BLAST VULNERABILITY EVALUATION OF CONCRETE MASONRY UNIT INFILL WALLS RETROFITTED WITH NANO PARTICLE REINFORCED POLYUREA: MODELLING AND PARAMETRIC EVALUATION

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ABSTRACT
This paper investigates the performance of a new generation of nano-particle reinforced polymeric materials, as an alternative to fiber reinforced polymer (FRP), for the protection of masonry structures against blast loads. The nanoparticles used in this study include the exfoliated graphene nano platelets (XGnP®), and the polyhedral oligomeric silsesquioxane (POSS). The polymer is polyurea. One quarter scale physical model of unreinforced masonry walls, spray coated with the nano-particle reinforced polymers, are subjected to blast load in the ERDC Blast Load Simulator facility. It is observed that POSS reinforced polyurea significantly enhanced the performance of masonry walls sustaining blast load; while XGnP® reinforcement has only marginal improvement. To validate experimental observations a multiscale numerical-experimental program was employed. Results of computer models constructed using ANSYS AUTODYN and simplified analytical model are presented.

1. INTRODUCTION

Conventional building components are highly vulnerable to terrorist bomb attack. One of the greatest threats from blast loading is the fragmentation–pieces from walls, windows, equipment, or vehicles flying at such high speeds that they can result in extensive injury or death. Un-reinforced masonry (URM) walls have low resistance to out-of-plane blast loadings due to low flexural capacity and brittle mode failure. These problems lead to a critical need to develop effective retrofitting techniques to improve the load carrying capacity of such members to resist blast loads. Good amount of work had been done on using elastomeric materials as a retrofit technique. Johnson, et al (2005) conducted a series of static and dynamic experiments to investigate the potential benefits of using both reinforced and unreinforced elastomeric materials to retrofit hollow, unreinforced, concrete masonry walls. The static experimental results demonstrated an increase in the ultimate flexural resistance of the retrofitted CMU walls. And it supported the idea that the polyurea spray-on materials did significantly increase the stiffness of the reinforced polyureas as compared to the unreinforced ones. Dynamic results showed that the unreinforced polyureas did add minor additional flexural resistance to the hollow unreinforced CMU wall, whereas the addition of reinforcement to the polyurea retrofit system significantly increased the flexural resistance of the CMU walls. Davidson, et al (2004) used full-scale explosive tests to determine the effectiveness of using sprayed-on polymers to improve blast resistance of unreinforced masonry walls. They concluded that a sprayed-on polymer retrofit approach to strengthening masonry walls against blast loads was an effective technique. Davidson, et al (2005) experimentally and numerically studied damage and failure mechanisms of polymer reinforced concrete masonry walls subjected to blast loadings. They observed that a thin elastomeric coating on the interior face of the wall can be effective in minimizing the fragmentation and potential for collapse of unreinforced concrete masonry walls resulting from a blast. They also found that the elongation capacity was more important for damage reduction than having a high stiffness, so an effective balance between stiffness and elongation potential was required. Finite element results indicated that a spray-on polymer reinforcement approach can be effective in reducing the vulnerability of unreinforced CMU walls subjected to blast loading. Eamon, et al. (2004) analyzed CMUs subjected to blast pressure using the Finite Element Method. Their model had the ability to replicate experimental results with good agreement, generally matching the failure shape, the location of break lines, and the size and the number of primary pieces of debris. In order to protect the nation's infra structure one need to employ the best available materials. When existing materials cannot deliver the performance, it is important to design new material. Recent interest in the use of polymer based composite materials in infrastructure applications requires further improvements in blast resistance of these materials. The main objectives of this study are to investigate the ability of nano particle reinforced polymers to protect masonry infill wall against blast loading, and to study the effect of some factors like boundary conditions, thickness and arrangement of retrofitted layers, and ductility of retrofitted materials on the behavior of the system during and after blast.

2. DESCRIPTION OF MATERIALS USED

Polyhedral Oligomeric Silsesquioxane (POSS) reinforced polymers were used in the current research to protect masonry walls against blast loads. The polymer used in was polyurea Line-XS 350 produced by Protective Coatings Inc.

2.1. Material Properties

The static stress-strain behavior of POSS reinforced polyurea was determined by performing standard direct tension tests using a Servo-hydraulic Material Test Systems (MTS) machine on coupons cut from large panels. Important mechanical properties such as modulus of elasticity, tensile strength, and strain at failure were obtained directly from the generated curve. Table 1 lists the average modulus of elasticity, ultimate tensile strength, and strain at failure. Figure 1 shows typical stress-strain curves for one tested specimen.

Table 1: POSS reinforced polyurea mechanical properties

Modulus of Elasticity (MPa)	210.56
Ultimate Strength (MPa)	13.81
Strain at Rupture (%)	116

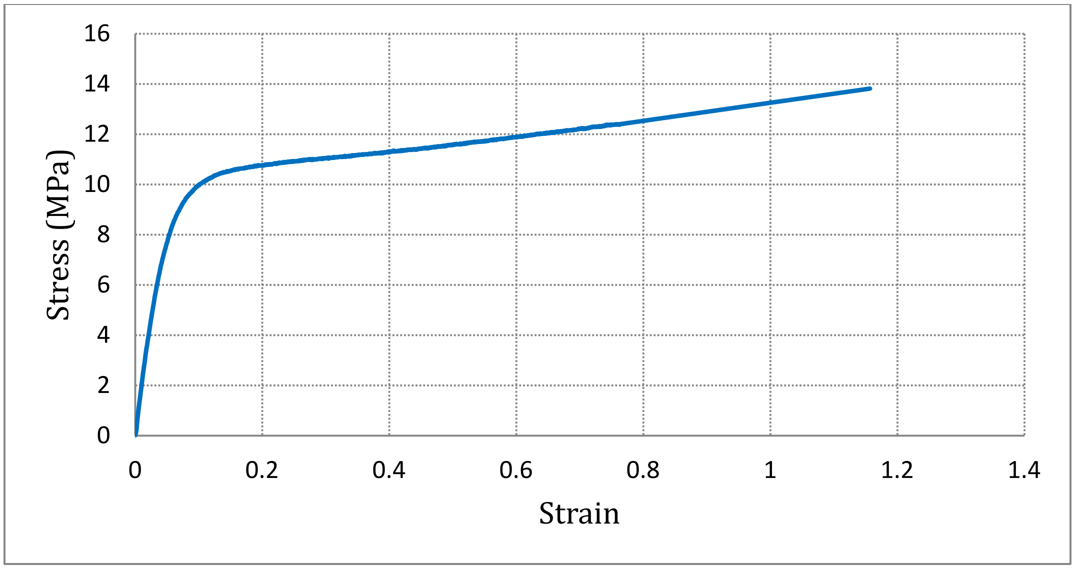


Figure 1: Typical stress-strain behavior for POSS reinforced polyurea under quasi-static tensile loading

Limited number of tensile dynamic testing was performed for POSS reinforced polyurea being used in this research using SHPB in order to compare the high strain rate response to quasi-static response. The results are shown in Figure2.

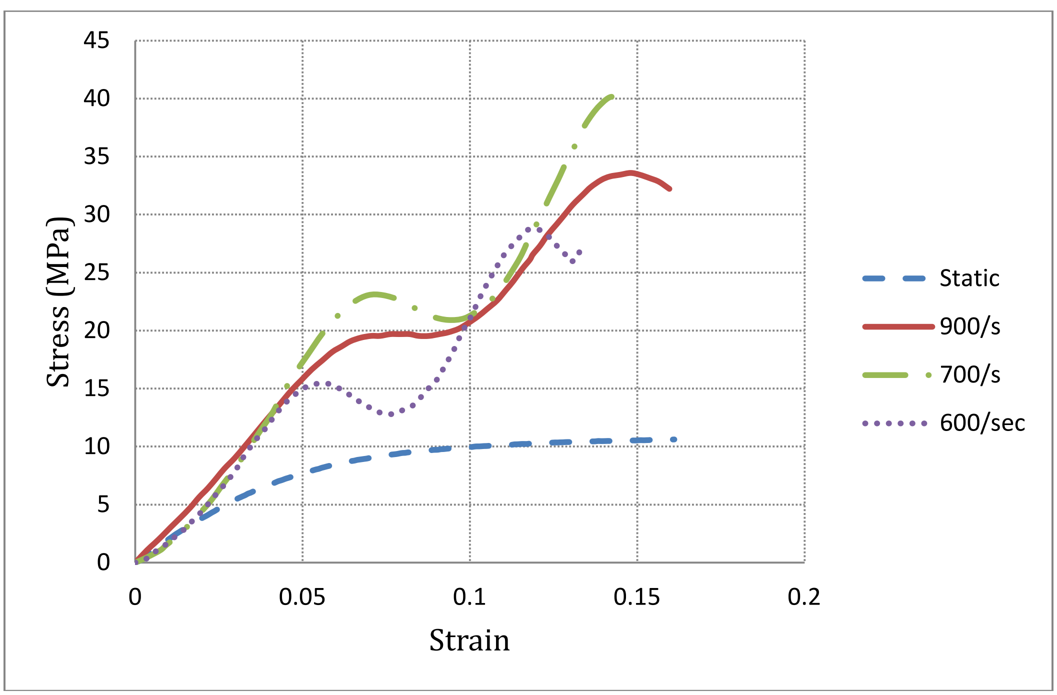
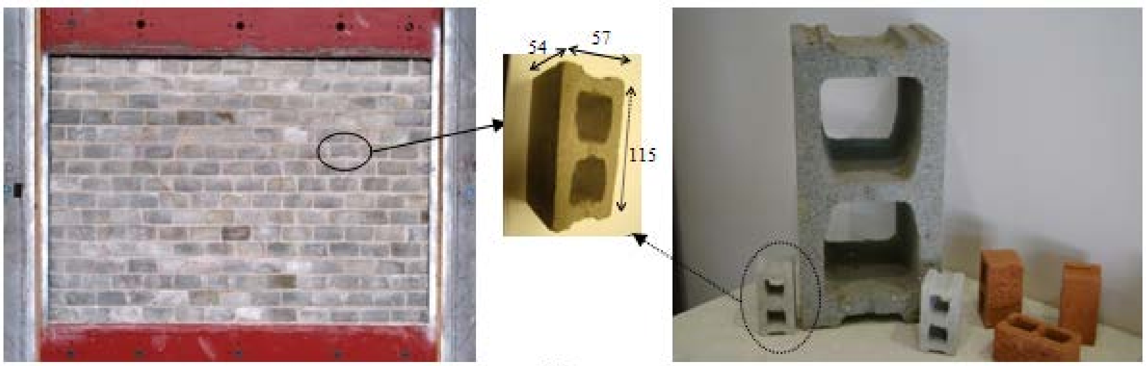


Figure 2: Stress-strain relation for POSS reinforced polyurea under dynamic tensile loading (SHPB)

3. EXPERIMENTAL WORK

Quarter scale model walls made of scaled down brick units (Figure3) were used to investigate the response of POSS reinforced polyurea retrofitted CMU panels subjected to air blast loading produced by Blast Load Simulator (BLS). The average mass of brick units was 252 gm. The walls were fully grouted with approximately 16 blocks tall and 12 blocks wide as shown in Figure3 below. The wall was casted in a steel frame with dowels at top and bottom to simulate simply supported conditions and free boundary conditions at left and right. The average unconfined compressive strength and density of the mortar were 15.9 MPa and 1.700 kg/m^3, respectively, and the average unconfined compressive strength and density of the grout were 15.9 MPa and 1.800 kg/m^3 respectively. The walls were tested at the US Army Engineer Research and Development Center (ERDC) using the blast simulator (Figure4).



(a) (b) (c)

Figure 3: Masonry wall panel (b) Concrete masonry unit brick (all dimensions in mm) (c) Comparison between full scales and scaled down dimensions of masonry unit

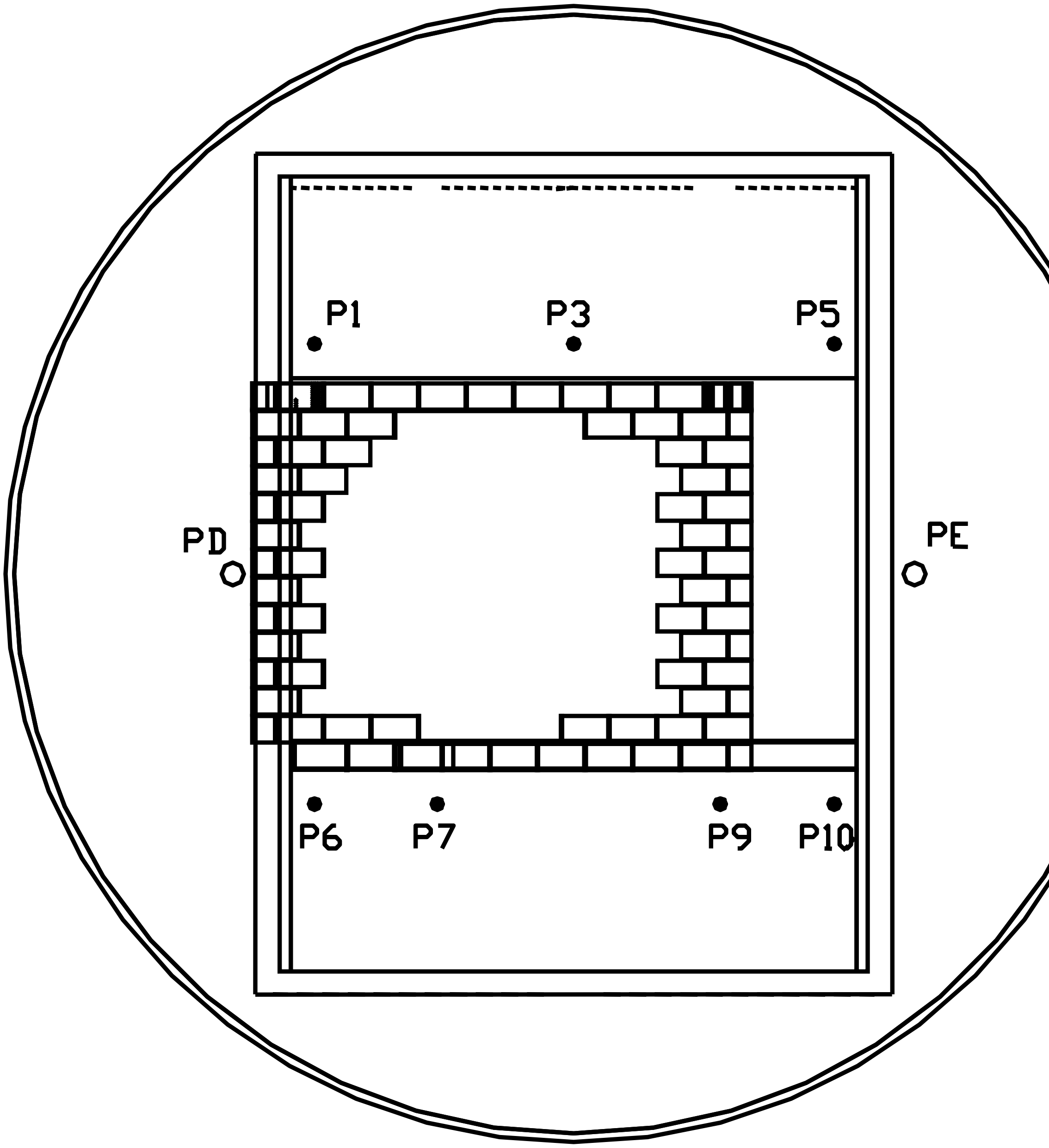
Figure 4: Blast simulator at ERDC, Vicksburg, MS

3.1. Experimental Setup

Spraying technique was used to apply POSS reinforced polyurea to the back (interior face) of the CMU infill walls (Figure5). This technique was used because of the fast reaction between the polyurea resin and the *cyanates* hardener. The walls were sprayed back and forth three times. Retrofitted layer thickness was observed to be 1.8mm.

Figure 5: Spray-on retrofitted material

A pre-adjusted air blast pressure and impulse were applied to each wall. Nine pressure sensors mounted on the steel loading frame were used to collect pressure time history (Figure6). Typical pressure time history and calculated impulse time history are shown in Figure 7.



Gage	P	I
	(psi)	(psi-msec)
P1	33.65	71.7
P3	33.13	71.5
P5	29.5	72.1
P6	32.21	70.1
P7	31.63	71.5
P9	27.95	71.1
P10	30.87	71.6
PD	35.22	72.3
PE	31.6	73.2
Sum	285.76	645.1
Avg	31.75	71.7
IP1	0.37	

Figure 6: Locations of pressure sensors and typical peak pressure values

It was noted that, for all cases, there was an initial rise to a peak reflected pressure (compression pressure wave) followed by a decay to zero pressure and then a negative phase (suction pressure wave). Therefore, if a wall system can be retrofitted adequately to resist the initial compression pressure wave, then it can be allowed to fail on the opposite side (non occupant side) when subjected to the negative pressure wave. Average values of reflected pressure and impulse subjected to the wall were observed to be 218.91 kPa and 494.35 kPa.ms respectively.

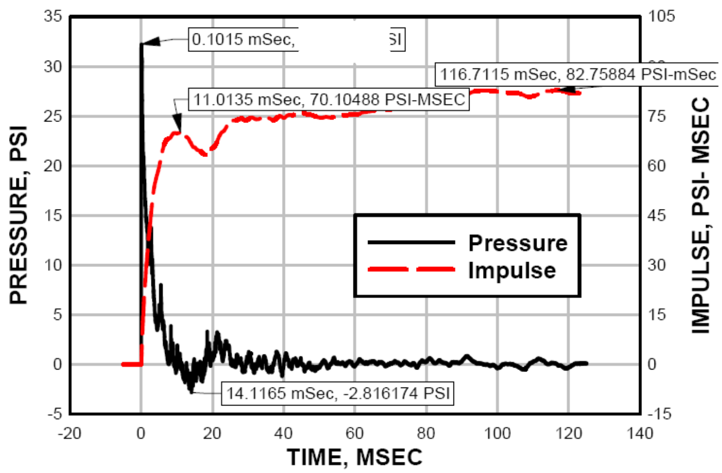


Figure 7: Typical pressure-time history and associated impulse time history obtained using pressure Sensor.

3.2.Experimental Investigation

Wall retrofitted with POSS reinforced polyurea had hairline shear and horizontal crack at blast peak pressure of 218.91 kPa. Shear damage was observed at the top left corner of the wall at the same peak pressure. The results showed that the addition of POSS reinforcement to the polyurea retrofit system increased the flexural resistance of the CMU INFILL wall significantly. However, the retrofit helped the whole panel to have no damage (Figure8).

Figure 8: Wall #3 (a) Back view after the blast event (b) Front view after the blast event

4. COMPUTATIONAL MODELING

To study the effect of blast loads on CMU infill walls and to understand the behavior of these structures under previously noted loading conditions, a number of experiments is required to get enough data that allow the researchers to analyze clearly and process the results. Unfortunately, the expense involved in blast experiments limits the number of tests that are predictable at a given time. Alternative methods as substitutes for actual experimentation had to be sought. The focus of this part of the study is to develop a computationally-efficient model that can replicate with reasonable accuracy the behavior of retrofitted CMU infill wall subjected to blast loads. Finite Element (FE) models provide cost and time effective solutions compared to the experimental alternative. A finite Element model was built into this research to predict the experiments as mentioned previously. Due to time and cost constraints of the research program, development of a specific finite element analysis code for this project was not feasible. Therefore, ANSYS AUTODYN, an explicit hydrocode that used finite difference, finite volume, and finite element techniques to solve a wide variety of non-linear dynamic problems in solids, fluids, gases, and their interactions, was used to model and analyze the Nano Reinforced Elastomeric Materials retrofitted masonry walls subjected to blast loading.

4.1. Finite Element Configuration and Mesh

The importance of the computational modeling was measured by the ability of the finite element model to replicate with reasonable accuracy the experimental behavior of the system. Therefore, the same 16 blocks tall and 12 blocks wide CMU infill walls used in the experimental work were modeled using finite element software called AUTODYN. Each retrofitted wall was represented by 8670 Lagrangian cells, 3840 of which were filled with masonry material to represent the bricks; 2440 were filled with the mortar material bonding the bricks together; with remainder represented the retrofitted material. Figure9 shows the geometry and the mesh of the walls.

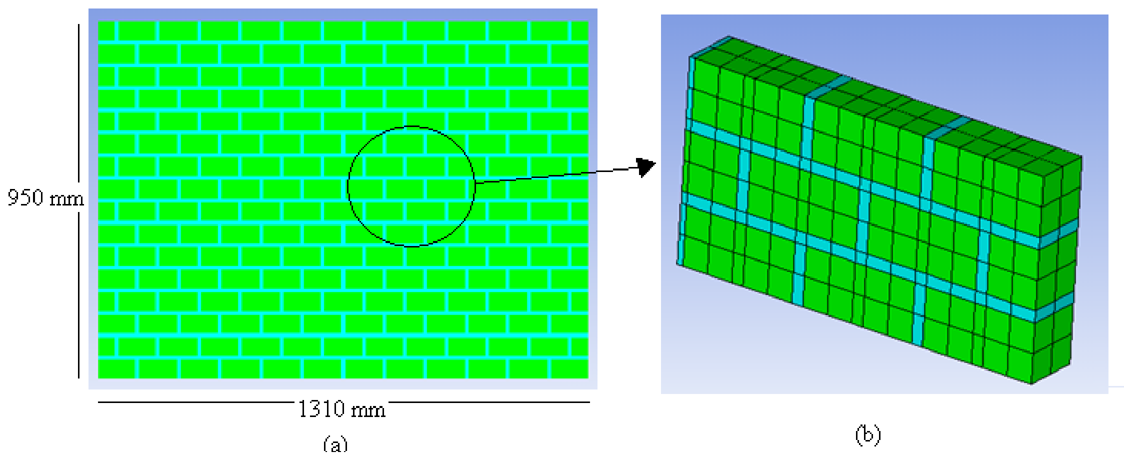


Figure 9: (a) Wall geometry (b) F.E. mesh

4.2. Material Modeling

To model a new material in AUTODYN, the parameters of equation of state (EOS), strength model, and failure model should already be defined.

Unreinforced masonry

The response of masonry under shock loading is a complex phenomenon. A variety of constitutive models for the dynamic and static response of masonry have been proposed over the years. In this research, Porous equation of state (EOS), Drucker-Prager strength model, and Hydrodynamic tensile failure (P_{min}) model were used to represent the unreinforced masonry. These models are discussed in detail in AUTODYN theory manual.

Mortar

Compaction equation of state (EOS), Mo Granular strength model, and Hydrodynamic tensile failure (P_{min}) model were used to represent the mortar.

POSS

A real EOS should be defined for these new elastomeric materials; however, due to the low pressure level introduced by blast waves, a linear equation of state works as a start for this study. Equation 10 shows the linear EOS used to model all three retrofitted materials,

$$P = K\mu \tag{10}$$

Whereas, K is the material bulk modulus; μ is volumetric strain as given by Equation 11; ρ is the material density; and ρ_o is the reference density.

$$\mu = \frac{\rho}{\rho_o} - 1 \tag{11}$$

Johnson-Cook Strength Model and Principal Strain Failure Criterion were used to model these materials. All material models used in this research are summarized in Table 2. More details are available in AUTODYN Theory Manual.

Table 2: Material models

Material	EOS	Strength Model	Failure Model
Masonry	Porous	Drucker-Prager	Hydrodynamic tensile failure (P_{min})
Mortar	Compaction	Mo Granular	Hydrodynamic tensile failure (P_{min})
Polyurea with POSS	Linear	Johnson-Cook	Plastic strain
E-glass/ Epoxy	Puff	Von Mises	Hydrodynamic tensile failure (P_{min})

4.3. Finite Element Results and Discussion

Un-retrofitted wall (Base Line)

Results of FEA showed a maximum midpoint deflection of 95 mm and maximum debris velocity of 6.834 m/s as compared to a maximum midpoint deflection of 86 mm and a maximum debris velocity of 5.91 m/s obtained experimentally (Table 5). FEA experiments likewise showed that the wall failed in four main segments, and that all debris was captured by the retrofit material. Table 3 shows good agreement between experimental and numerical deformation shapes at the time of maximum deflection and at the end of the test.

POSS reinforced polyurea retrofitted wall

Results of FEA showed a maximum midpoint deflection of 112 mm as compared to a maximum midpoint deflection of 95.65 mm obtained experimentally (Table 5). The wall did not fail in either experiment or FEA. Table 4 shows good agreement between experimental and numerical deformation shapes at time of maximum deflection and at the end of the test.

Table 3: Numerical and experimental results comparison for the case of un-retrofitted CMU infill wall

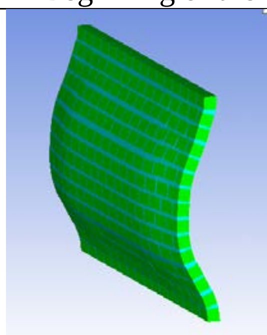
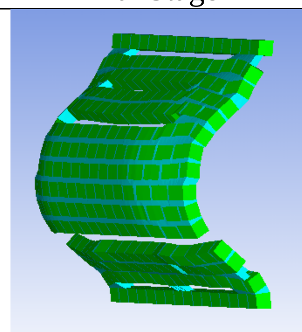
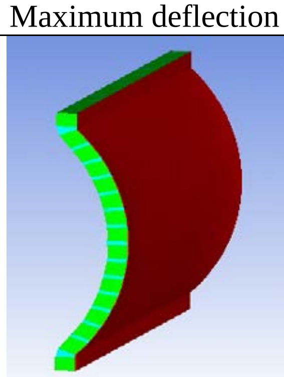
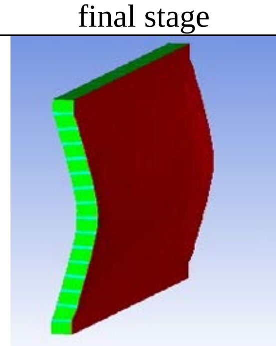
Beginning of the Failure	Final Stage	
		Numerical results obtained using AUTODYN hydrodynamic code
		Experimental results obtained using BLS

Table 4: Numerical and experimental results comparison for the case of CMU infill wall retrofitted with POSS reinforced polyurea

Maximum deflection	final stage	
		Numerical results obtained using AUTODYN hydrodynamic code

		Experimental results obtained using BLS

Table 5: Midpoint deflection and debris velocity

Wall	Maximum Midpoint deflection (mm)		Maximum debris velocity m/s	
	Experiments	Finite element	Experiments	Finite element
Un-retrofitted wall	86.0	95.0	5.9	6.8
Retrofitted wall	95.7	112.0	N.A	N.A.

5. PARAMETRIC EVALUATIONS

To get complete and better understanding of the behavior of retrofitted CMU infill wall under blast loading, a series of finite element analysis was conducted. The focus was to study the effect of some factors such as boundary conditions, thickness and arrangement of retrofitted layers, and ductility of retrofitted materials on the behavior of the system during and after blast.

5.1. Effect of Boundary Conditions

Two types of boundary conditions were applied to the top and bottom of the wall: simply supported (S.S.) and fixed. All retrofitting was applied at the back side of the wall. To neglect the thickness effect, thickness of retrofit layer was kept constant at 1.8mm for all simulations. Same finite element model in the previous section was used here. The effect of the boundary conditions was clear in the results. Using simply supported boundaries allowed the wall to deflect much more than fixed boundaries (Figure10). Both walls did not fail.

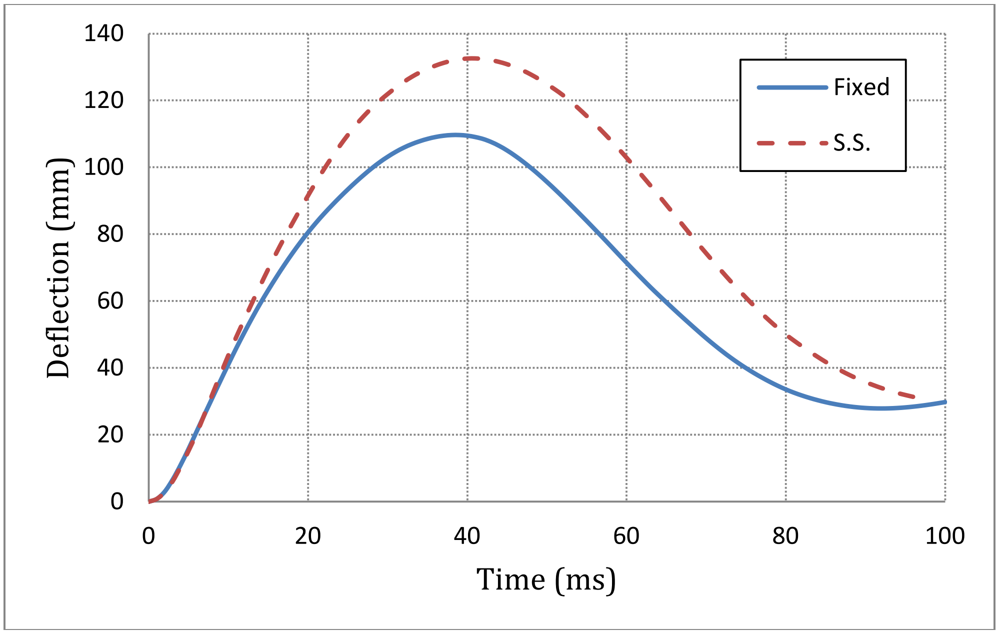


Figure 10: Midpoint deflection of retrofitted CMU infill wall with different B.C. under blast loading

The maximum deflection was observed to be 133mm and 110mm for the case of simply supported and fixed boundaries, respectively. By allowing the retrofitted wall to deform, more energy will be absorbed by the system as shown in Figure 11. The more energy absorbed the less reaction forces transmitted to the beams and columns (Figure 12) where the energy will be dissipate to deform the panel, to destroy the wall itself, or to separate the retrofitted layer from the wall.

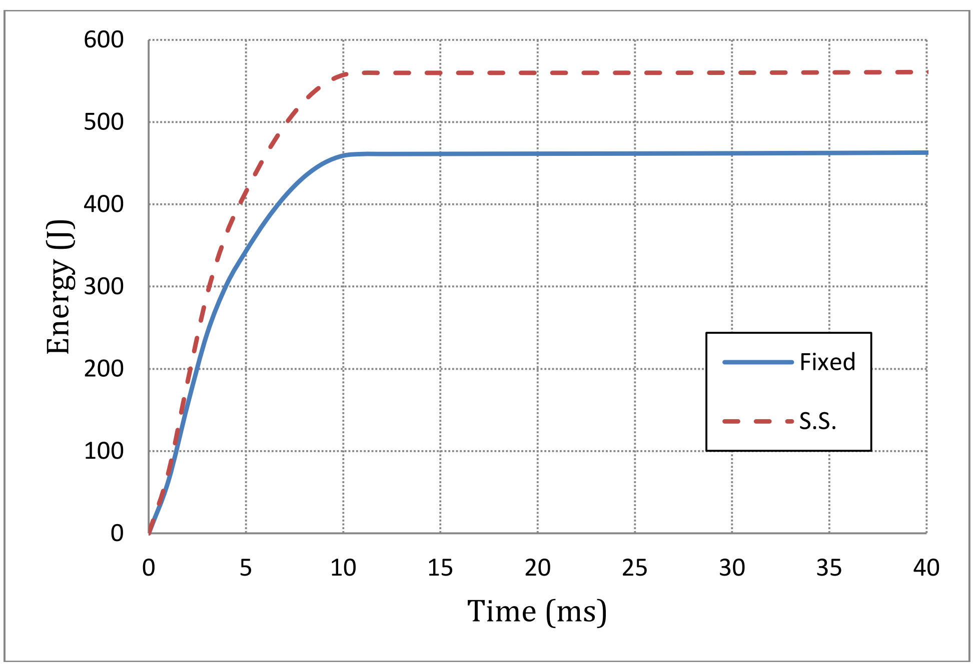


Figure 11: Energy absorbed by retrofitted CMU infill wall with different B.C. under blast loading

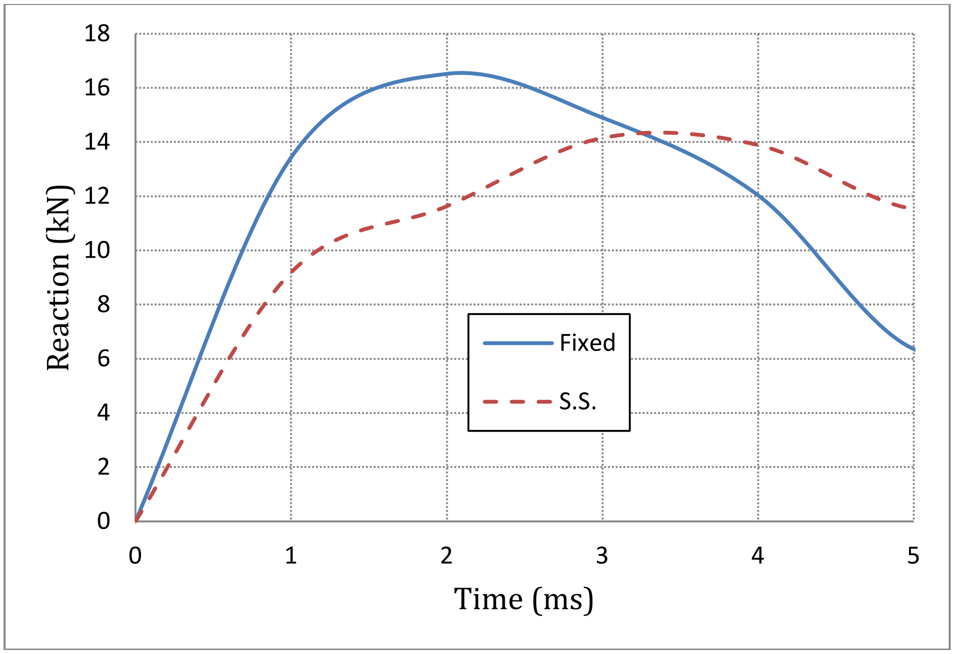


Figure 12: Reaction forces of retrofitted CMU infill wall with different B.C. under blast loading

5.2. ***Effect of Retrofitted Layer Thickness***

In order to study the effect of retrofitted layer thickness, the wall was coated with POSS reinforced polyurea with various thicknesses; 1.25mm, 1.5mm, 1.8m, and 3.0mm. All retrofitting was applied at the back side of the wall. The top and the bottom of the wall were fixed, while the two sides were left free for all simulations. The results show that the less thickness the more deformation due to blast until the wall failed when it was coated with 1.25 mm POSS reinforced polyurea at the opposite side of the blast (Figure 13).

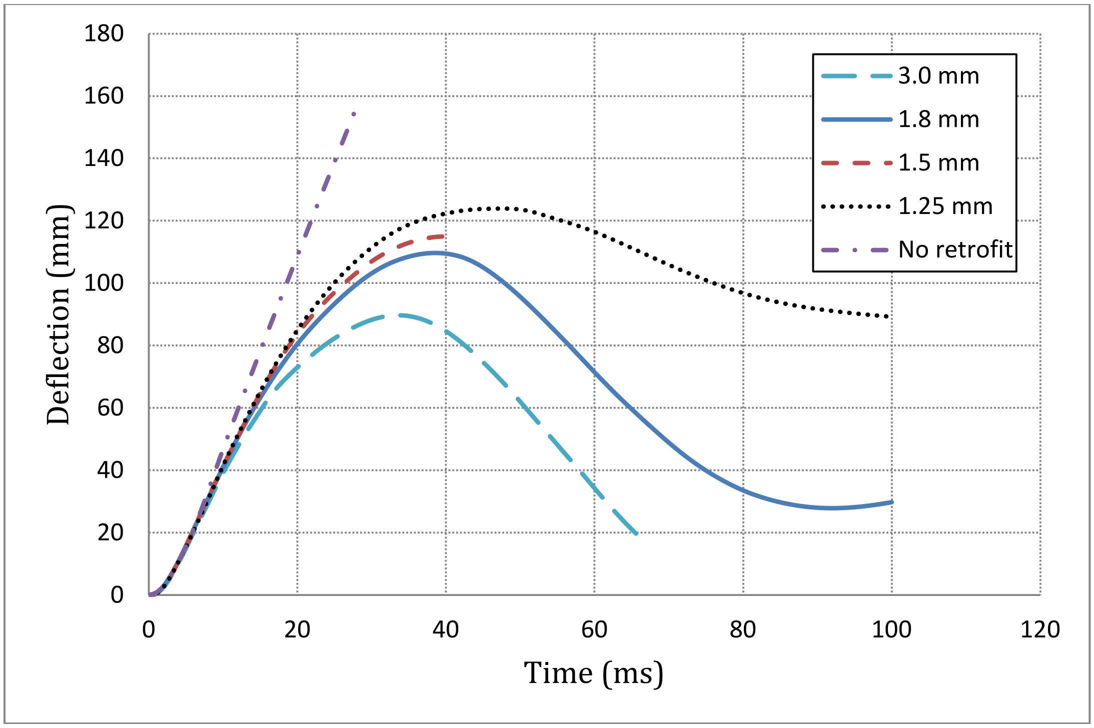
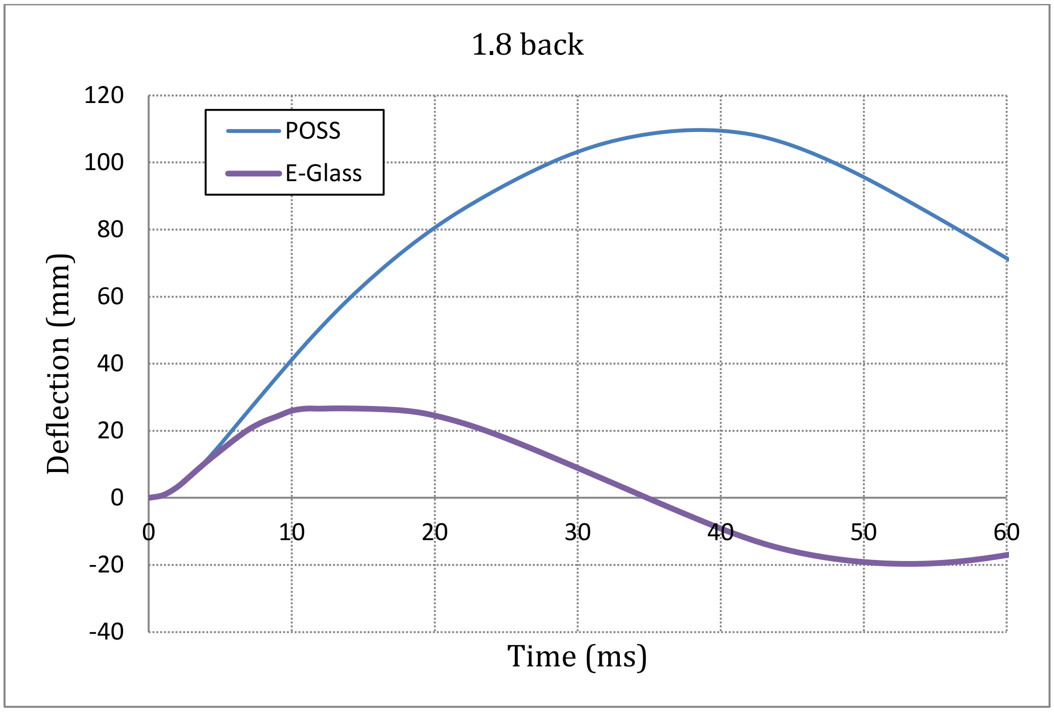


Figure 13: Midpoint deflection of retrofitted CMU infill wall with various coating thicknesses under blast loading

5.3. *Hybrid Retrofitting System*

In order to investigate the ability of using hybrid retrofitting system, one can play with the arrangement of retrofit layers and the ductility of retrofitted materials. A series of finite element analysis was conducted on different retrofit scenarios (back retrofit, front retrofit, and both sides retrofit) for two extreme cases of retrofit materials: rigid (E glass- epoxy) and relatively softer materials (POSS reinforced polyurea). To neglect the thickness effect, thickness of retrofit layer was kept constant at 1.8mm for all cases. The results (Figure 14 and Table 6) show that for the case of retrofitting with elastomeric materials it is better to apply the retrofit at the back side since this will be associated with no failure, when compared to front side retrofit, and a larger deflection (e.g. more energy dissipation) when compared with two side retrofit with a smaller amount of material. In the case of retrofitting with rigid materials, it was also observed that applying the retrofit at the back side was the best scenario.

In order to evaluate effect of wall retrofitting on structural elements (e.g. columns and beams), reaction forces were compared for two extreme retrofit cases. The results of FEA parametric evaluation (Figure 15) showed that retrofitting with rigid material will result in a higher reaction force. This means a higher possibility of failure beams and columns, which leads to failure of the whole structure.


1.8 back
POSS
E-Glass
Deflection (mm)
Time (ms)
120
100
80
60
40
20
0
-20
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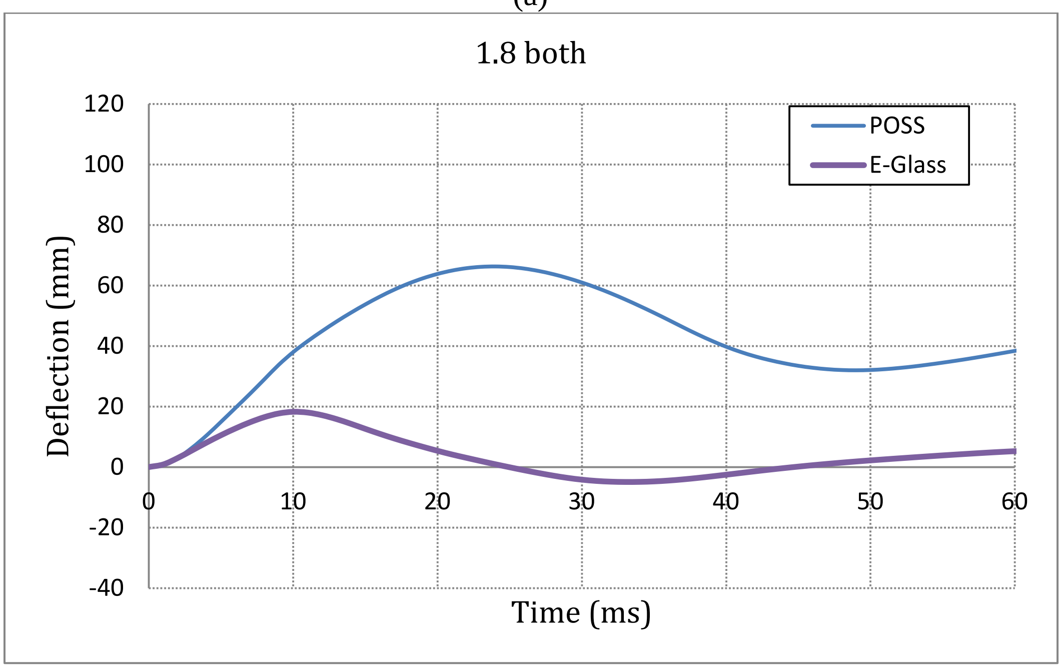
0
10
20
30
40
50
60

(a)


1.8 both
POSS
E-Glass
Deflection (mm)
Time (ms)
120
100
80
60
40
20
0
-20
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0
10
20
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40
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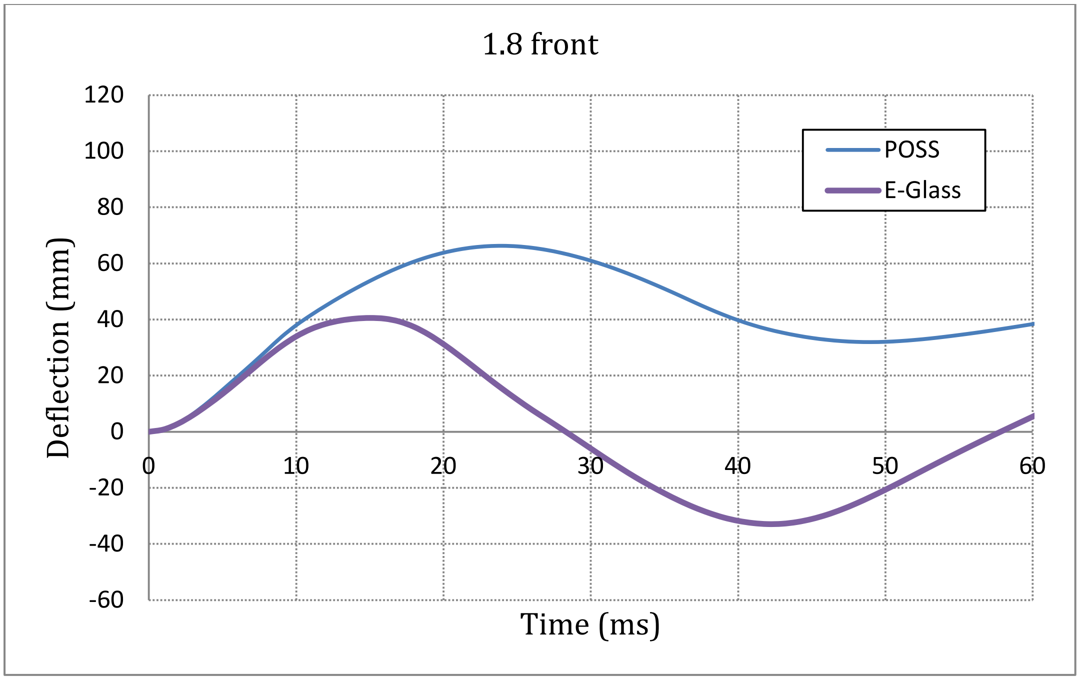
60

(b)



(c)

Figure 14: Midpoint deflection of CMU infill walls retrofitted with two different materials under blast loading (a) Back side retrofit (b) Front side retrofit (c) Both sides retrofit

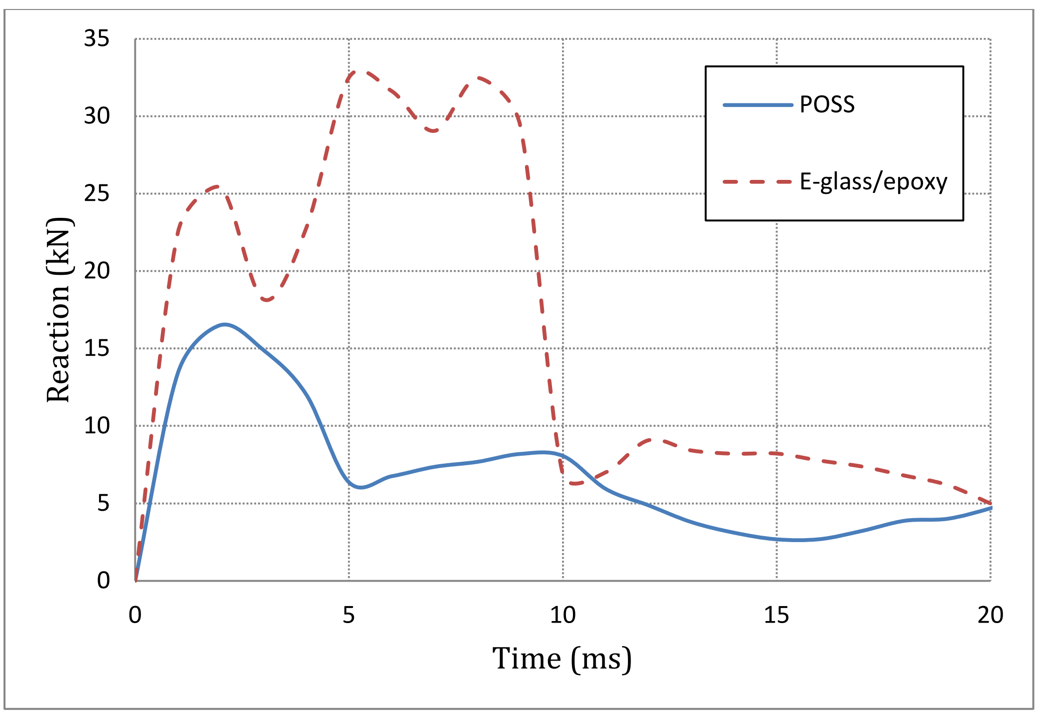
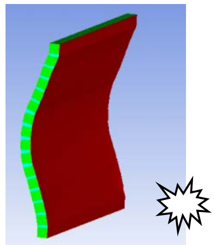
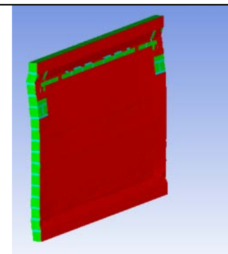
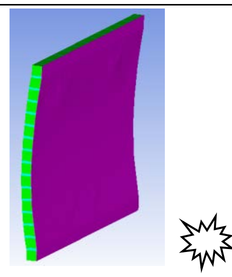
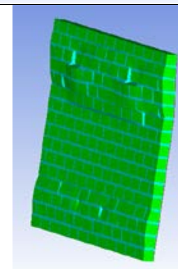
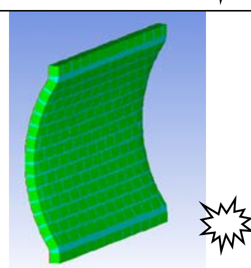
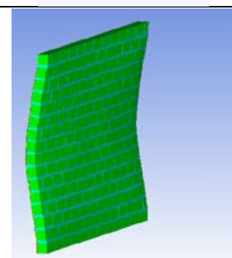
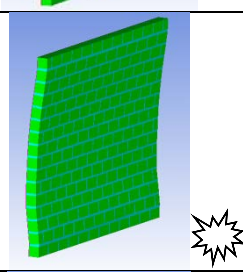
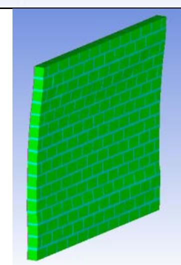
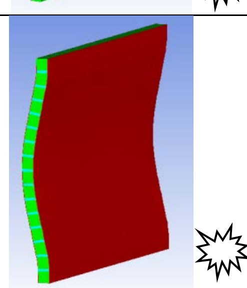
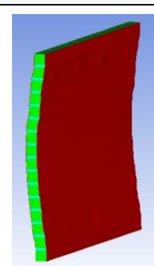
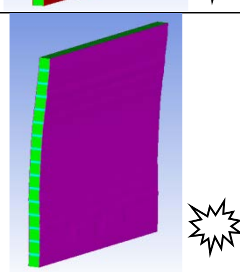
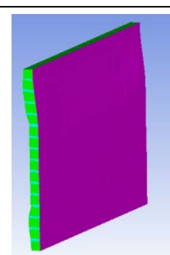


Figure 15: Reaction forces of CMU infill walls retrofitted with two different materials under blast loading

Table 6: Effect of retrofit scenarios

Type of Retrofit	At max. deflection	Final stage	Max. deflection (mm)
Blast Side (POSS)			Failed
Blast Side (Glass-Epoxy)			Failed
Back Side (POSS)			110
Back Side (Glass-Epoxy)			27
Both Sides (POSS)			66
Both Side (Glass-Epoxy)			18

6. CONCLUSION

This study focused on blast vulnerability assessment of concrete masonry infill walls retrofitted with nano particle reinforced polyurea. Quarter scale model concrete masonry infill walls made of scaled down brick units were retrofitted with Polyhedral Oligomeric Silsesquioxane (POSS) reinforced polyurea and subjected to a pre-adjusted airblast pressure and impulse in the ERDC Blast Load Simulator facility. A computationally-efficient model was built using an explicit hydrocode called ANSYS AUTODYN to replicate with reasonable accuracy the behavior of retrofitted infill walls subjected to blast loads. Finite element parametric evaluation was conducted to study the effect of boundary conditions, thickness and arrangement of retrofitted layers, and ductility of retrofitted materials on the behavior of the system during and after blast. Results from blast experiments showed that POSS reinforced polyurea significantly enhanced the performance of masonry walls sustaining blast load. The parametric evaluation results show that for the case of retrofitting with elastomeric materials it is better to apply the retrofit at the back side since this will be associated with no failure, when compared to front side retrofit, and a larger deflection (e.g. more energy dissipation) when compared with two side retrofit with a smaller amount of material.

7. ACKNOWLEDGEMENT

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