International Journal of Engineering Sciences & Research Technology

(A Peer Reviewed Online Journal)
Impact Factor: 5.164

IJESRT

RESEARCHERID
THOMSON REUTERS

[Mahmoud * *et al.*, 8(2): February, 2019]
ICTM Value: 3.00

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

EVALUATION OF STRUCTURAL BEHAVIOR AND MECHANICAL STRENGTH OF MULTIPLE-LEAF MASONRY WALLS AT JEDDAH'S HERITAGE BUILDINGS UNDER UNIAXIAL COMPRESSION LOADS AND THEIR APPROPRIATE STRENGTHENING TECHNIQUES

Hassan Salah Mahmoud[*1],Yaser Yehya Abdel–Aty[2] & Abdulnaser Abdulrahman Al-Zahrani[3]
[1]Department of Conservation, Faculty of Archaeology, Cairo University, Giza, Egypt
[2]Department of Conservation, Faculty of Archaeology, Cairo University, Giza, Egypt
[3]Department of Archaeology, Faculty of Tourism and Archaeology, King Saud University, Riyadh, Kingdom of Saudi Arabia

DOI: 10.5281/zenodo.2566101

ABSTRACT
The current work represents the results of the intensive experimental study of the outer leaves of the multiple-leaf load bearing masonry walls in Jeddah's heritage buildings at Kingdom of Saudi Arabia (KSA). It studies the structural behavior and mechanical properties of the walls and their stone units under uniaxial compressive standard tests. Besides, it evaluates their strengthening and retrofitting by using a number of techniques, mainly, bedjoints reinforcement and nanolime injections. The fossil if erouslimestones of these heritage buildings are characterized by very high porosity and shell-formation inside. Although, the big number of heritage buildings in Jeddah (more than 500), there is very few studies concern the present research field. Standard mechanical tests were conducted for stone and mortar cubic samples, in addition to nine masonry prisms that represent the heritage walls. Results showed the low intrinsic mechanical strength and behavior of these walls and its constituting main building materials, which requires strengthening. The paper proved the great advance of applying injection with nanolime mortar than reinforcement of bed-joints to enhance structural behavior and strength.

KEYWORDS: Loadbearing walls-Masonry prisms-Compressivestrength - Strengthening -Reinforcement - Nanolime.

1. INTRODUCTION
Jeddah, the port of the two holy cities, the gateway to the city of Makkah and main seaport of contemporary Saudi Arabia [1], is located at 21°29' north and 39°12' east on the Tihama coastal plain of the Red Sea in the Western Region of Saudi Arabia [2]. Its historic core, known as al-Balad district or historic Jeddah is the historic quarter of the city that has been preserved since the city was established in 646 AD, which has been listed on the world heritage list as world heritage site at UNESCO. The historical values of old Jeddah date back to 250 BC[1].

Heritage buildings in historic Jeddah have been used primarily as the gravity load bearing buildings to resist compression. So that the stone loadbearing masonry walls are designed mainlyto resist vertical loads.Initially the levels of stress were low and factors of safety against compression failure were high, over time the variousdeterioration forces and factors inflicted damage onit and reduced their bearing capacity. Since the main function of these load bearing walls is to carry the compressive loads, compressive strength is the most important property required in the evaluation of its structural behavior and mechanical strength.

In fact, most of the heritage buildings in historic Jeddah suffer from many structural deficiencies and deterioration aspects, this is because ithave been turned into neglected places for many years, exposed to all types of deterioration and encroachments, as well as encircled by new high buildings and have born too much stamp of wear and tear because of dearth of serious maintenance for centuries. Therefore, the load bearing walls in these buildings were vulnerable to the ambient aggressive environment, vertical and horizontal forces and internal damage force, in addition to the building materials which were used in the construction of these walls were marine origin stones (e.g. fossil iferouslimestone), locally called hajar Mangabi, it is weak, extremely porous and quite soft as a construction material,also a weak marine mud served as a cementing material to bind the stone blocks[2].For these reasons, it is necessary to evaluate some strengthening techniques of these walls.

Among the most used and investigated strengthening techniques are the bed joint reinforcement technique, this technique is a traditional retrofitting technique commonly used especially historic masonry structures [3].itis essentially intended to control the cracking phenomena, more than to improve the mechanical characteristics of the stone masonry walls. In fact, the main scope is to reduce the dilatancy of the load bearing wall in order to avoid the cracks propagation in the stones [4].It is particularly applicable to facing masonry having regular courses (e.g., coursed ashlar stone walls rather than rubble stone walls). It is based on the insertion of reinforcing materials in the mortar bed joints previously excavated for few centimeters and then refilled by a repointing material [5]. Several reinforcement materials (e.g., steelbars, FRP laminates or bars) and different types of mortars (e.g., hydraulic lime or cement based mortars, special polymeric mortars) can be used [4]. In the present study, stainless steel bars and polymeric mortars have been considered. The relevant results of an experimental campaign are presented and discussed.

In a structural intervention on heritagestone masonry walls, aspects such as the structural effectiveness, durability and compatibility must be taken in account, where the chosen intervention materials have an important role, in order to be observed certain requirements, fundamental for a good intervention, such as the mechanical, physical and chemical compatibility between the original and intervention materials[6, 7]. Accordingly, consolidation with nanolime for weak external leaves components is appropriate technique.It aims to reduce the weakness of their components and then improve their mechanical strength. Where nanolime is used mainly to recuperate the cohesion between particles in calcareous substrates such as limestone and lime mortar [8].In the present study, a combination of CalosilIP5 (which contains 5g nanolime per liter), E25 (25g per liter), andE50 (50g per liter),have been considered. The relevant results of an experimental campaign are presented and discussed.

2. TEST PROGRAM

2-1 Characterization of the stone masonry prisms components

2-1-1 Stone:

The stone used in the construction of the experimental masonry prisms is a locally available Mangabi stone (Fossiliferous limestone)was brought from ruins of one of the collapsed heritage building are not registered in historic Jeddah (where it used as unity in the external leaves masonry and as limestone scrabblings in the inner core), Based on a preliminary analytical study developed by the authors.

The compressive strength tests are usually conducted to determine the ability of a material to resist deformation under load. Similarly, density often relates to the strength, toughness and stiffness of masonry material. Likewise, apparent porosity and water absorption are characteristics of masonry materials that indeed paints a true picture of moisture movement and storage which play a key role in the durability of building [9]. The Compressive strength of this stone was performed in three cubic specimens of dimensions 50×50×50mm, tested under uniaxial compressive loading according to ASTM C170[10], where the following average values were obtained; compressive strength of 7.3 N/mm^2.It was found that the mangabistone used for constructing the masonry prismsis weak stone, crack and crushing at failure.

The apparent Porosity of this stone was determined to be with an average value of 29.4%, its water absorption property was determined to be with an average value of 19.7%and itsbulk density was carried out according to ASTM C97[11], to be with an average value of 1.48 kg/cm^3. Such density is very low if compared with that of other types of stones which usually higher than 1.9 kg/cm^3, indicating that this stone is highly porous, non-homogenous and consequently weak. But the reason for such a common use despite its low strength properties and high porosity is the fact that mangabi stone is a locally available, lightweight, easy to process and has good isolation properties.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

2-1-2Mortar:

Mortar is a mixture with water of a binder such as lime and some inert material such as sand in the form of smooth paste. Mortars play important role of binding masonry units together into one mass[12]. For a reliable experimental simulation of the structural behaviour of archaeological masonry components, the selection of an appropriate mortar is a key issue in the sense that of archaeological mortars and binders were completely different from the ones used nowadays[13]. Aiming at obtaining a low compressive strength traditional lime mortar and representative of existing authentic lime mortars in stone load bearing walls at heritage building in historic Jeddah, a pozzolana-lime based mortar was used to build the stone masonry prisms, which was made from slaked lime (lime putty) combined with local desert sand and red brick dust. Based on the results of a preliminary composition study developed by the authors, a binder/sand/ pozzolana ratio equal to 1.5: 3: 0.5, and a water/binder ratio equal to 0.8 were selected for the compositions of the mortar (all ratios in weight), a pozzolana was used to improve the construction procedure of the prisms. The mechanical behavior of mortar was assessed using cubic specimens of 50×50×50 mm were sampled during the construction of the prisms and tested under uniaxial compressive loading according toASTM C97at the age of 90 days (the same age of testing the prisms). The cure conditions of these cubic specimens were the same of the constructed prisms. The average compressive strengths computed for the aforementioned age were 1.1 N/mm^2, the value was obtained considering the average of three specimens.

2-2 Masonry prisms construction

A series of single-leaf ashlar stone masonry prisms were constructed to represent the external leaves of the multiple-leaf stone loadbearing walls to be tested under the impact of vertical uniaxial compressive loads, to study the compressive strength and the structural behavior of the outer leaves of the these walls under the impact of these vertical loads and the effect of some strengthening methods on their resistance for these loads; such as:

a- Bed joint reinforcement (Structural repointing with stainless steel bars).

b- Consolidation with Nano lime (calcium hydroxide nanoparticles).

The geometry and dimensions of the prisms were chosen and determined according to the recommendations described in the (ASTM C1314-10) [14], which recommended that, masonry prisms used for compression testing be at least two blocks high whilst having a height to thickness ratio between 1.3 and 5.0, and correction factors are provided inthis specification according to the sample height to thickness (hp/tp) ratio to account for the influence of varying sample dimensions.

Based on the recommendations described in the ASTM C1314-10, the stone masonry prisms were constructed using stone blocks brought from ruins of one of the collapsed heritage building are not registered in historic Jeddah, which were cut and dressed with the required dimensions, wherea geometrical scale factor of 1/4 was applied to the typical dimensions observed in the loadbearing walls of the historic buildings in Jeddah. A four-block high stone masonry prism was prepared using stone units of 10 x 6.25 x 6.25 cm^3. The prisms were built carefully in order to simulate as much as possible the external leaves, where the prisms were cast by laying stone units one on top of the other with a mortar bed between the masonry units(see Fig. 2),a mortar joint thickness of 1 cm. As shown in Figures (1 and 3)a total of nine prisms with dimensions of 10×6.25×28 cm^3 (height/width ratio of 4.48) were built and tested under uniaxial compressive loading and at a displacement control rate of 10 μm/s.

All prisms were prepared and left for mortar maturation until they were tested after approximately90 days of curing.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

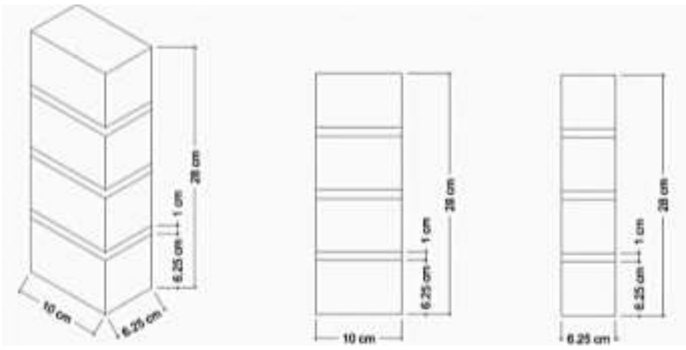


***Figure. 1: Typical geometry of the tested stone masonry prisms*.**

(a) ***(b)*** ***(c)***

Figure. 2: Duringthe stone masonry prisms construction.

Figure. 3: The tested stone masonry prisms.

2-3 Masonry prisms strengthening

2-3-1 Bed joints reinforcement:

The main procedures of the bed joints reinforcement technique for three stone masonry prisms were carried out as follows:

- Cutting of the bed mortar joints between stone units by using suitable metallic tools; the recesses are 1 cm high and 1.5 cm deep(see Fig. 6a and b);
- Removing the dust resulted from the cutting with compressed air and hair brush,Then cleaning the grooves with a solution of acetone and alcohol 1:1 ratio in order to keep the grooves of the joints dry to receive the polymeric mortar used to fix the reinforcement bars (the grooves should be kept dry in the case of use of polymeric mortar).
- Placing of a first layer of the polymeric mortar or polymer based-mortar (Araldite Aw1306, Hardener HV 1306mixed with sand), which was accurately compacted(see Fig. 6c), then Placing of the threaded stainless steel reinforced bars number 306 (Ø5 mm)(see Fig. 6d), then a second layer of the polymeric mortar has been applied over the stainless steel bar to cover it completely(see Fig. 6e);.
- Placing a final layer of improved lime mortar (which was used in the construction ofstone masonry prisms) in the last available area of the grooves to seal the horizontal joints and for a good appearance and homogeneity for stone masonry prisms(see Fig. 6f).

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

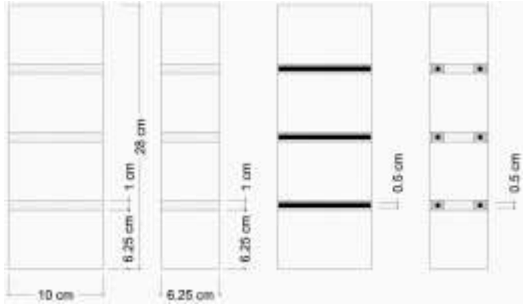


Figure. 4: Geometrical characteristics of the masonry prisms and reinforcement layout.

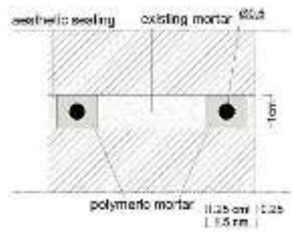
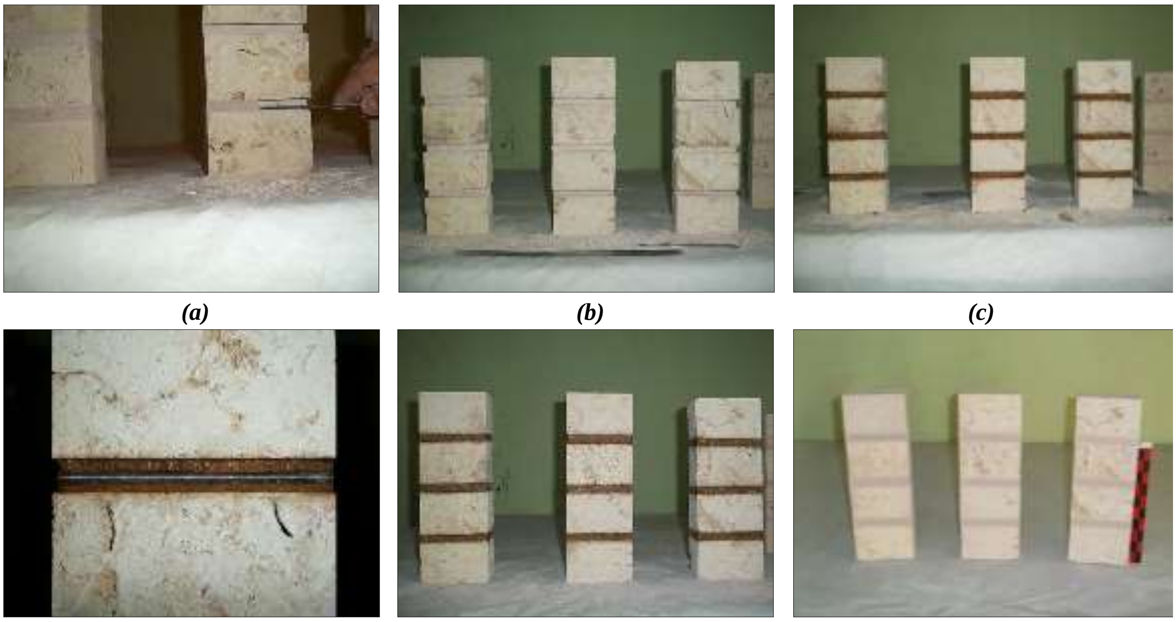


Figure. 5: Details of the reinforced mortar joints after repointing by resin.



(a) ***(b)*** ***(c)***

(d) ***(e)*** ***(f)***

Figure. 6: Implementation phases of the bed joints reinforcement process.

2-3-2 Strengthening with Nano lime:

Three stone masonry prisms were consolidated and strengthened with Calcium hydroxide nanoparticles (a combination of Calosil-IP-5, Calosil-E-25andCalosil-E-50) as showed in (Fig. 7-A, B and C)as follows:

- The entire surfaces of the stone masonry prisms were cleaned with a soft hair brush and air pump to remove any dust or other disintegrated material. After that, these surfaces were washed witha solution of ethyl alcohol and water 2:1 ratio to clean and disinfect their pores.
- The stone masonry prisms were treated with a combination of calosil E5 (which contains 5g nanolime per litre) and E25 (25g per litre), the rationale being that the E5 will give greater penetration to start with, followed by the E25 to deliver maximum amounts of nanolime to the structure of prisms. The calosil was applied with a soft hair brush; six applications of E5 followed by three of E25 over a three-day period, In addition to the injection withcalosilE50(50g per litre)by medical syringesfor holes, cracks and cavities (fossils traces) found in stone units during applications. The prisms were covered with polyethylene bags between applications to prevent premature evaporation of the iso-propanol andethanol and so promote maximum penetration. A layer of water-wet gauze cloth has been placed on the treated surface, because the calcium hydroxide requires both air and water forcarbonization. The prisms were left until the completion of the carbonization process.

(a) (b) (c)

Figure. 7: Strengthening with Nano lime, (a): before Strengthening, (b): during Strengthening, (c): after strengthening.

2-4 Masonry prisms test procedure and test setup

It is worth to mention that, the prisms were confined. In addition, each prism was protected on all sides with gauze cloth, thick packaging foam(20 mm) and sponge (10 mm), placed in sturdycrates, and the crates completely filled with packing material to ensure the prisms cannot move within the crate during transport.

Prior to testing, all loading surfaces of the stone masonry prisms were scraped and leveled to ensure a smooth contact area. The specimens were placed on the lower platen of the 500 kN capacity Shimadzu testing machine as shown in Figures (8 and 9), Both centroidal axes of the specimen were aligned with the center of thrust of the machine. A uniform load of 8,000 N/min was applied to all specimens until the failure of the specimen. Testing was stopped when an irreversible load drop of more than 50% of the maximum load was observed. The load and displacement data were recorded through a built-in data acquisition system in Shimadzu.

Figure. 8: 500 kNShimadzu testing machine.

(a) (b) (c)

Figure. 9: position of the masonry prisms inside testing machine.

3. MASONRY PRISMS TESTS RESULTS AND DISCUSSION

The mean compressive strength for all masonry prisms was calculated by dividing each prism's maximum failure load by cross sectional area of that prism. Then, the value of the compressive strength obtained for each prism was multiplied by the corresponding correction factor for that prism (1.22), which was determined based on a prism's height to thickness ratio h_p/t_p in accordance with the recommendations set forth in ASTM C1314-10, where the correction factor provided in this specification are based on ratio of prism height to least lateral dimension of prism$h_p/t_p$to calculate the effect of the variation in the dimensions of the sample. The modulus of elasticity *E*, computed between 30% and 60% of the prism's compressive strength.

3-1 Plain masonry prisms:

The compressive strength test results of the three unstrengthened stone masonry prisms are tabulated in Table 1.From these results, it was found that the strength of masonry prisms is weak and less than the strength of the stone masonry units, while much more than the mortar strength (Fig. 10),Where the average compressive

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

strength of the masonry prisms was 4.7 N/mm^2, while the average compressive strength for the masonry units was 7.3 N /mm^{2}and the average compressive strength of the construction lime mortar was 1,1 N /mm^2.

A reduction of 55% was observed when shifting from stone specimens to stone masonry prisms, where it has been established that the compressive strength of the masonry assemblage differs from the compressive strength of individual components of the prism. Typical compressive strength of masonry units is relatively high but the compressive strength of mortar is low. The resulted prism strength is found to be somewhere in between[15]. This is attributed to the effect of the combined behavior of both stoneunits and mortar with different strains and modulus of elasticity as well as the effect of the properties and thickness of the mortar, the dimensions and construction method of the masonry prisms.

Table 1. Summary of results of the unstrengthened masonry prisms.

Prism ID	Average Measured Dimensions (mm)			Ultimate Load (N)	Mean Compressive Strength (N/mm2)	*Modulus of Elasticity E* (N/mm2)	Modified Compressive Strength (N/mm2)
S1	100	61	286	25.6	4.2	1280	5.12
S2	100	61	285	16.6	2.7	1682	3.29
S3	100	62	285	29. 5	4.8	1048	5.85
Average compressive strength (N/mm2) (after applying correction factor : 1.22)							4.75

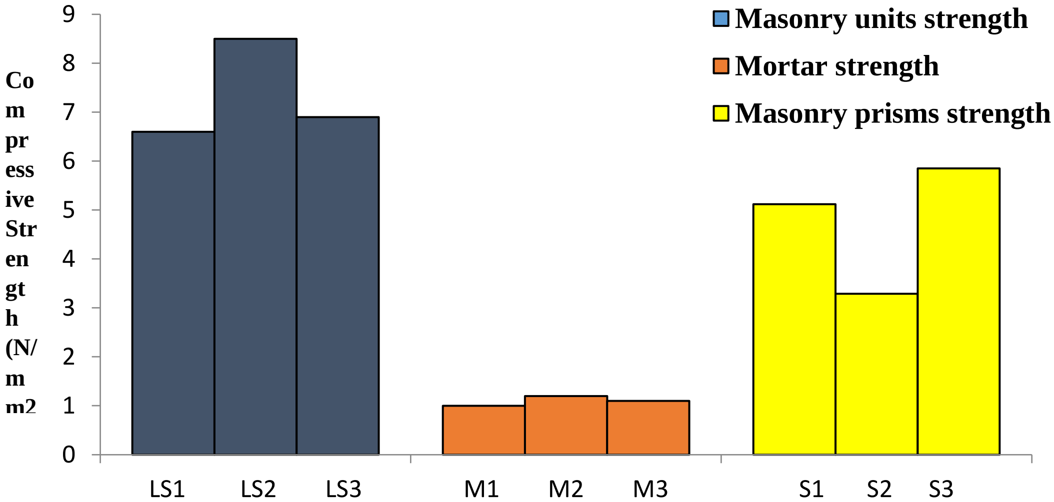


Figure. 10: The compressive Strength of masonry prisms and their individual components.

Through the investigation of load-displacement curves of the unstrengthened stone masonry prisms (Fig. 11)their structural behavior was determined under the impact of vertical uniaxial compressive loads. The prisms exhibited a ductile failure after reaching the maximum stress value; this was shown in the form of load-displacement curves; where noticed a large elongation and horizontal extension of the descending portion of the load-displacement curves, also noticed that the deformation didn't change linearly.At the beginning of loading where low stress levels, the curves partially influenced by initial confinement of the masonry prism that occurs at the bed joints due to the compaction of the stone units at the mortar bed joints; where the mortar was pressed and its thickness reduced gradually. After the full contact of the bed joints for higher level of compressive strength, the compressive behavior of the masonry prisms is dependent on the composite behavior of the stone units and mortar joints. Up to the values of compressive strength corresponding to the peak strength, all prisms exhibit reasonable linear behavior as a result of the composite performance of the units and mortar due to the bonded interface. After the peak stress is reached which exceeds the cohesion strength between units and mortar, a considerable elongation of the descending portion of the curves is noticed in all prisms.

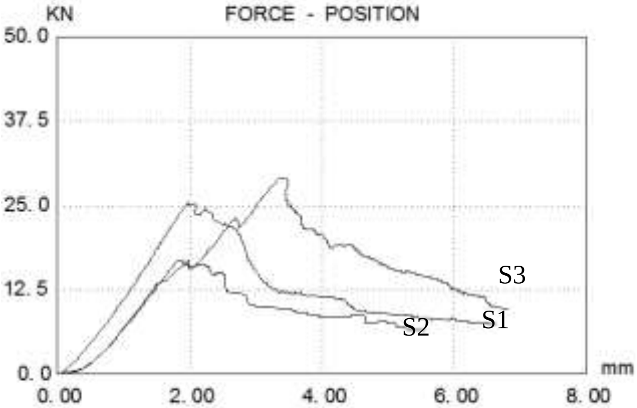


Figure. 11: load - displacment curves of the unstrengthened masonry prisms.

With regard to the failure mechanism and mode of unstrengthened stone masonry prisms, at the beginning of loadingit was noticed that the horizontal separation cracks began to appear atthe interface between units and mortar in upper and lower bed joints simultaneo us with cracking of stone units. As the compressive strength increases up to reach to ultimate strength, vertical cracks propagated through boss stone units and mortar along the entire surface of prisms. Apparently, the mortar is confined laterally by the stone units. Because of this reason, shear stresses develop at the mortar-stone interface that causes triaxial compression in the mortar and bilateral tension couple with uniaxial compression in the stone units which have a triaxial behavior as a result of being subjected to compression- tension-tension, that caused crack initiation in the stone units and eventually failure.

Fig. 12showsthe typical failure patterns of unstrengthened stone masonry prisms. There is a vertical cracking of stone unitsas well as bond failure at the interface of stoneunits and mortar (horizontal separation cracks).Cracking of the stoneunits and thebond failure were practically simultaneous. It has been observed that all stoneunitsof the prism was getting crack, and both upper and lower joints atthe prism were failing in bond for all cases.


(a)

(b)

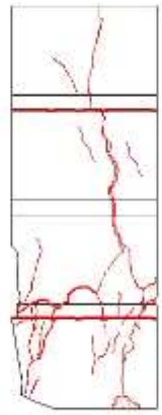

(c)

Figure. 12: Shows the typical failure mode of the unstrengthened masonry prisms, (a): during failure, (b): failure mode, (c): a sketch for failure patterns (vertical cracking and bond failure).

3-2 Masonry prisms strengthened with Nanolime:

The compressive strength test results of the three strengthened stone masonry prisms with nanolimeare tabulated in Table 2.From these results, it was found that the strengthening of masonry prisms with nanolime resulted in an increase of its strength to vertical uniaxial compressive loads, that resulted from strengthened its weak calcareous components and improved their mechanical strength. This was shown in the increase of the ultimate

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

load value of the prisms. Where the average compressive strength of strengthened stone masonry prisms strengthened with nanolime was 7.27 N/mm^2.Itrecorded an increase in compressive strengthby53% from unstrengthened masonry prisms.

Table 2. Summary of results of the strengthened masonry prisms with nanolime

PrismI D	Average Measured Dimensions (mm)			Ultimate Load (N)	Mean Compressive Strength (N/mm2)	*Modulus of Elasticity E* (N/mm2)	Modified Compressive Strength (N/mm2)
C1	100	63	286	44	7.0	2480	8.54
C2	100	63	285	28.4	4.5	1974	5.49
C3	100	62	285	40. 05	6.4	2688	7.80
Average compressive strength (N/mm2) (after applying correction factor : 1.22)							7.27

Through the investigation of load-displacement curves of the strengthened stone masonry prisms with nanolime (Fig. 13). A change in the behavior of strengthened prisms has revealed from the behavior of unstrengthened prisms, where strengthened prisms have lost their ductility and the failure mechanism has been transformed from ductile failure to brittle failure. This has been shown in the form of load-displacement curves; Where was noticed a decline in the elongation of the descending portion of the load- displacement curves significantly and It became a slope and did not extend horizontally for a large distance. The high strength prisms showed brittle failure after reaching maximum stress value during the test, as the stone units rapidly exhausted their fracture energy due to tensile stresses.

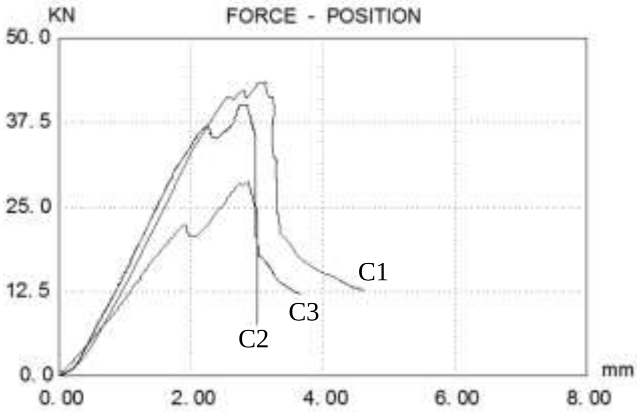


Figure. 13: load - displacment curves of the masonry prisms strengthened with nanolime.

The investigation of failure mechanism of strengthened prisms with nanolime revealed that the typical failure pattern was a shear break (a semi-conical break and diagonal shear cracks) on each side of the prism as well as crashing and spalling in the upper mortar joint and parts of the adjacent stone units due to the occurrence of the bond failure between them at ultimate compressive stress, as shown in Fig. 14.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

(b) *(c)*

Figure. 14: shows the typical failure mode of the strengthened masonry prisms with nanolime, (a): during failure, (b): failure mode, (c): a sketch forfailure patterns (semi-conical break, diagonal shear crack and spalling).

3-3Masonry prisms strengthened with Bed joints reinforcement:

The compressive strength test results of the three strengthened stone masonry prisms with bed joints reinforcement are tabulated in Table 3.From these results, it was found that the strengthening of masonry prisms with bed joints reinforcement has increased somewhat their mechanical strength. This was shown in the increase of the ultimate load value of the prisms. Where the average compressive strength of strengthened stone masonry prisms strengthened with bed joints reinforcement was 5.77 N/mm^2. It recorded an increase in compressive strength by 21.47% fromun strengthened masonry prisms.

Table 3. Summary of results of the strengthened masonry prisms with nanolime

PrismID	Average Measured Dimensions (mm)			Ultimate Load (N)	Mean Compressive Strength (N/mm2)	*Modulus of Elasticity E* (N/mm2)	Modified Compressive Strength (N/mm2)
R1	100	62	285	31.8	5.1	1344	6.22
R2	100	63	285	22.3	3.5	1953	4.27
Rs3	100	64	285	35. 4	5.6	1927	6.83
Average compressive strength (N/mm2) (after applying correction factor : 1.22)							5.77

It has been observed through the investigation of load-displacement curves of the strengthened stone masonry prisms with bed joints reinforcement (Fig. 15) that the reinforcement of masonry prisms with stainless steel bars embedded in the bed joints groves did not significantly change the behavior of prisms, where the behavior and shape of the load-displacement curves of the reinforced prisms were somewhat similar to the shape of curves of the unstrengthened masonry prisms but with a higher failure load than them. These reinforced prisms also kept their ductility and showed a ductile failure after reaching the maximum break stress value.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

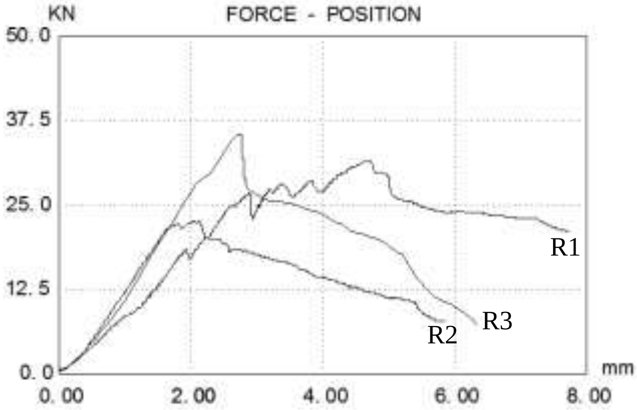


Figure. 15: load - displacment curves of the prisms strengthened with bed joints reinforcement.

The investigation of failure mechanism of strengthened prisms with bed joints reinforcement revealed that the reinforcement process has improved the bond strength between the stone units and mortar joints, thus enhanced the strength of these prisms;as the strength of stone masonry mainly depends on the strength of bonding between the stone units and the Interface between the mortar and stone plays a vital role in enhancing the strength of these masonry [16]. It also prevented the occurrence of the mechanisms and patterns of failure that were observed in the unstrengthened prisms and strengthened with nanolime such as: bond failure and a shear break (a semi-conical break and diagonal shear cracks).In addition to the absence of any vertical cracks on the front and back faces of these reinforced prisms. his is attributed to the reinforcement has worked to resist the generated tensile and shear stresses, the cohesion between stone units and mortar played an important role in the ability of reinforced prisms to resist these stresses. Thus, the reinforcement process made the masonry prisms work as a homogenous unit to resist compressive loads.

As shown in Fig. 16. the typical failure pattern of the reinforced prisms is the crushing failure of one a weak stone units on both front and back faces of the prism, as well as a small vertical crack on both sides of the prism, that extends in the stone units and through the mortar area which is located between the reinforced polymeric mortar zonesbecause it represents a weakness area between them.

(a) *(b)* *(c)*

Figure. 16: shows the typical failure mode of the strengthened masonry prisms with bed joints reinforcement, (a): during failure, (b): failure mode, (c): a sketch for failure pattern (crushing).

4. CONCLUDING REMARKS

With regard to the stone masonry units Characteristics, it was found that the stones used for constructing the masonry prisms are weak stones, highly porous, non-homogenous, crack and crushing at failure.

The results of compressive strength tests on unstrengthened stone masonry prisms showed that these prisms have low mechanical strength. As these prisms exhibited bond failure and vertical cracking at failure.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

All the strengthening techniques tested on stone masonry prisms exhibited a compressive strength increase. The technique that allowed the higher improvement and the great advance was the strengthening with nanolime, with an improvement of 53%, then the bed joints reinforcement technique with 21.47% increase of compressive strength.

The strengthening of masonry prisms with nanolime has led to the strengthening of their weak calcareous components, consequently, led to increasing their resistance to the vertical uniaxial compressive loads. As a result, this technique will play an effective role in strengthening the external layers of the load bearing walls at heritage buildings in historic Jeddah, thus this techniques presented as a proposal to strengthen these layers to increase their mechanical strength and improve their structural efficiency.

The bed joints reinforcement technique resulted in an enhancing the bond strength between the stone units and mortar substantially, that resulted from the reinforced bars endured the tensile stresses otherwise directed to the stone units, thus made the masonry prisms work as a homogenous unit to resist compressive loads, it also prevented the occurrence of cracks in the front and back faces of the masonry prisms. Accordingly, this technique is presented as a proposal to treat the structural cracks (vertical, diagonal and horizontal) in the load bearing walls at the heritage buildings in historic Jeddah, as this technique control of these cracks and directly limits its development, thus improves the performance and achieves the structural integrity of these walls.

REFERENCES

[1] Bagader, M., "The Old City of Jeddah: from a Walled City to a Heritage Site", WIT Transactions on the Built Environment, Vol 143, pp. 365, 2014.
[2] Al-lyaly, S. M., "The Traditional House of Jeddah: a Study of the Interaction between Climate Form and Living Patterns", Ph.D. thesis, Department of Architecture, University of Edinburgh, p. 46. 1990.
[3] Murat, M. M. and Kılınç, H. Ç., "Comparison on Repair and Strengthening Techniques for Unreinforced Masonry Structures", Journal of Engineering Research and Application Vol. 6, Issue 11, p. 2, 2016.
[4] Valluzzi, M. R., *et al.*, "Mechanical Behaviour of Historic Masonry Structures Strengthened by Bed Joints Structural Repointing", Construction and Building Materials 19, Elsevier Ltd, pp. 64-66, 2005.
[5] Kaya,S. M.,"Inventory of Repair and Strengthening Methods with Iron and Steel",MSc Dissertation,Technical University, Catalonia, p. 79, 2009.
[6] Silva , R. A., *et al.*, "Three-leaf Stone Masonry Repair and Strengthening",TOPIC 3 – Repair procedures,p.1. 2007.
[7] Binda,L.,"The Difficult Choice of Materials used for the Repair of Brick and Stone Masonry Walls",1st International Conference on Restoration of Heritage Masonry Structures, Cairo, Egypt, CD-ROM, 2006.
[8] Otero, *et al.*, "An Overview of Nanolime as a Consolidation Method for Calcareous Substrates", Ge-conservación, 1 (11), p. 3, 2017.
[9] Lucian, C., "Engineering Properties of Building Materials inHistoric Buildings in Bagamoyo (Tanzania)", International Journal of Engineering and Innovative Technology (IJEIT),Volume 3, Issue 9,p. 15, 2014.
[10] ASTM C170 1990. Compressive Strength of NaturalBuilding Stone.
[11] ASTM C97 1990. Absorption and Bulk Specific Gravity ofNatural Building Stone
[12] Joshi, D. A. and Jain, R. K., "Evaluation of Compressive Strength and Basic Compressive Stress of Clay Brick Unreinforced Masonry by Prism Test", International Journal of Science and Research (IJSR), p. 914, 2013.
[13] Oliveira, D. V. andLourenço, P. B.,"Experimental Behaviour of Three-Leaf Stone Masonry Walls",Conference and Brokerage Event, The Construction Aspects of Built Heritage Protection, Dubrovnik, Croatia, p. 357, 2006.
[14] ASTM C1314– 10,"Standard Test Method for Compressive Strength of Masonry Prisms",ASTM Standard, USA.
[15] Kaaki,T.,"Behavior and Strength of Masonry Prisms Loaded inCompression",MSc Dissertation,Dalhousie University,Halifax, Nova Scotia, p. 5, 2013.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

[16] Nagarajan, T.,*et al*.,"Experimental Approach to Investigate theBehaviour of Brick Masonry for Different Mortar Ratios", International Conference on Advances in Engineering and Technology March 29-30, p. 586, 2014.

CITE AN ARTICLE

Mahmoud, H. S., Abdel–Aty, Y. Y., Kuligin, V., & Al-Zahrani, A. A. (2019). EVALUATION OF STRUCTURAL BEHAVIOR AND MECHANICAL STRENGTH OF MULTIPLE-LEAF MASONRY WALLS AT JEDDAH'S HERITAGE BUILDINGS UNDER UNIAXIAL COMPRESSION LOADS AND THEIR APPROPRIATE STRENGTHENING TECHNIQUES. *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY*, *8*(2), 150-162.