced performance under both static and blast loads compared to walls retrofitted with GFRP rods or those that were not modified.

Ehsani *et al*.[10] performed an experiment with two unreinforced masonry (URM) walls that were strengthened with CFRP. The investigation concluded that the CFRP retrofitting effectively trapped all masonry debris within the CFRP and averted the collapse of the URM wall.

Wang *et al.* [8] conducted an experimental study with GCB masonry that was strengthened with TRM. Despite the absence of mechanical anchorages in the TRM systems, experimental evidence indicates that there is no debonding of the TRMs from the masonry, suggesting a good compatibility of the TRMs in this work with GCB masonry.

Recent investigations have focused on the analysis of masonry walls reinforced with TRM subjected to in-plane cyclic loads. Typically, these investigations have predominantly focused on brick walls. Typically, small-scale specimens were utilized; nevertheless, in light of the research aims, several investigations employing full-scale walls very pertinent. The effectiveness of textile-reinforced mortars (TRMs) including meshes composed of various fiber types has been examined, including glass, carbon, basalt, aramid, steel, polymeric nets, and natural fibers. In the majority of published studies, TRM is often applied to both sides of walls, while the impact of reinforcements applied to only one side has been examined in only a limited number of instances[11-13] , a scenario frequently encountered with facades or party walls.

In masonry structures, TRM offers notable benefits as compared with Fiber Reinforced Polymers (FRP), including enhanced bonding with base materials, applicability under moist conditions, allow to pass water vapour, reinforcement can be remove when required, and superior resistance of fire, as compare with others [14].

Recently, the shortage of natural gas over worldwide led to a rising trend of households possessing portable natural gas or LNG cylinders. Where, the protection of cylinders poses significant concerns, since numerous deaths are recorded because of the half or total damage to rural structures. Moreover, such loading may not lead to total structural failure, the damage inflicted on individual structural elements may necessitate reinforcement for safe and efficient work. As, numerically investigates the performance of masonry walls blast damaged because of the cylinder and also investigate the performance after the application of TRM. During this work, a nonlinear finite element model in ABAQUS [15] was used. For blast loading CONWEP[16]model was available in ABAQUS[15] that was used.

2 NUMERICAL INVESTIGATION

2.1 Analysis approach

To proceed with this numerical study, FE software ABAQUS [15] was used. The brick masonry was simulated with the Drucker-Prager plasticity model [17]. The approach employed in this investigation is illustrated in Figure 1. The initial phase involved a computational analysis of the masonry wall subjected to static loads (incremental compressive load) from the upper surface of the unreinforced masonry structure. A second procedure included a masonry wall following blast loading to determine its residual capacity. The final step involved reinforcing the masonry wall with TRM, which was subsequently subjected to numerical analysis to check its maximum load-bearing.

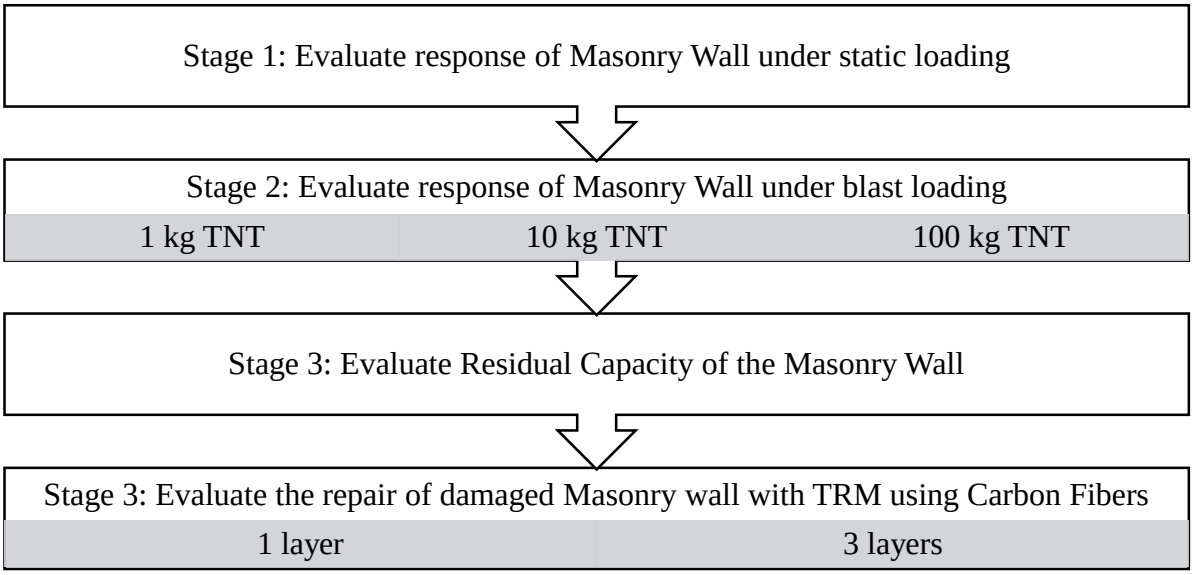


Figure 1: Procedure of Masonry Walls Simulations.

2.2 Theoretical Analysis for Blast Analysis Model

For blast loading, ABAQUS[15] FE software was used for analysis using the method of explicit finite element. Explosion loading used on an unreinforced masonry wall which was assigned fixed all boundary structure and not allow to move at the base of the wall. A concrete beam having compressive strength of 17.2 MPa was placed on the top of the wall as can be seen in Figure 2. The wall had a span of 3600 mm, height of 3000 mm and thickness of 200 mm considering a typical wall of an urban residential unit. A simplified Micro-model approach was used to model the wall. To capture the linear and non-linear behaviour of the masonry units interfaces were identified. The bricks were modeled using 3D eight-node hexahedral solid elements (Type C3D8R) with reduced integration and hourglass control. The joint/mortar interfaces were modelled using surface based cohesive approach. The sharing contact between adjacent masonry blocks were defined through surface discretisation method with finite slide fomrulation with further properties mentioned in Table 1. Additionally, hard contact behaviour was defined between the adjacent surfaces of masonry units by the contact pressure-overclosure relationship. In addition, the penetration and the transfer of tensile stress between the contacting surfaces are prevented in the hard contact model [1]. Each masonry unit (400 mm long × 200 mm high × 200 mm thick) was modelled with 20 × 10 × 10 elements having mesh size 20 mm. The beam was also modelled using similar element type with mesh size of 30 mm. The walls were subjected to a vertical compressive stress via the top beam.

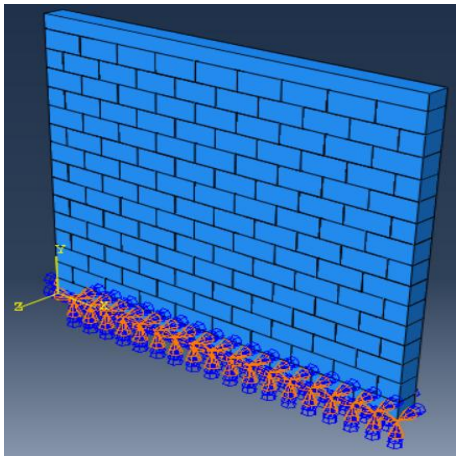


Figure 2: Illustration of the modeled Masonry wall.

Modulus of Elasticity (E) MPa	Poisson Ratio	Dilation angle (ψ)	Friction angles (β)	Flow stress ratio (R)	Friction coefficient	K_{nn}	K_{ss}	K_{tt}
2888	0.15	11.3	36	1	0.75	63	25	25

Table 1: Properties of brick masonry used for Drucker Prager Model [1].

Due to symmetry, only one panel of the masonry wall was modelled and similar behaviour was assumed on the rest of the panels. For the blast simulation, the distance between the blast and the wall is 1524mm. The blast was placed at the center of the wall and central elevation in the considered room simulated at the mid of the wall. Aditionally, for modelling the blast loading, three varying TNT masses were used i.e. 1,10 and 100 kg [18].

2.2.1 Blast Load Simulation using CONWEP

For blast simulation, ABAQUS [15] have already the access of CONWEP method. CONWEP is known as Conventional Weapon [16] method that is used for simulation blast. The blast dissemination to be monitored, according EN 1991-1-7[19] 0.2 s step time. The masonry wall was tested for blasting at the internal mid height, the result of the blast on a typical interior wall as can be seen in Figure 3.

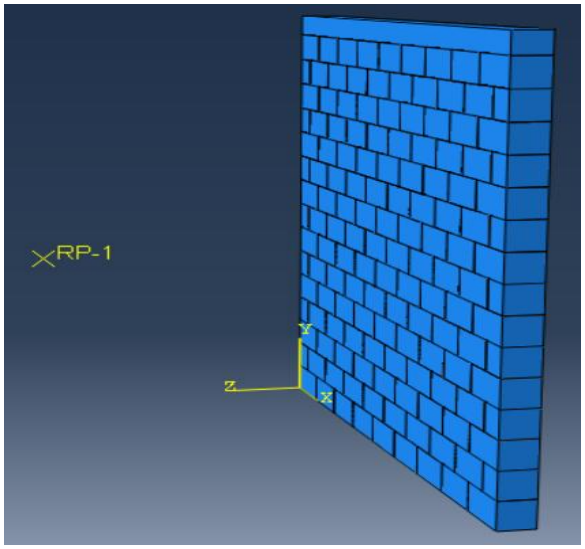


Figure 3: Explosion Configuration for the wall.

2.3 Theoretical Analysis for Static Model

To perform the static analysis, the FE model for the masonry wall, those material properties were used in previous section they were also applied in this section. The pressure was gradually increase at the top of the masonry wall.

2.4 Details for Calculating Residual Capacity for Post-Blast Analysis

The theoretical collapse condition for a URM wall occurs when the center of gravity of the wall segments shifts beyond the midpoint, often occurring when $\delta_{max} \sim t$. The wall primarily rotates around the base joint, as it is secured at the bottom while the force is applied at the top. The maximum rotation θ, which is calculated using Equation 1 [20] occurs at the base plastic hinge. Having established that the wall's thickness (t) is 200 mm, the displacement-to-thickness ratio (δ/t) to assess the extent of the damage. This ratio is the standard method for assessing stability and residual capacity in masonry blast analyses previously employed by Varma *et al.*[21] and Ahmad *et al.*[22].

$$\theta = arctan\left(\frac{\delta_{max}}{H}\right) \tag{1}$$

2.5 Theoritical Analysis for Post Blast Model

For this post blast analysis, the residual capacity was calculated as explained in the previous section. For a wall that underwent a blast from 1 kg TNT, the capacity was analysed by a 10% reduction in its material properties whereas for the wall that underwent a blast of 10kg, the material properties of the wall were reduced by 60% percent as calculated using Table 3.

The post blast analysis has two stages.Initially, first stage included adding 1 layer of TRM on the masonry wall for which it's load carrying capacity was tested. Afterwhich, 3 layers of Carbon fiber was added and capacity of the wall was noted.

To examine the post blast after the strengthened of TRM RC slab, For RC slab FE model TRM layers of 1st and 3rd were applied which is made from (carbon fiber) each as shown in Figure 4. In the 1st layer of TRM, 5mm of concrete was used, placed on inside face to masonry wall and 15mm of concrete was used in the 3rd layer of TRM, placed on inside face of the masonry wall.

Elastic Modulus (GPa)	Weight (g/m^2)	Standard thick-ness (mm)	Fiber spacing (mm)	Mortar com-pressive strength (MPa)
225	348	0.095	20 × 20	36.6

Table 2: TRM material properties applied [23].

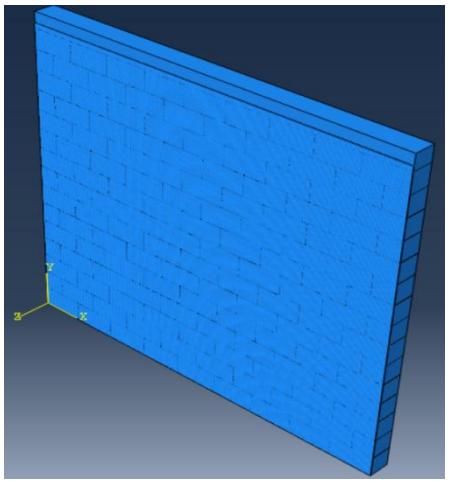


Figure 4: F.E model for strengthened wall.

The 2-node unit of truss (Type T3D2) have a grid of 20 mm which is used in the designing of textile fiber reinforcement however, the mortar was modelled using eight-node hexahedral solid elements (Type C3D8R) elements with a mesh size of 30 mm. For defining mortar material, model of Concrete damage plasticity was used however, to specify strengthening damaged substances we can used TRM material properties can be seen in RC slabs Table 2. As a contact pair, a masonry wall base and the TRM were selected. The interaction between both components that was defined as master and slave surfaces by using TRM acting as master and the wall as slave.

3 RESULT EVALUATIONS WITH DISCUSSION

3.1 Static Analysis under Incremental Axial Compression Load

Figure **5** (a) depicts the displacement contours from the initial static analysis of the masonry wall subjected to incremental axial compression. The contour map illustrates the displacement magnitude, indicating a peak deflection of around 1403 mm in the upper section of the wall. This prominent lateral deformation signifies that the wall has transitioned into a post-buckling condition, where the vertical load induces a considerable out-of-plane instability.

Figure **5** (b) illustrates the distribution of Equivalent Plastic Strain (PEEQ) throughout the masonry wall at the maximum axial compression showing areas of material failure. A peak plastic strain of 1.908 is recorded at the wall's base, signifying extensive material compaction and the development of a plastic hinge at the fixed support. The concentration of plastic strain verifies that the structural failure results from a combination of material yielding and geometric buckling.

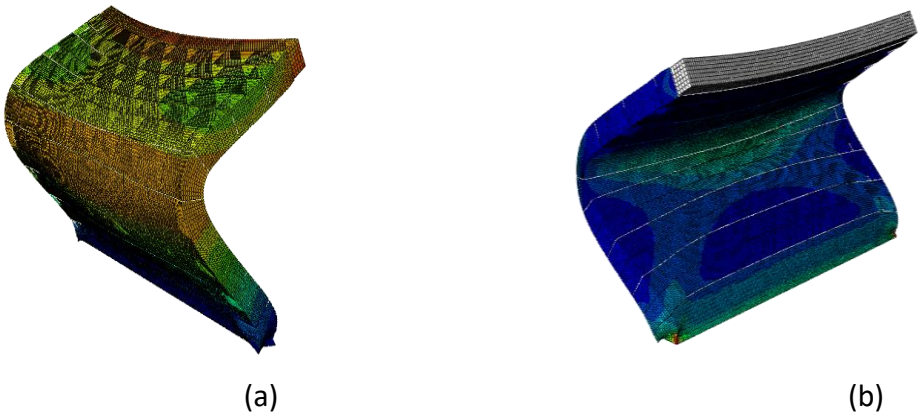


Figure 5: Displacement and Equivalent Plastic strain of Masonry wall under pure axial compression.

3.2 Blast Analysis using CONWEP

By using CONWEP[16], as show in Figure 6 pressure time histories obtained. It can be seen that the reflected pressure using IWCONWEP feature in ABAQUS [15] depicted a higher pressure for the larger mass and thus higher damage. The damage experienced by the masonry wall is reported in Figure 7. The wall that was subjected to a 100 kg blast load toppled off completely thus leaving no threshold for strengthening. The other two cases however indicated some residual capacity which could be enhanced using strengthening techniques.

3.3 Residual Capacity Calculations

The calculations for the residual capacity are shown in Table 3. These methods have been previously used by researches conducted by Varma *et al.*[21], Ahmad *et al.*[22] and in the UFC 3-340-02 code [20] to understand the damage underwent by structure owing to application of blast load.

Since there was no arching action for the resistance of the wall, the wall relied entirely on the tensile/bond strength at the base and the "restoring moment" provided by the wall's own weight. The wall toppled when the top displacement reached 200 mm. Subsequently, masonry is brittle and the base will likely crush or "spall" under the high-pressure collapse was more

likely to occur when δ_{max} around half the thickness of the wall. The damage categorization is carefully calculated as shown in Table 3 and the residual capacity was noted.

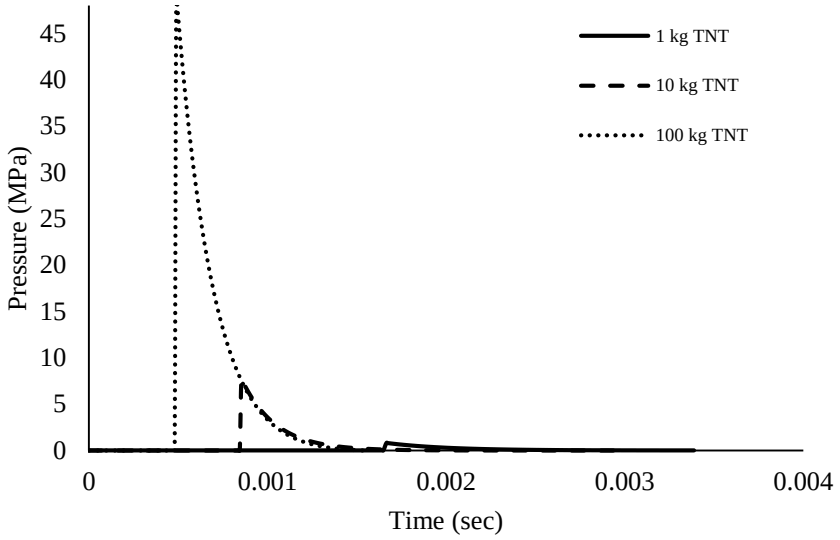


Figure 6: Pressure time histories using varying TNT masses.

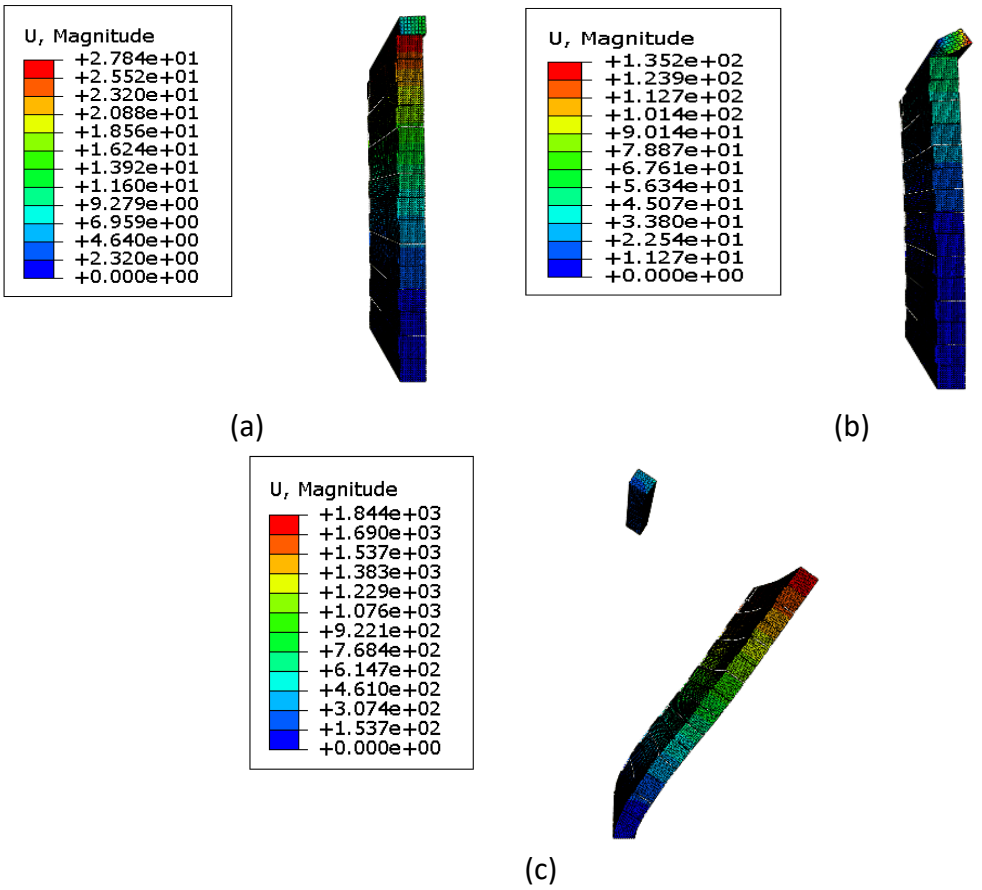


Figure 7: Displacement contours for varying TNT masses on Masonry walls.

Mass of TNT (kg)	Maximum Displacement (mm)	Rotation	Displacement to thickness ratio	Damage state	Estimated Residual Capacity
1	12	0.23^0	0.06	Elastic / Slight: Minor cracking.	90%
10	64	1.20^0	0.32	Heavy: Permanent offset; rocking.	~30–50%
100	918	16.75^0	4.59	Complete Collapse: Geometric instability.	0%

Table 3: Damage state of the walls.

3.4 Masonry Wall Enhanced with TRM

To enhanced the damaged of the masonry wall, the result of TRM was evaluated with a masonry wall by using incremental axial compression load. A unreinforced masonry wall was numerically evaluated by two categories by strengthening with carbon and fibers i.e 1 and 3 layers of reinforcement. Figure 9 illustrates about axial load-deflection result of the masonry wall across various reinforcing and damage conditions. The findings demonstrate that walls exposed to low-level blast loading (1 kg TNT) benefit significantly from the implementation of carbon fiber TRM; a three-layer reinforcement strategy not only restored the lost capacity but also elevated the peak axial load to approximately 14,000 kN, representing a 27% enhancement over the original wall. In contrast, the wall that sustained pre-damage from a 10 kg TNT explosion demonstrated markedly diminished performance, reaching a maximum of only 4,000 kN. Since, no increase in capacity was noted by strengthening the damaged wall (10 kg TNT), the wall was not further strengthened with a three-layer reinforcement strategy.

The initial stiffness zones of the repaired walls exhibit distinct non-linear curvatures that reflect the complex connection between earlier damage and TRM activation process. The original walls and those destroyed by 1 kg of TNT have significant initial tangent stiffness, indicating that the brick's elastic properties are mostly retained. The initial low tangent stiffness in the 10 kg TNT scenario is mainly due to crack closure, wherein axial compression must first seal blast-induced tensile cracks before the entire cross-section can engage fully. The 'softening' is generated by plastic yielding at the base hinge and residual blast due to displacement-induced geometrical eccentricity as can be seen in Figure 8.

Moreover, the master/slave contact interaction between the masonry and TRM layers offers an additional non-linearity as the carbon fibers gradually engage to offer confinement. In contrast to the original wall exhibiting a distinct bifurcation pattern, the pre-damaged walls experience a gradual buckling transition resulting from initial geometric irregularities, which induce early P-Δ effects and a lower buckling limit.

The displacement path along the height of the wall is illustrated in Figure 10 for the original wall and the masonry walls (1 kg TNT) that were strengthened with TRM. It can be seen that the displacement response of the unreinforced masonry wall demonstrated a maximum displacement of roughly 1000 mm at its midpoint (1500 mm), signifying a severe structural failure under the applied load. The specimens reinforced with TRM exhibited a significant decrease in peak displacement relative to the unreinforced wall and shifted the buckling mode of the wall from inwards to outwards. This indicates that fiber-based retrofitting offers essential lateral

support and energy absorption, hence preserving the structural integrity of non-engineered residential buildings that are particularly susceptible to the intense pressures generated by constrained explosive forces.

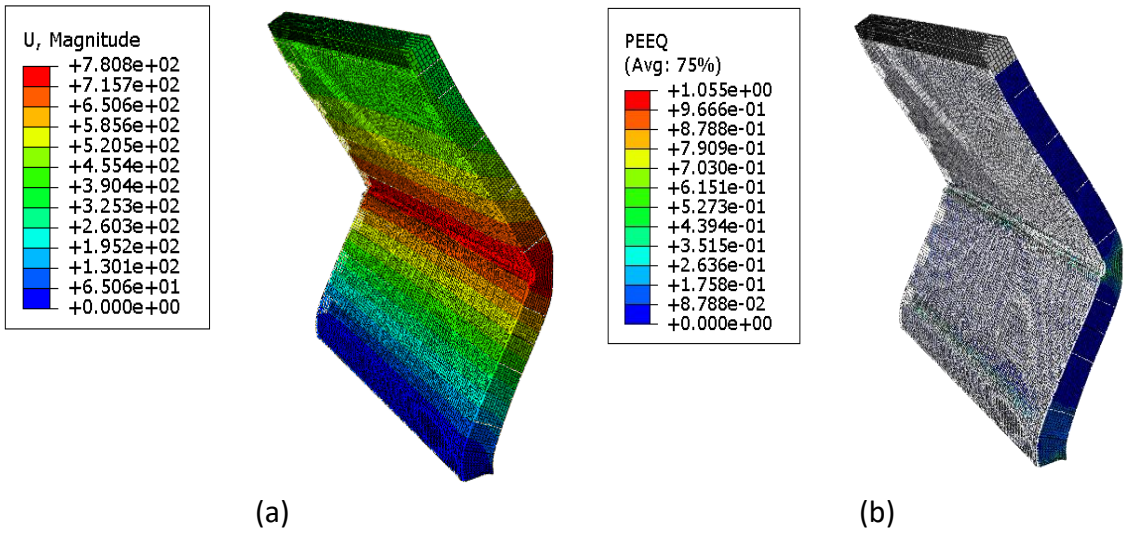


Figure 8: Displacement and Equivalent Plastic Strain Contours for Strengthened Masonry Wall.

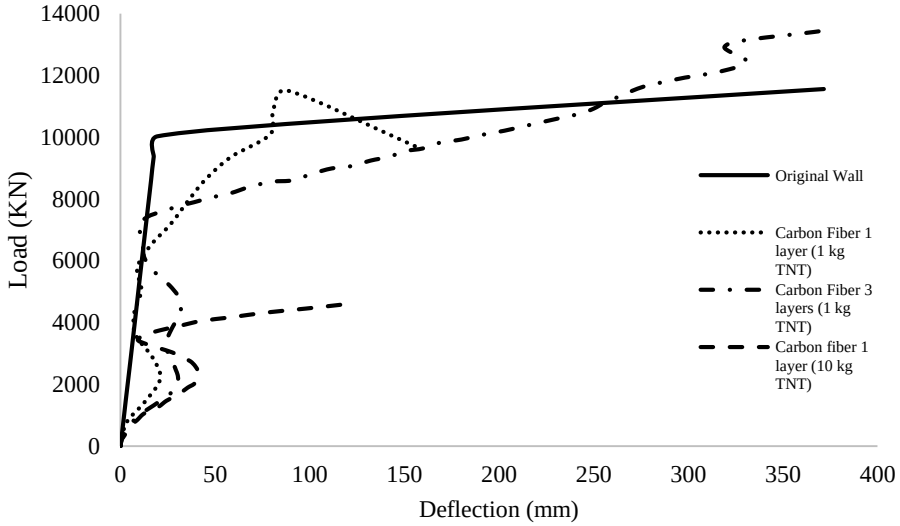


Figure 9: Comparison of Load Deflection Response of Strengthened and Unstrengthened Wall.

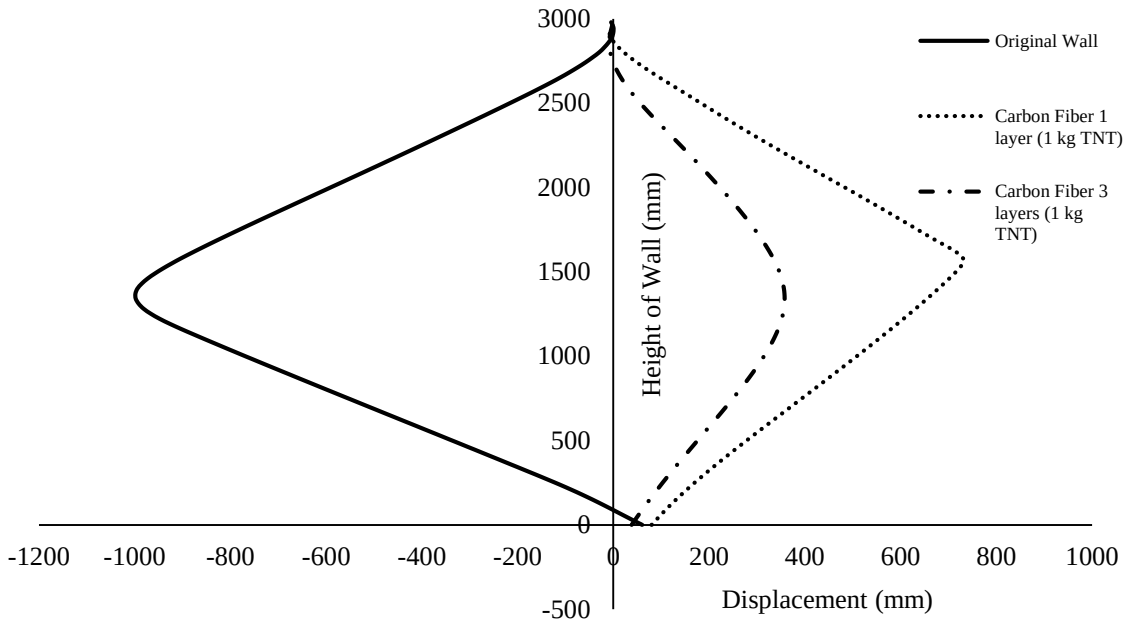


Figure 10: Displacement Path along the height of the masonry walls.

4 CONCLUSIONS

Based on the detailed numerical investigation, it was found that the TRM has proven to be an effective solution which significantly improved the performance of masonry walls subjected to the in-plane loads. It was also found that the TRM-reinforced walls demonstrate a significant improvement in the post-cracking phase, characterized by enhanced ductility and greater energy dissipation compared to unreinforced walls. Furthermore, it was also found that applying three layers of TRM to protect from damaged wall suffering low damage was proved beneficial for restoring the loss of load bearing resistance with a higher peak load value. It was also found that upon reaching a critical damage position accompanied by substantial residual displacement and material yielding, the mechanical bond and confinement provided by TRM are insufficient to restore structural stability, rendering the wall unsuitable for further retrofitting.

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