International Journal of Disaster Recovery and Business Continuity
Vol. 11, No. 1, (2020), pp. 2442-2460

Retrofitting Unreinforced Masonry Walls under Blast Loading Using Steel Wire Mesh and Shotcrete

Hossein Esteghamat*[,1], Amir Azhari[2] and Kambiz Takin[3]

Abstract

Retrofitting of the existing masonry buildings, especially the peripheral fences (brick walls), has grown in importance due to the increase in terrorist attacks in recent years. Most studies have explored the behavior of slabs, beams, and columns exposed to large-scale blasts. In these studies, the blast is huge enough to destroy all the walls and wall elements. While the weak structural elements are destroyed in small-scale blasts, the overarching goal of this study is to retrofit brick walls under blast loads. To this end, structures have to be retrofitted against small-scale blasts such that the weak elements are also strengthened. In this study, it is tried to assess the extent of destruction in different states by changing the steel mesh and shotcrete specifications. As for the steel mesh, the spacing between the reinforcement bars (rebars) are 10 and 15cm, while the shotcrete thicknesses are 5, 10, and 15cm. Blasts are also administered at short, medium and long distances. Finally, analyses are carried out for different steel mesh and shotcrete combinations to analyze and study the destruction of the brick and concrete walls.

Keywords: pressed brick, unconfined blast explosion, blast load, masonry wall, steel mesh, shotcrete, retrofitting, explosive

1. INTRODUCTION

The rate of terrorist attacks has increased in recent years and most attacks are carried out using blockbuster bombs that explode around buildings, causing fatalities and structural damage especially to masonry walls. However, these events cannot be prevented and masonry walls often experience failure due to their inadequate ductility and material strength. Hence, given that most walls used in buildings Protection of these walls against perpendicular blast loads is contingent upon the analysis of their retrofitting.

Ahrari Roudi (2016) [1] studied the optimization and the increased durability of stone veneers. They proposed a novel method for increasing the durability of stone veneers to describe and prove this method with objective evidence. To ensure and increase the cohesion between the stones and the sand-cement mortar, first parallel and transverse

---

***Corresponding author:** Hossein Esteghamat
Email: hosseineste@gmail.com
[1] MSc. in Civil Engineering, Structures, Faculty of Engineering, Safa Dasht branch, Islamic Azad University, Tehran, Iran
[2] Assistant Professor, Ph.D. in Hydraulic Structures, Faculty of Engineering, Safa Dasht branch, Islamic Azad University, Tehran, Iran
[3] Assistant Professor, Ph.D. in Hydraulic Structures, Faculty of Engineering, Safa Dasht branch, Islamic Azad University, Tehran, Iran

grooves with a maximum depth of 0.5cm were created behind the stone veneers using a polishing machine while the stones were being scoped to create the required strength. In this procedure, the durability and cohesion between the stone and the structure and the durability, safety, and quality can be improved within a shorter period if the project is industrialized. In another study in 2016, Maleki Toulabu [2] addressed the necessity of landscaping for buildings and analyzing the newest landscaping materials. In this study, first, the necessity of landscaping for buildings was studied using the desk research method and then the newest landscaping materials were introduced briefly.

Alipour and Mousavinik [3] (2016) studied the solutions for designing urban buildings with an emphasis on the principles of passive defense. They used the desk and documentary research techniques in the theoretical research section and carried out various graphical and photographic analyses in the field studies. According to their findings, it is possible to significantly improve the safety factor and security of the urban environment. The results of this study were presented as a set of design-based solutions for the design of urban buildings with a defensive approach. These solutions can serve as the basic guidelines for increasing the safety of urban public spaces and retrofitting them against force majeure. Mansouri [4] (2016) also studied the effect of the dimensions and the longitudinal and transverse bar placement of horizontal and vertical ties on the ductility of confined brick walls. In this research, 30 different models including a brick wall with a length of 3m, a height of 3m, and a thickness of 30cm confined by a concrete tie were analyzed in ABAQUS to study the effect of the dimensions and longitudinal bar placement and transverse bar placement of horizontal and vertical ties on the ductility of brick walls. The results of these analyses were classified by parameter and conclusions were drawn. Mozafarpour Taremi and Khosravi [5] (2016) studied the response of the occupants and nonstructural members to ground level blasts from the passive defense point of view. They selected two 4- and 8-story buildings and presented the results in the form of maximum values and dynamic responses by applying four selected blasts and carrying out a dynamic time history modal analysis. Their findings suggested that structural health does not represent the occupants' health. From the viewpoint of passive defense, ensuring the health of structures regardless of the health of their occupants under blast loads in terrorist attacks is not desirable. Maleki et al. [6] (2016) studied the effect of adding linings to unreinforced masonry buildings with shotcrete on the seismic behavior of these buildings. They simulated a 120x180cm single-brick masonry wall in the unreinforced state and the same wall retrofitted with two-way reinforced shotcrete as a lining plate covering the wall in ABAQUS finite element software. Afterward, they compared the analysis results with the experimental results to prove the accuracy of the model. Afterwards, they compared the analysis results and the considerable effect of the shotcrete on both sides of the unreinforced wall, which reflected the higher strength and energy absorption of the wall featuring shotcrete. Asadi et al. (2016) [7] studied the application of shotcrete with polymer fiber-reinforced concrete to the cover system of the tunnel walls. This study was carried out to propose novel methods of correcting the flaws and solving the problems caused by the implementation of the tunnel linings as compared to the conventional methods. Fiber-reinforced concrete is increasingly used in different types of structures. Besides, these materials have become proper options for many designs due to their significant efficiency and durability. This method improves the impact resistance, tensile strength, and concrete abrasion, reduces permeability, and increases durability and stability. These fibers increase concrete ductility, and this application is particularly important in environments subjected to considerable deformations and displacements such as different underground structures. The findings from this study are the results of a set of tests and suggestions for creating an optimal design based on the experimental results. Hence, this type of concrete has advantages over the common types of concrete, and these advantages are the reasons for their growing popularity in the industry despite their high prices.

In this study, the brick wall specifications are constant while the mesh and shotcrete properties are changed to study the wall responses to these changes under blast loads. This analysis has never been carried out in previous studies. Besides, studying the effect of the blast distance on the performance of shotcrete and measuring destruction in each state are among the unique advantages of this study.

2. RESEARCH METHOD

In this study, a brick wall with reinforced concrete cover is simulated under blast loads in ABAQUS 2017. Concrete covers with different thicknesses and different arrangements of steel bars are used to study the role of the reinforced concrete cover under blast loads. The effect of blasts at the near, average, and long distances is also studied.

2.1. Modeling

The study model consists of three parts, namely the brick wall, the concrete cover, and the reinforcement bars, that are modeled in ABAQUS . A 2.5x2.5m brick wall with a thickness of 20cm is defined as an integrated homogenous component. A bar set with spacing between the bars with a diameter of 10mm is used and the bars are modeled in two states with 10 and 15cm spaces. The concrete cover is also simulated as an integrated homogenous component in three states with 5, 10, and 15cm thicknesses and it is placed in front of the brick wall. The reinforcement bar set is placed inside the concrete cover.

2.2. Material Properties

After completing the modeling, the properties of each model component are defined. To this end, the plasticity damage state is selected for the brick wall, and the plasticity properties and the compressive and tensile properties are defined separately in the software as shown in table (1) [8]. The bars are made of St37 steel, and the Johnson-Cook criterion is used to simulate their destruction. table (2) presents the coefficients and properties [9]. Similar to the brick wall, the plasticity damage state is used to simulate concrete destruction, and the specifications are depicted in table (3) [9].

As stated, the cross-section defined for the brick and concrete walls is homogeneous, and it is made using the solid element. The truss element is also used for the bars.

Young's Modulus	Poisson's Ratio	Mass Density
11800000000	0.15	2000

A) The mechanical properties of the brick wall

Dilation Angle	Eccentricity	fb0/fc0	K	Viscosity Parameter
10	0.1	1.16	0.67	0.001

B) The plasticity damage parameters for the brick wall

Yield Stress	Cracking Strain
200000	0
10000	0.0015

C) Tensile state

Yield Stress	Inelastic Strain
1224566.667	0
1304875	0.0001
1381722.222	0.0002
1455208.333	0.0003
1525333.333	0.0004
1592097.222	0.0005
1655500	0.0006
1715541.667	0.0007
1772222.222	0.0008
1772222.222	0.0009

D) compressive state

Table 1: The properties defined for the brick wall [8]

Young's Modulus	Poisson's Ratio	Mass Density
210000000000	0.3	7850

A) The mechanical properties of the bars

A	B	n	m
792000000	510000000	0.26	1.03

B) The plasticity properties of the bars based on Johnson-Cook’s criterion

dl	d2	d3	d4	d5
0.05	3.44	-2.12	0.002	0.61

C) The plasticity damage properties of the bars based on Johnson-Cook's criterion

Table 2: The properties defined for the steel wire mesh [9]

Young's Modulus	Poisson's Ratio	Mass Density
23500000000	0.2	2400

A) Concrete mechanical properties

Dilation Angle	Eccentricity	fb0/fc0	K	Viscosity Parameter
30	0.1	1.16	0.667	0.001

B) The plasticity damage parameters of the concrete

Yield Stress	Cracking Strain
3150000	0
2081789.971	0.000288922
1705996.394	0.000548379
1494560.766	0.000800842
1353338.316	0.001050318
1249964.252	0.001298183

C) Concrete tensile behavior properties

Yield Stress	Inelastic Strain
7500000	0
15211379.82	5.27072E-005
19864488.68	0.000154703
22934534.23	0.000324062
24542121.1	0.000555654
25000000	0.000837273
2332573228	0.001475119
20613051.44	0.002157152
17881110.95	0.002840005
15474205.04	0.003509026

D) Concrete compressive behavior properties

Table 3: The properties defined for the brick wall [9]

2.3. Boundary Conditions

Since the wall is connected to the beams and columns, the surrounding of the wall is considered to be completely restrained so that the rotations and displacements equal zero.

2.4. Blast Load Simulation

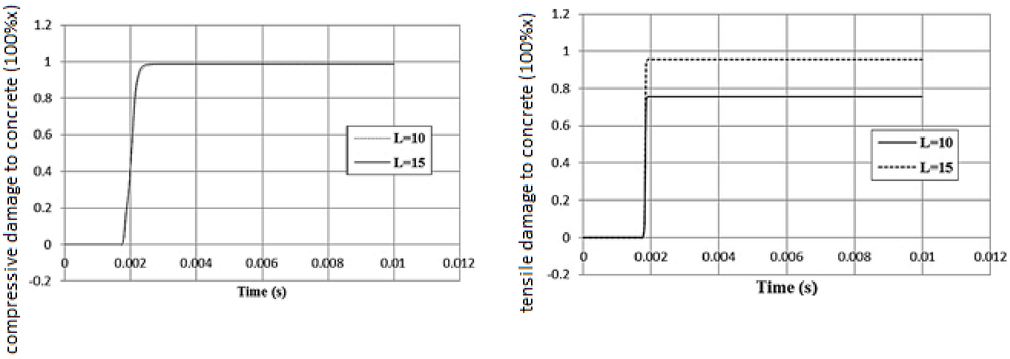
An air explosion with 700 kilogram of TNT was carried out and the blasting cap was placed at the 5, 9 and 13-meter distances to simulate the blast loads. The explicit dynamic analysis method was also used to solve the problem.

3. RESULTS AND DISCUSSION

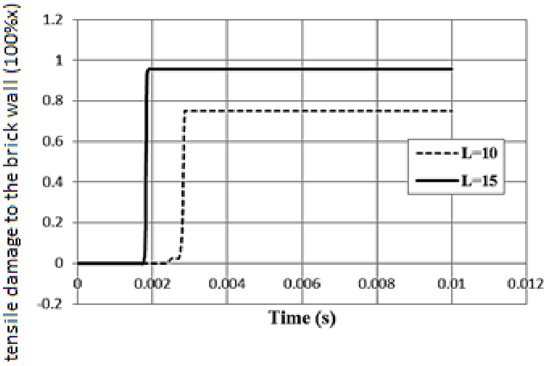
After extracting the results and data from 18 different finite element analyses presented in the previous section, the resulting data are compared in this section and the results of each state are explained. It is worth noting that T, S, and L denote the thickness of the concrete cover, the distance between the point of explosion and the wall center, and the spacing between the bars in the steel wire mesh, respectively.

3.1. The Effect of the Spacing between the Bars

In this section, the results of different states are compared by changing the spacing between the bars in the steel wire mesh.



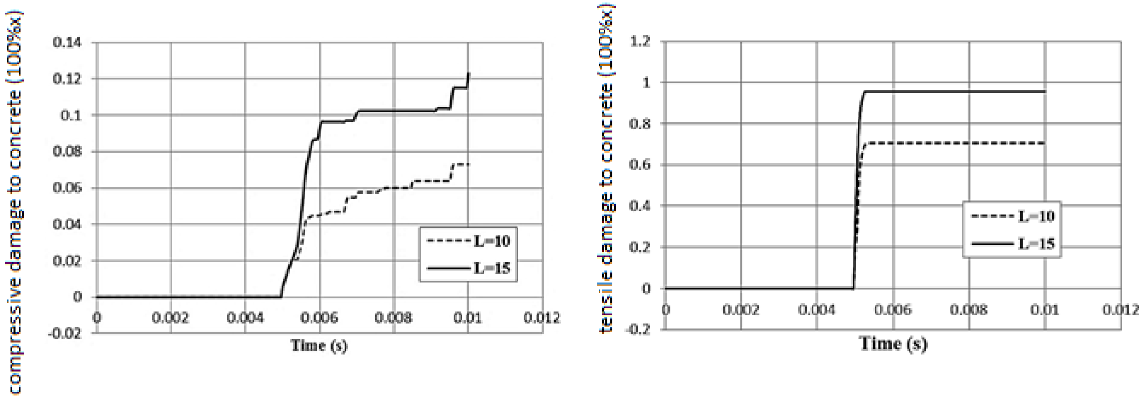
B) compressive damage to concrete **A) tensile damage to concrete**



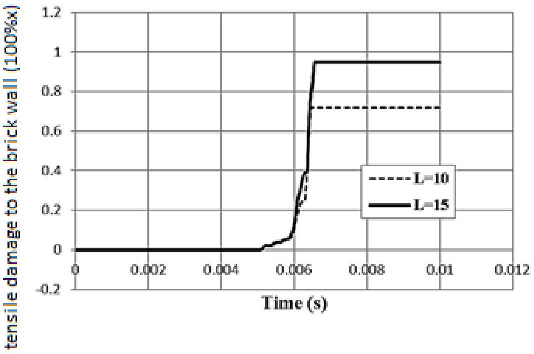
C) tensile damage to the brick wall

Figure (1): The effect of the spacing between the bars on the maximum damage for T=5cm and S=5m

As seen in figures (1) A and B, the spacing between the bars does not considerably affect the compressive damage caused to concrete, but the higher density of the steel wire mesh reduces tensile damage caused to concrete by almost 20%. However, the maximum damage is caused in both states within 0.002 seconds. According to Figure (1) C, with an increase in the spacing between the bars, maximum damage occurs more rapidly and the damage decreases (app. 21%). As a result, the brick wall resists the blast loads for a shorter period with an increase in the spacing between the bars. Besides, the compressive damage caused to the brick wall is insignificant, reflecting the positive effect of the reinforced concrete cover.



B) Compressive damage to concrete **A) tensile damage to concrete**



C) tensile damage to the brick wall

Figure (2): The effect of bar spacing on the maximum damage for T=5cm and S=9m

As seen in figures (2) A and B, the smaller spacing between the bars considerably reduced the tensile damage and compressive damage to concrete. The decrease in the tensile damage and compressive damage was approximately 25% and 50%, respectively. Figure (2) C depicts the positive effect of the smaller spacing between the bars (app. 23%) at the peak of the blast load (which is approximately 0.006sec) on the decrease in the tensile damage to the brick wall. As a result, the brick wall resists the blast loads for a longer period.

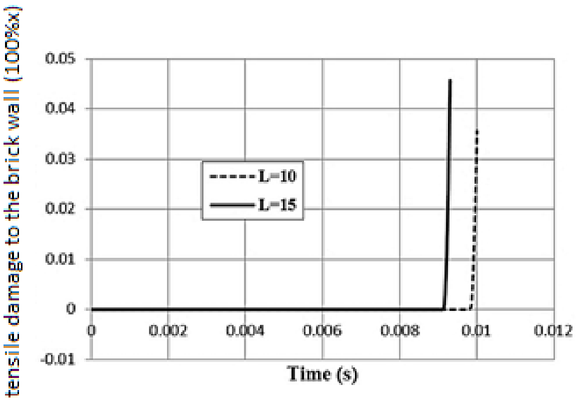
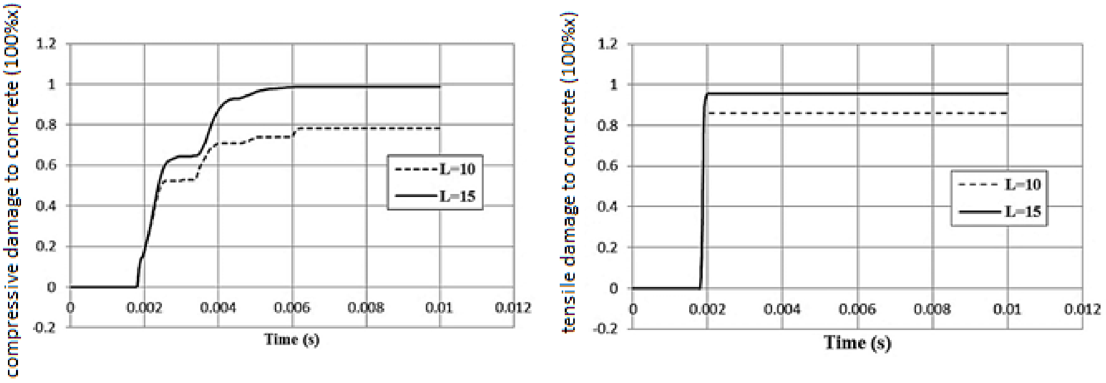
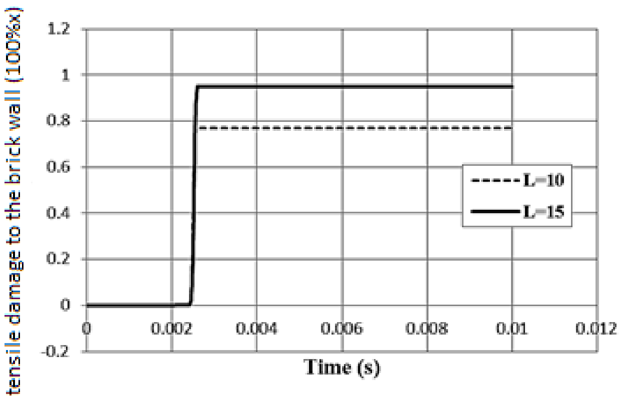


Figure (3): The effect of the spacing between the bars on the tensile damage to the brick wall for T=5cm and S=13m

As seen in Figure (3), the highest density of the bars postpones the tensile damage to the brick wall and reduces the damage from 45% to 37%. Similar to the previous states, the compressive damage to the brick wall and the tensile and compressive damage to concrete in this state are insignificant due to the long distance between the point of explosion and the wall.



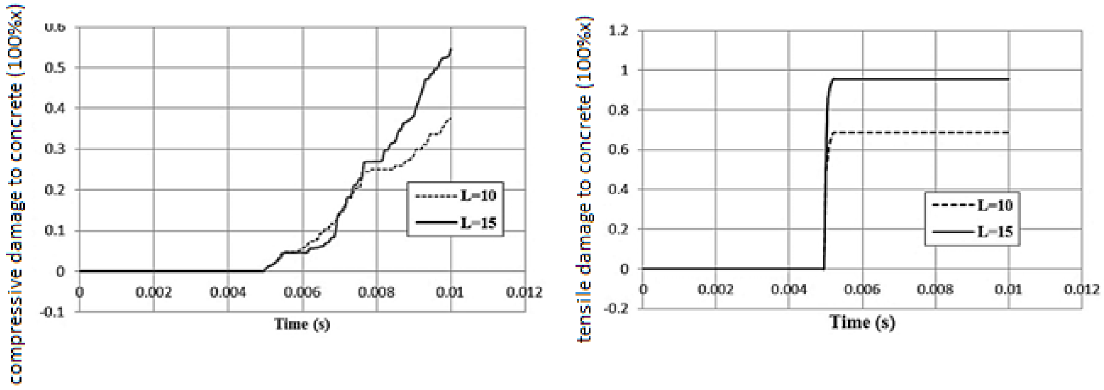
B) The compressive damage to concrete **A) the tensile damage to concrete**



C) The tensile damage to the brick wall

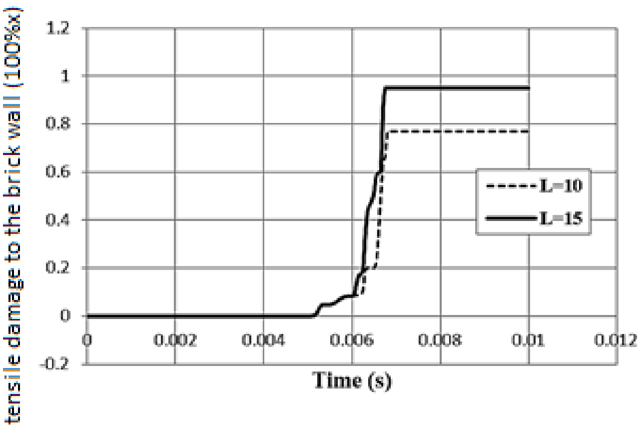
Figure (4): The effect of the spacing between the bars on the maximum damage for T=10cm and S=5m

As seen in figures (4) A and B, the smaller spacing between the bars reduced the tensile damage and compressive damage to concrete by 11 and 21%, respectively. The higher shotcrete thickness also contributed to the damage. Figure (4) C depicts the positive effect of the increase in the density of the bars on the decrease in the tensile damage to the brick wall. The extent of the compressive damage to the brick wall is also insignificant, mirroring the positive effect of the reinforced concrete cover.



B) the compressive damage to concrete

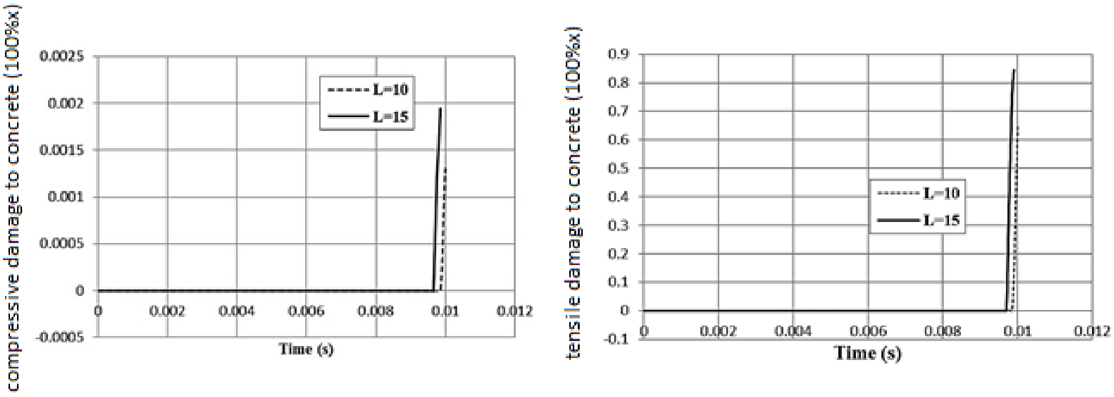
A) the tensile damage to concrete



C) The tensile damage to the brick wall

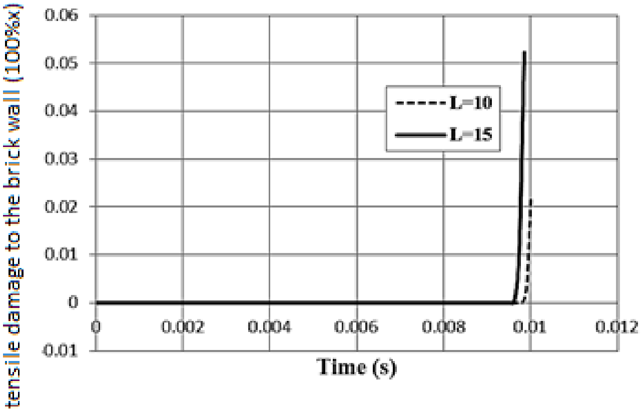
Figure (5): The effect of the spacing between the bars on the maximum damage for T=10cm and S=9m

As seen in figures (5) A and B, the smaller spacing between the bars in the steel mesh considerably influenced the decrease in the tensile and compressive damage to concrete (app. 27% in both states). The compressive damage to concrete also decreased by about 40% due to the increased shotcrete thickness. In Figure (5) C, the positive effect of the smaller spacing between the bars at the peak of the blast load (app. 0.006 sec) is significant on the decrease in the tensile damage to the brick wall.



B) the compressive damage to concrete

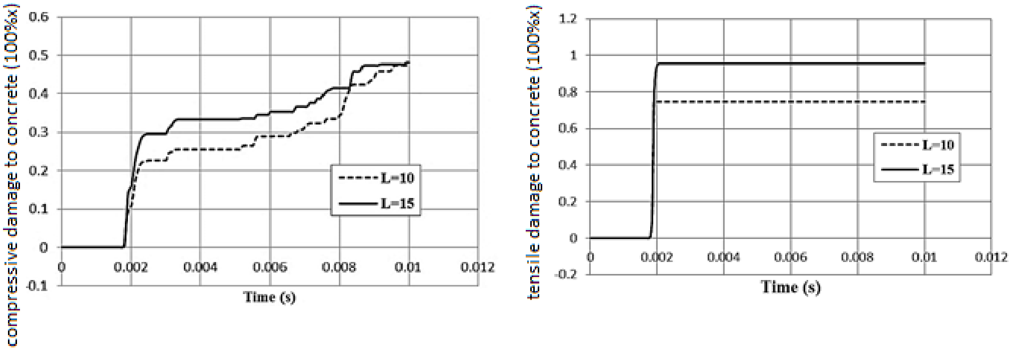
A) the tensile damage to concrete



C) the tensile damage to the brick wall

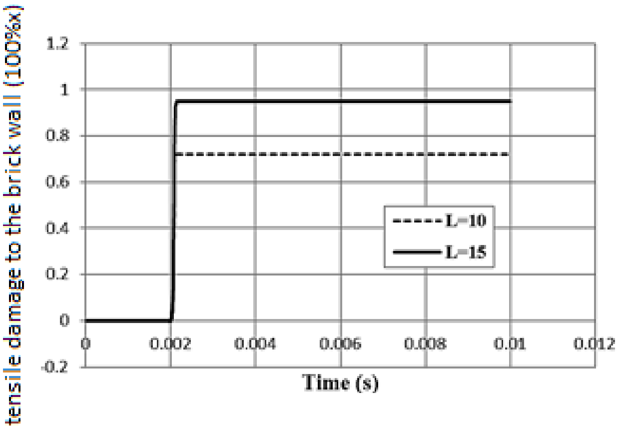
Figure (6): The effect of the spacing between bars on the maximum damage for T=10cm and S=13m

As seen in figures (6) A and B, the smaller spacing between the bars properly affected the decrease in the compressive and tensile damage to concrete, which culminated in the decrease in the tensile damage to the brick wall in Figure (6) C.



B) compressive damage to concrete

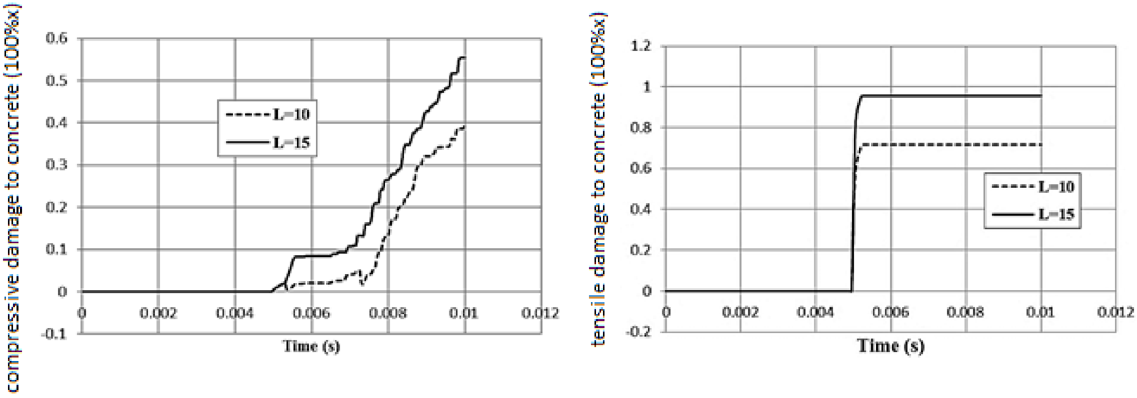
A) tensile damage to concrete



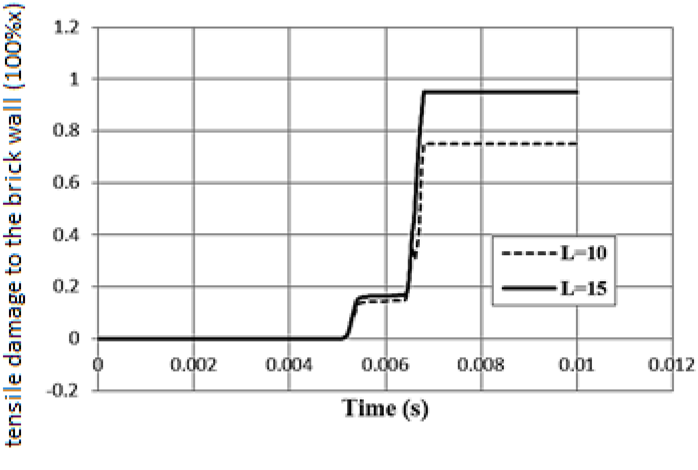
C) the tensile damage to the brick wall

Figure (7): The effect of the spacing between the bars on the maximum damage for T=15cm and S=5m

As seen in figures (7) A and B, the smaller spacing between the bars reduced the tensile and compressive damage to concrete. Figure (7) C depicts the positive effect of the smaller spacing between the bars on the decrease in the tensile damage to the brick wall.



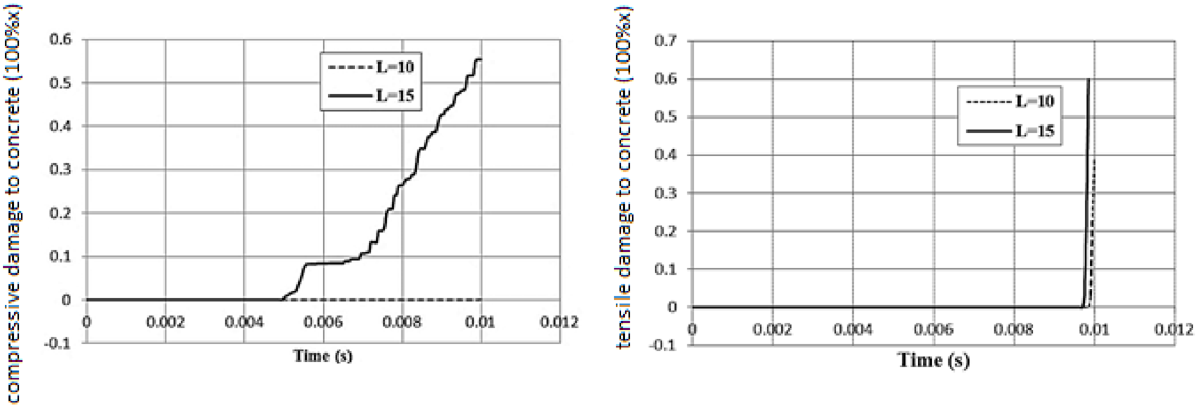
B) the compressive damage to concrete **A) the tensile damage to concrete**



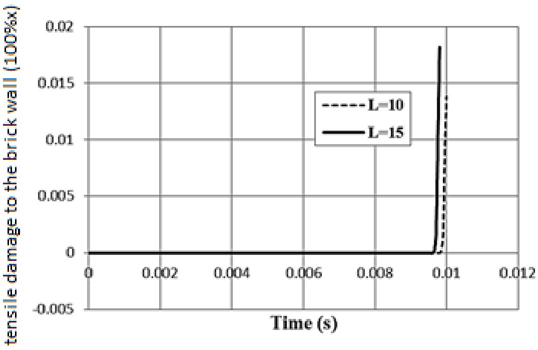
C) the tensile damage to the brick wall

Figure (8): The effect of the spacing between the bars on the maximum damage for T=15cm and S=9m

As seen in figures (8) A and B, the smaller spacing between the bars considerably influenced the extent of the tensile and compressive damage caused to concrete. In other words, with a decrease in the spacing between the bars in the steel wire mesh, the damage subsides. Figure (8) C depicts the considerable effect of the smaller spacing between the bars on the decrease in the tensile damage to the brick wall. Besides, the compressive damage to the brick wall is insignificant, reflecting the positive effect of the reinforced concrete cover.



B) compressive damage to concrete **A) tensile damage to concrete**



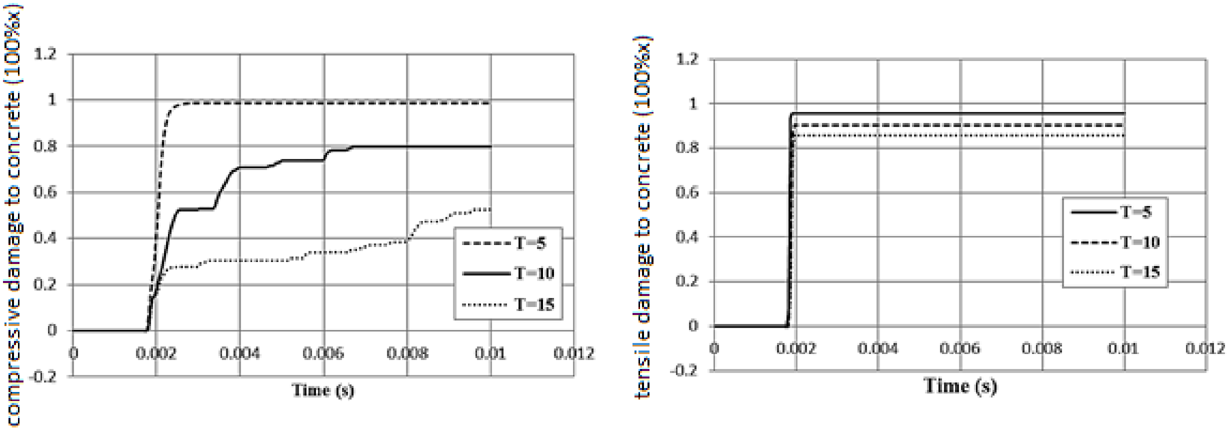
C) the tensile damage to the brick wall

Figure (9): The effect of the spacing between the bars on the maximum damage for T=15cm and S=13m

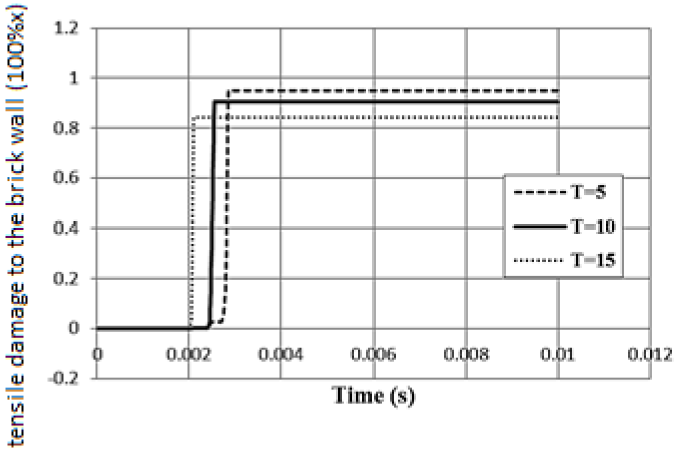
As seen in figures (9) A and B, the smaller spacing between the bars in the steel wire mesh reduced the compressive and tensile damage caused to concrete. Figure (9) C depicts the positive effect of the smaller spacing between the bars on the decrease in the tensile damage to the brick wall. Furthermore, the compressive damage to the brick wall is insignificant, mirroring the positive effect of the reinforced concrete cover.

3.2. The Effect of Concrete Cover Thickness

In this section, the results of different states are compared by changing the thickness of the concrete cover in shotcrete.



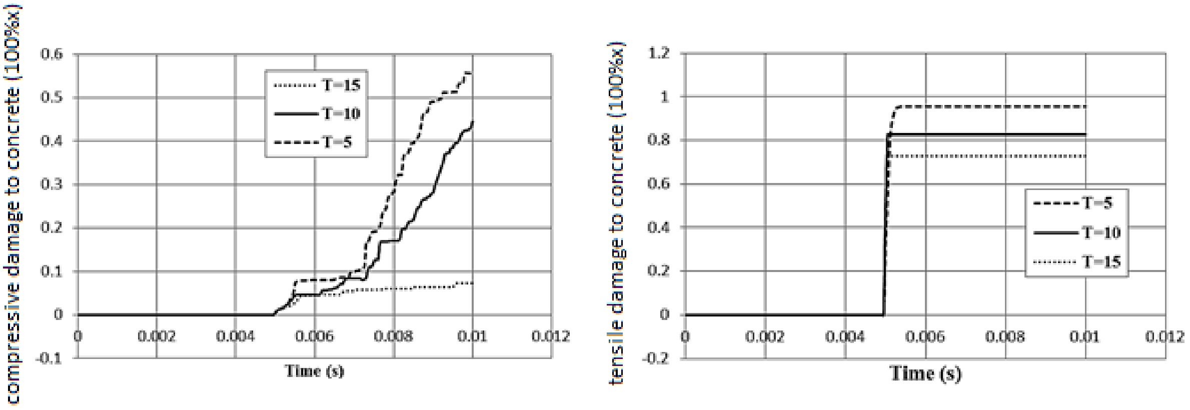
B) compressive damage to concrete **A) tensile damage to concrete**



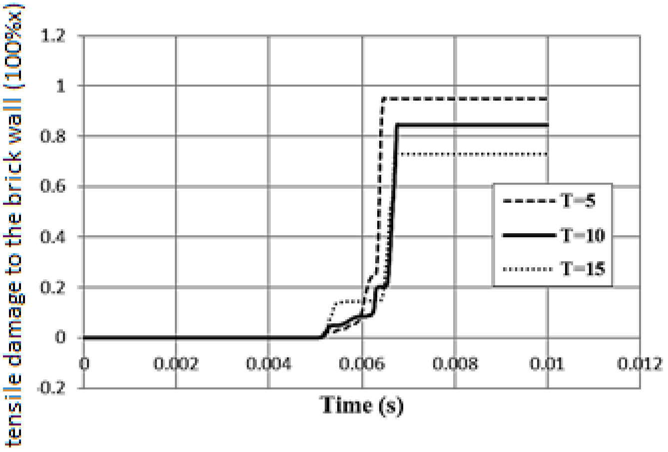
C) tensile damage to the brick wall

Figure (10): The effect of the thickness of the concrete cover on the maximum damage for L=10cm and S=5m

As seen in figures (10) A and B, the increase in the thickness of the concrete cover considerably reduces the tensile damage to concrete (10%) and the compressive damage to concrete (44%). Figure (10) C presents the positive effect of the increase in the thickness of the concrete cover on the decrease in the tensile damage to the brick wall. The compressive damage caused to the brick wall is also insignificant, indicating the positive effect of the reinforced concrete cover. It is worth noting that the effect of the increase in the shotcrete thickness is cushioned in some cases due to the proximity of the point of explosion to the wall and the intensity of the blast load.



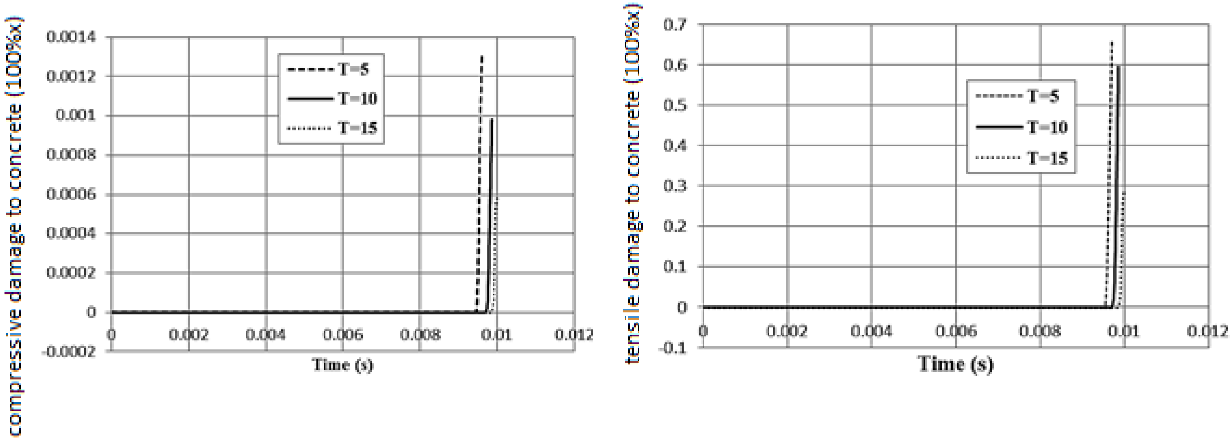
B) the compressive damage to concrete **A) the tensile damage to concrete**



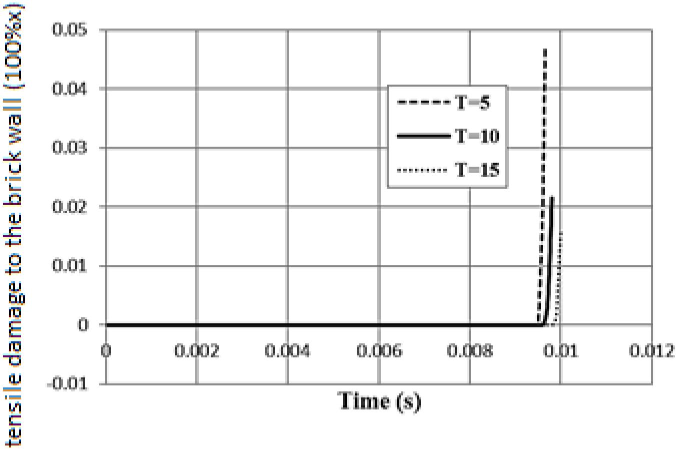
C) the tensile damage to the brick wall

Figure (11): The effect of the concrete cover thickness on the maximum damage for L=10cm and S=9m

As seen in figures (11) A and B, the higher thickness of the concrete cover considerably reduces the tensile and compressive damage to concrete. The maximum decrease in tensile damage and compressive damage is 14% and 47%, respectively. The positive effect of the higher thickness of the concrete cover on the decrease in the tensile damage caused to the brick wall is illustrated in Figure (11) C. Moreover, the compressive damage to the brick wall is insignificant, proving the positive effect of the reinforced concrete cover.



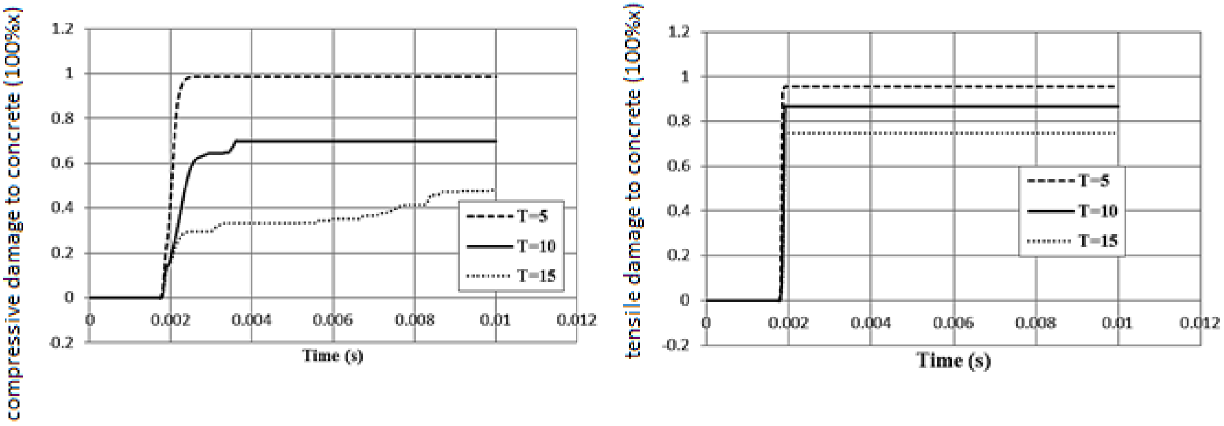
B) the compressive damage to concrete **A) the tensile damage to concrete**



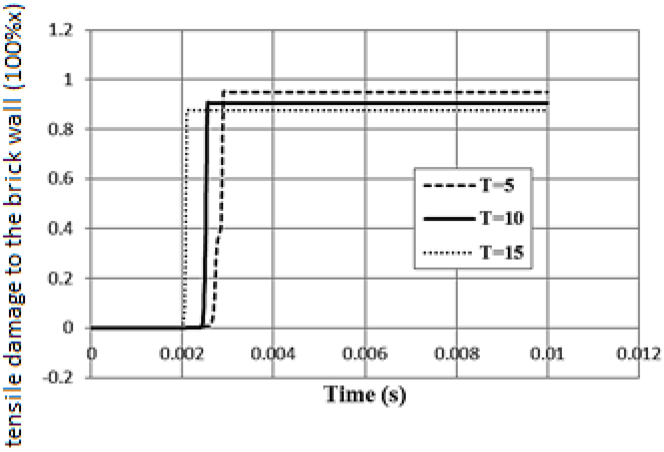
C) the tensile damage to the brick wall

Figure (12): The effect of the concrete cover thickness on the maximum damage for L=10cm and S=13m

As seen in figures (12) A and B, the higher thickness of the concrete cover reduced the tensile and compressive damage to concrete. However, the damage decreased significantly due to the long distance from the point of explosion. The positive effect of the higher thickness of the concrete cover on the decrease in the tensile damage to the brick wall is illustrated in Figure (12) C. As seen, the damage decreased from 46% to 17%.



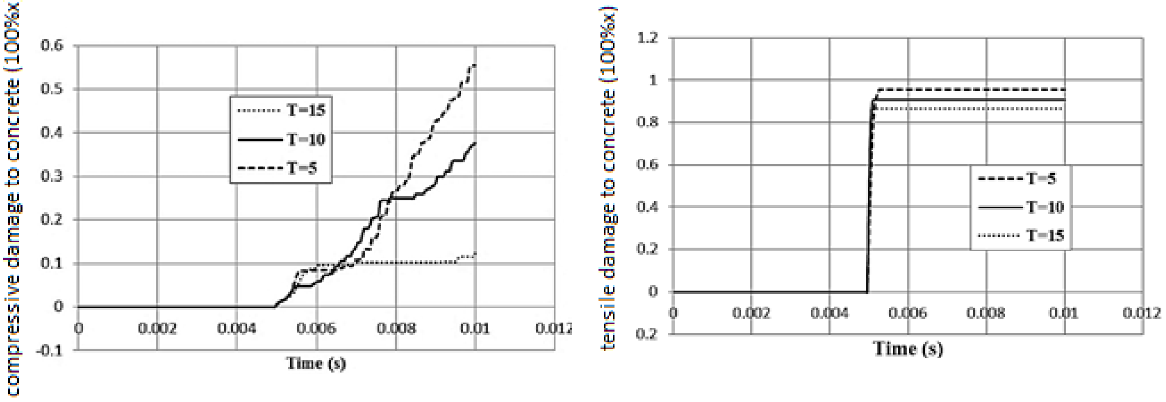
B) the compressive damage to concrete **A) the tensile damage to concrete**



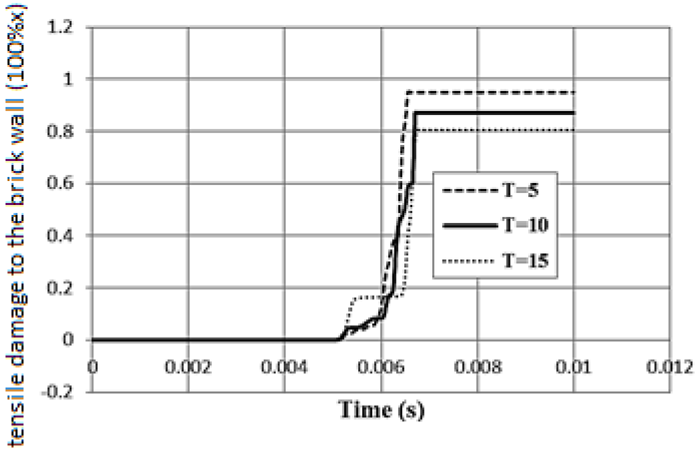
C) the tensile damage to the brick wall

Figure (13): The effect of the thickness of the concrete cover on the maximum damage for L=15cm and S=5m

As seen in figures (13) A and B, the higher thickness of the concrete cover considerably reduced the tensile and compressive damage to concrete. Figure (13) depicts the positive effect of the increase in the concrete cover thickness on the decrease in the tensile damage to the brick wall. Similar to the previous cases, the proximity of the point of explosion to the wall and the larger spacing between the bars lessened the effect of the increased shotcrete thickness.



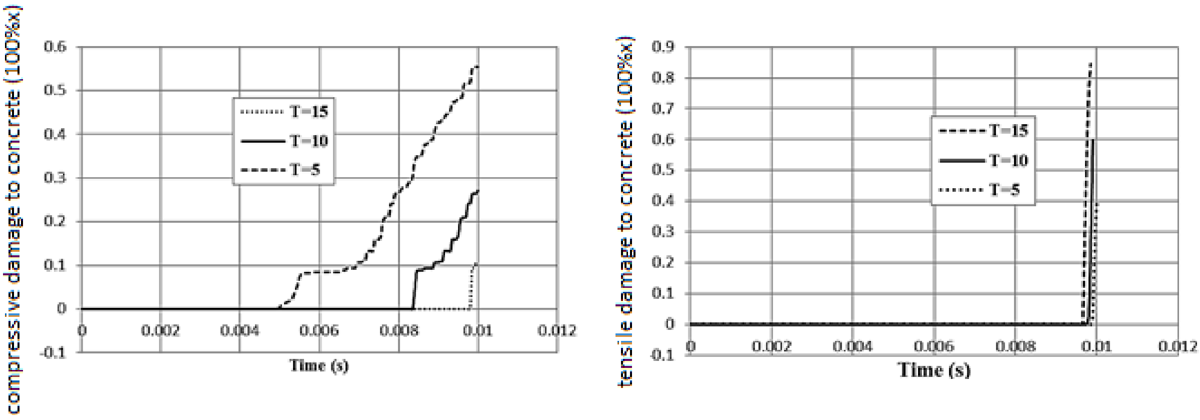
B) the compressive damage to concrete **A) tensile damage to concrete**



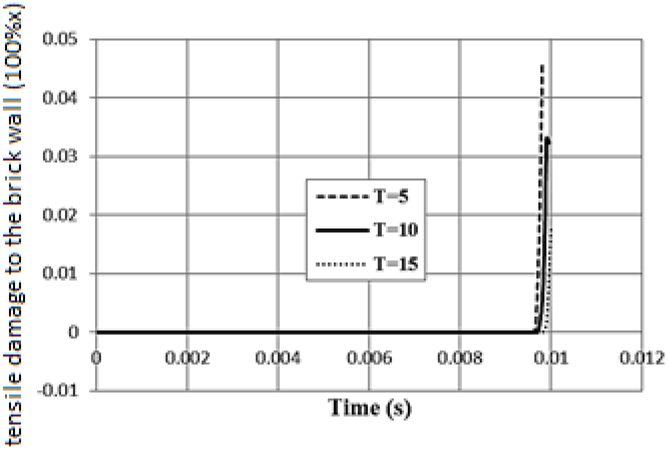
C) tensile damage to the brick wall

Figure (14): The effect of the concrete cover thickness on the maximum damage for L=15cm and S=9m

As seen in figures (14) A and B, the increase in the shotcrete thickness reduced the tensile and compressive damage to concrete by 10 and 42%, respectively. The positive effect of the increased concrete cover thickness on the decrease in the tensile damage to the brick wall is illustrated in Figure (14) C.



B) the compressive damage to concrete **A) the tensile damage to concrete**



C) the tensile damage to the brick wall

Figure (15): The effect of the concrete cover thickness on the maximum damage for L=15cm and S=13m

As seen in figures (15) A and B, the increased thickness of the cover increases the tensile and compressive damage to concrete. However, the long distance from the point of explosion reduced damage in three states. Figure (15) C depicts the positive effect of the higher concrete cover thickness on the decrease in tensile damage to the brick wall.

4. CONCLUSION

This study revolved around the retrofitting of the existing masonry walls under blast loads using steel wire meshes and shotcrete. The finite element analysis of 18 different steel wire mesh and shotcrete combinations was carried out in ABAQUS and the results were compared. The following findings were obtained from the finite element analyses.

1. In all states, the maximum decrease in stiffness and the maximum damage were observed in the bearing area. The maximum displacement and displacement speed were also observed at the center of the wall.
2. The spacing between the bars in the steel wire mesh considerably influenced the maximum stiffness, the maximum failure, and the maximum displacement and displacement speed at the center of the wall, but these effects were more limited when the point of explosion was near the wall due to the intensity of the applied load.
3. The thickness of the concrete layer in shotcrete significantly contributed to the reduction in the maximum decrease in stiffness, the subsequent maximum failure, and the maximum displacement and displacement speed at the center of the wall in most cases. Hence, it is possible to prevent the destruction of the building walls and the main components by increasing the shotcrete thickness or minimizing the damage. Similar to the previous case, these effects are further cushioned when the point of explosion is near the wall due to the intensity of the applied load.
4. In sum, the increase in the shotcrete thickness contributes more than the increase in the density of the steel wire mesh to the protection of the masonry wall as compared to the other states. Hence, it is possible to only increase the shotcrete thickness to ensure cost-effectiveness.

REFERENCES

1. Ahrari Roudi, Moheyiodin (2016). Optimizing and increasing the durability of stone veneers in buildings. The Second International Conference on Geology and Urban Development
2. Maleki Toulabi, Hussein, and Maleki Toulabi, Amir Mohammad (2016). The necessity of landscaping in buildings and analyzing the newest landscaping materials. The First National Conference on Islamic Architecture, Urban Heritage, and Sustainable Development
3. Alipour, Hamed and Mousavinik, Seyyed Mohsen (2016). Analyzing the solutions to the design of urban buildings with an emphasis on the passive defense principles. The National Conference on the Novel Approaches to Sustainable Regional Development and Planning
4. Mansouri, Heydar (2016). Analyzing the effects of the dimensions and longitudinal and transverse bar placement of horizontal and vertical ties on the ductility of confined brick walls. The National Conference on Applied Research on the Novel Civil Engineering and Architectural Horizons
5. Mozafarpour Taremi, Mohamad Reza Khosravi Hussein (2016). Analyzing the response of occupants of buildings and non-structural members to ground level explosions from the passive defense point of view. The Fourth National Conference on Applied Research on Civil Engineering, Architecture, and Urban Management
6. Maleki, Salman, Omidinasab Fereydoun, Piriyan Safar Abad Kamran (2016). Analyzing the effect of adding lining to unreinforced masonry buildings with shotcrete on their seismic behavior. The International Conference on Civil Engineering
7. Asadi Beygzadeh Mahaleh, Mohamadreza Eshghi, Payam Tavana Roudsari, Majid Peymayian Bahri, Iman (2016). The application of shotcrete reinforced with polymer fiber-reinforced concrete in the cover system of tunnel walls. The National Conference on Novel Research on Technical and Engineering Sciences
8. Ibrahimi, Seyyed Mohamad (2015). A finite element analysis of engineering problems in ABAQUS. Andisheh Sara Press, Tehran
9. Kalali, Arsalan, Zaman Kabir Mohammad (2011). Calculating the constants of unreinforced brick walls from the homogeneity and micromechanics point of view in the membranous and moment-resistance performance. The Civil Engineering and Survey Journal, Faculty of Engineering, 45th round, no. 2, July 2011: 203-217