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EXPERIMENTAL STUDY OF SOME MASONRY-WALL COURSEWORK MATERIAL TYPES UNDER HORIZONTAL LOADS AND THEIR COMPARISON

EKSPERIMENTALNA RAZISKAVA ZGRADBE NEKATERIH ZIDARSKIH ZIDOV – VODORAVNA OBREMENITEV IN PRIMERJAVA UPORABLJENIH MATERIALOV

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In this study, the collapsing loads and shear stress of wall samples made of full blend bricks have been examined under horizontal loads within their planes using various bricking types and the results have been compared. To this end, samples were produced using the plain-bricking, lock-bricking and cross-bricking methods. In the performed experimental study, the standard sliding-resistance test technique for the masonry-wall samples was used as recommended in ASTM 1391-81.The behaviours observed with the experimental samples and the cracks that occurred at the end of the experiment were examined and the τ (shear stress) graphs and the horizontal load-displacement graphs were drawn and compared with the experiment results obtained with numerical modelling using the ANSYS program. When these three bricking types were compared, the biggest collapse load occurred for the cross bricking with 240 kN. The biggest shear stress was also found in the cross bricking, with a value of 55 000 kN/mm^2.

Keywords: materials, full blend brick, experimental, lateral load performance, shear stress

Raziskani sta bili rušilna obremenitev in strižna obremenitev zidov iz žgane opeke pri vodoravni obremenitvi v ravnini postavitve opek in primerjani so rezultati. Uporabljeni so vzorci, izdelani z enostavno, krožno in zaprto postavitvijo opek. Uporabljen je preizkus standardne drsne upornosti vzorcev zidov, priporočen v ASTM 1391-81. Vedenje vzorcev in razpoke, nastale na koncu preizkusa, in odvisnosti strižna napetost (τ) ter vodoravna obremenitev – premik so bile določene in rezultati primerjani z rezultati numeričnega modeliranja z uporabo programa ANSYS. Pri primerjavi treh vrst razporeditve opek je bila največja rušilna obremenitev 240 kN pri križni postavitvi. Pri tej postavitvi opeke je bila izmerjena tudi največja strižna sila 55 000 kN/mm^2.

Ključne besede: materiali, žgana opeka, preizkusi, bočna trdnost, strižna napetost

1 INTRODUCTION

Human beings have constructed buildings, bridges, and canals in order to maintain their lives using the existing possibilities and the technology of the day since the earliest times. The oldest building types in the history of humanity are the masonry buildings which are still being used today. Although reinforced concrete and steel constructions are the most common building types of today, masonry buildings are still being constructed in various countries of the world [1].

Especially in rural areas, people prefer masonry buildings for economic reasons, they are easy to construct from the local materials and they can construct buildings in places that are difficult to get at because of geographic conditions. These buildings which are constructed without complying with the existing regulations, getting engineering services and made of heavy and rusty materials are rather weak with respect to horizontal loads [2].

The carrier walls of a masonry building exposed to horizontal loads have two deficiencies. The first one is their failure that is not planar and the cracks are seen here all along the bed joint lines. The second one is planar failure and generally characterized by a diagonal shrinking crack. If the failure which is not planar can be avoided, then the structural resistance is radically affected by the planar behaviour of the cut wall [3].

The vertical carrier elements of masonry buildings are the walls. The horizontal loads may affect these vertical carrier walls due to earthquake, storm, or other reasons besides the vertical loads. In the case that the vertical and horizontal loads have an affect together, a two-axis loading condition occurs on the walls. It is of significant importance to know the behaviour of the wall, which is a composite material under two-axis resistance in terms of providing the loads overlaid on the building to carry securely [2].

The buildings should have the capacity of flexing and absorbing energy when they are exposed to an earthquake impact. This is related to the ductility of the building. As masonry buildings are rigid and friable, they have no capacity of flexing and absorbing energy like flexible buildings. Eventually, they are exposed to major horizontal forces as their capacity to decrease the energy exposed during the earthquake is low. Furthermore, they demonstrate unwanted behaviours in term of engineering due to the fact that the materials used with masonry buildings are friable and cause sudden cracks and breaks when they go beyond their loading limits. Because of these reasons, masonry buildings cannot be considered as buildings that are resistant to an earthquake. Nevertheless, masonry buildings should not be completely perceived as negative buildings in terms of an earthquake. Just like all other buildings, masonry buildings can be strong and secure provided that they are built in compliance with the standards, regulations and engineering studies are applied. Masonry houses such as earthen, brick and stone structures are composed of building blocks with weak inter-binding action which have low tension capacity [19].

Before starting the improvement and strengthening activities for a masonry building, the earthquake behaviour of the masonry building exposed to an earthquake and their collapsing mechanism should be well known. The earthquake behaviours of masonry building are diverse although they have similarities in comparison with reinforced concrete buildings. It can be said that the most impressive difference is the break of the masonry wall in the out of plane direction. The cutting forces and moments are constituted with masonry walls under horizontal loads. Therewith, the in-plane break of the masonry wall occurs by axial pressure/tensile forces formed by the moment and/or the slant inert tension effects the created moment [2].

Several studies have been carried out related to the behaviours of masonry buildings. A multi-surface plastic has been used so as to define the pressure, cut and resisting behaviours of the filling plaster using an interesting approach developed by Laurence [6,7] and modelled by an interface element. Gamboratta and coworkers have generated a model evaluating the constructive parity of the interface in terms of two internal variables representing the friction surface and the filling plaster damage using a similar approach [5]. This model has been broken under the stretching resistance and shown a decreasing hardness and friction distribution. This feature is used with the definition of hysteretic planar behaviours of masonry building walls. These that have experienced earthquakes have damaged constructions significantly and caused the deaths of thousands of people [20].

The above-mentioned numerical procedures are quite effective and take many facts which are seen with the behaviours of masonry building. However, their application is figuratively very difficult. In addition to these, a few more simple methods are available. For instance, the homogenization application or anisotropy elasto-plastic foundation equalities [3], which are some of the approaches [4,8] based upon the crack modelling of masonry buildings, are much simpler methods.

The horizontal loads occurring during earthquakes reveal strong planar and non-planar forces on these walls. The behaviour and the damages to these constructions under seismic forces are relatively big [7]. The walls in the direction of the shearing force have a big role in increasing the seismic force durability [15]. The majority of the existing buildings in this region have not been designed to withstand earthquakes. Most of them are typically unreinforced masonry, low-rise buildings and have been exiguously designed [16]. They showed poor performance during earthquakes and most of the damage and casualties resulted from these structures. However, in terms of earthquake engineering, significant lessons were learned from the surveys of damaged masonry buildings after earthquakes [17]. Damage and losses arising from landslides can include cracks in the masonry, damage to the electricity and water supply, subsidence or at worst the complete collapse of buildings [18].

Masonry building constructions constitute a significant part of the construction inheritance in the world. Actually, the structural walls of these buildings have been designed so as to resist the force of gravity. The horizontal loads incurred by earthquakes reveal strong planar and non-planar forces with these walls. The damage that occurs in these buildings under seismic forces are relatively big [2]. **Figure 1** shows some pictures of masonry buildings that were damaged after the Sultandagi-Cay Earthquake, 2002.

The masonry buildings are built with different rows and bricking forms positioning the bricks end-to-end and side by side in a net way. In this study, the lock bricking, cross bricking and plain bricking, which are some of the most commonly used bricking types in the world, are compared. The plain bricking is formed by plain rows which are piled over and over. The second row is started with a half brick and the vertical sutures are ensured not to match up with each other (**Figure 2**).

The lock bricking is formed by placing the rows over each other by sliding a quarter brick. In order to provide a quarter-brick sliding, the second row is completed flatways and two pieces of three quarter brick are

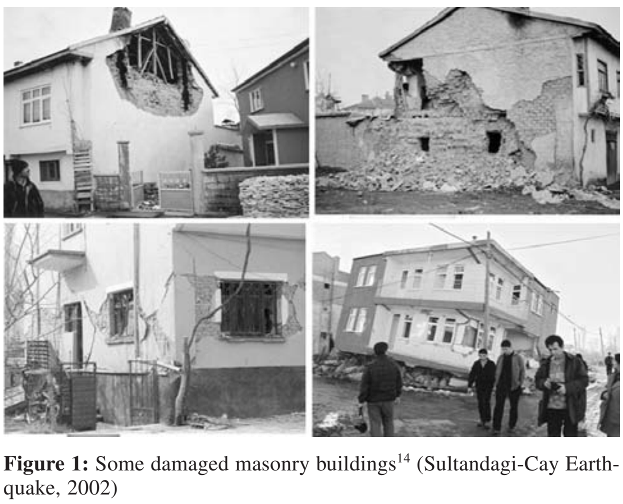

Figure 1: Some damaged masonry buildings[14] (Sultandagi-Cay Earthquake, 2002)

Slika 1: Nekaj zgradb, poškodovanih v potresu Sultanagi-Cayju, 2002 [14]

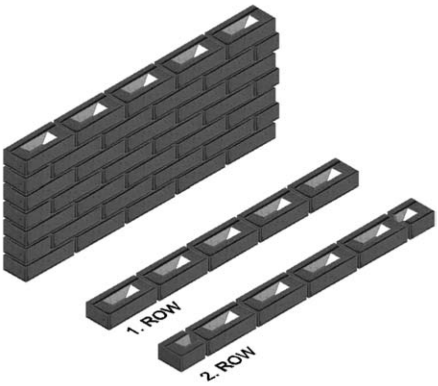

Figure 2: Plain Knitting
Slika 2: Enostavna postavitev opek

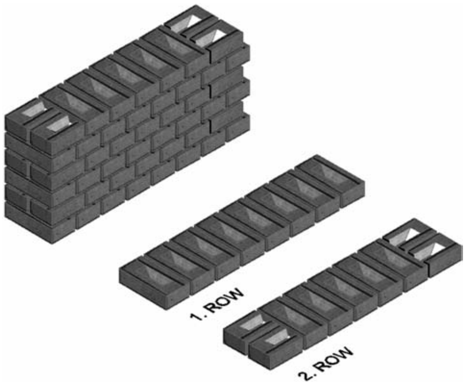

Figure 3: Lock Knitting
Slika 3: Zaporna razporeditev opek

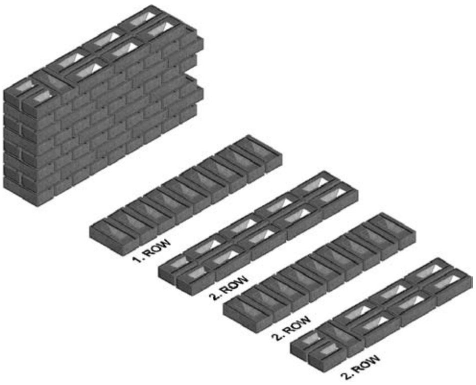

Figure 4: Cross Knitting
Slika 4: Križna postavitev opek

positioned flatways at the end. It is used to brick the plain and curved walls with a one brick thickness (**Figure 3**).

The cross bricking is made using lock and plain rows. The vertical sutures of the plain rows are skidded by half a brick from the vertical sutures of the plain row right under. Hence, the cross images are displayed on the surface of the wall (**Figure 4**). It is used for bricking in one-brick thickness or more thickness walls [5].

In this study a simple numerical modelling is recommended with an experimental approach in order to research the shear behaviours of the horizontal loads of walls made of full blend bricks within their planes. The wall samples prepared for this purpose were tested to see how they are forced to collapse and the shear stress of the wall samples in the non-linear zones and the change of the shear rigid of the wall sections were determined. The numerical modelling was performed using the ANSYS program with the finite elements taking into account the local mechanics parameters of the brick and plaster. The results that were obtained at the end of the modelling and the results obtained from the experiments were compared.

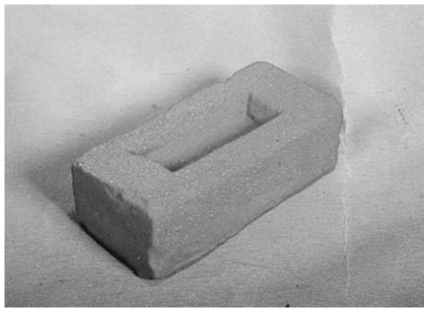

Figure 5: Full Blend Brick
Slika 5: Žgana opeka

2 THE FEATURES OF THE USED MATERIALS

2.1 The features of the full blend brick

Full blend bricks were used in the experiments (**Figure 5**). The average pressure resistance of the bricks is 12 MPa; the elasticity module is 3 000 MPa and the tensile strength is 0.9 MPa. While calculating the average pressure resistance, the gross area of the brick is the area where the pressure force affects and a very neat distribution is ensured, neglecting the pressure resistance values of the samples from the ones too high and too low.

2.2. Features of the plaster

The same type plasters whose volumetric composition rates have been used in the production of the wall samples were employed. The cement, sand, water volumetric composition rate of this plaster has been produced as 5 : 15 : 3 ratio. The calculated pressure resistance of the used plaster is 2.26 MPa and the tensile strength at bending is 1.64 MPa. The plaster thickness was 3 cm.

3 EXPERIMENTAL STUDY

3.1 Features and production of experimental samples

A total of 9 pieces of samples with 600 mm × 600 mm × 200 mm sizes have been produced, with 3 from each of the various bricking types. The vertical and horizontal suture thickness of the samples was about 10 mm. Although the calculation methods in the ASTM

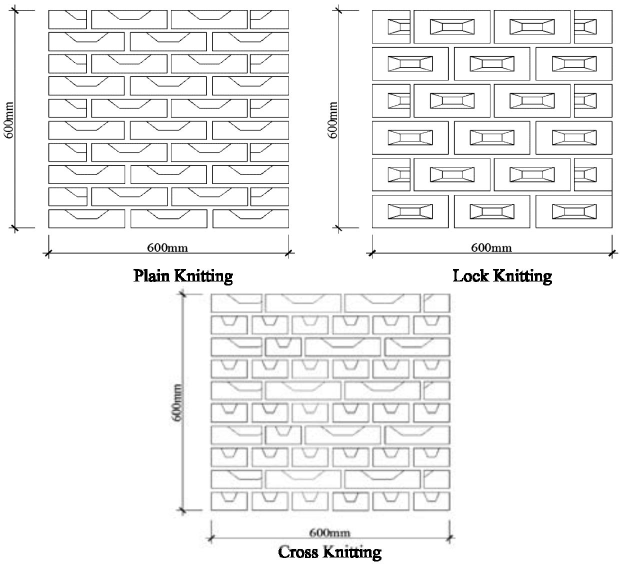

Figure 6: Bricking Types
Slika 6: Vrste križne postavitve opek

1391-81 are used [13], the sample size has been selected as 600 mm instead of 1200 mm, which is the sample size recommended in this standard taking into account the sizes of the bricks and the laboratory conditions (**Figure 6**).

All the samples were prepared in the laboratory under the same conditions. The full blend bricks were used in the formation of all the samples. The prepared plaster to brick the samples is also used in the same proportion. The wall samples were produced using the very first prepared plaster, according to the bricking rules (**Figure 7**). After completion of the wall bricking process, the plaster mortar was formed using the same composition rates and the facing process was started; after realizing the watering process for 7 days, they were left to dry for 3 days. The samples whose watering and drying process were completed have been made ready for the experiment by painting them using whitewash prepared in the laboratory.

3.2 Experimental technique and program

In this study, carried out for the purpose of finding the sliding resistance of the wall samples produced with full blend bricks using various bricking type, the force controlled experiment technique was used, trying to maintain the force increment rate. The displacements on the samples during the experiment were measured using ten units of Linear Variable Displacement Transducers. A vertical pressure force was applied to the wall samples whose horizontal sutures are positioned to make an angle of 45° by loading, and the breaking loads, breaking shapes, crack relieves and the displacement readings with the increasing load stages were recorded.

Figure 7: Production of the samples
Slika 7: Izdelava preizkušancev

3.3 Experiment setup and loading

Two pieces of steel heads were made to provide the samples to stand at 45° angle vertically. A surface made of plaster of Paris was prepared inside the lower head standing in its guide and the wall sample was positioned to the head in its plumb line (**Figure 8**). Also preparing the surface made of plaster of Paris in the upper head, the upper head was placed on the sample. Keeping the sample in its plane during the loading was ensured by the metal arms pulled up the front and back of the sample, as illustrated in **Figure 8**. In order to decrease the frictional effect between these metal arms and the sample, the slipperiness of it was increased, putting oil to the interfaces.

The vertical load on the experimental samples was applied by means of a 500 kN capacity manual hydraulic jack. A steel plate was placed on the steel upper head in order to adjust the level of the height and a hydraulic jack was placed right on it. The value of the applied load was measured using a 500 kN capacity load cell.

3.4 Collection of the experimental data and measuring system

The load measuring was carried out by using load cells and the displacements by LVDT displacement meters in all the experiments. The values that these devices read were instantly transferred to the computer by means of a data-logger system called CoDA and taken under records. All the values read from the

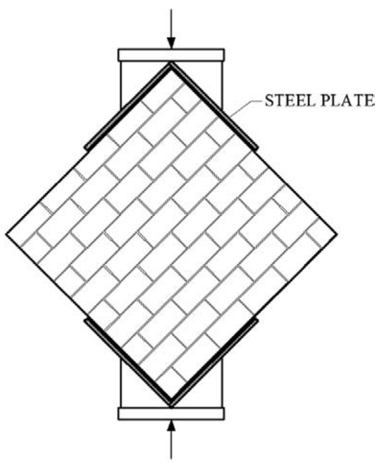

Figure 8: Loading form of the experimental samples
Slika 8: Način obremenitve preizkušancev

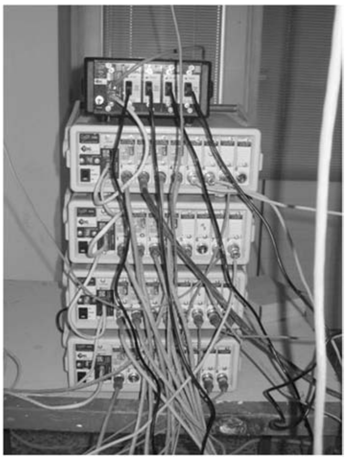

Figure 9: Data-collecting system
Slika 9: Sistem za zbiranje podatkov

channels are recorded to computers immediately and also all the readings taken from the requested channels can be monitored in graphics. All the print outs of the taken readings are in the form to be read by the "EXCEL" program. The data-collecting system used for the evaluation of the readings taken from the load cell and the LVDTs and the computer set up are shown in **Figure 9**.

The displacement readings with all the experiments were carried out using ten units of LVDT (Linear Variable Displacement Transducer). Two units of displacement transducers were placed on each surface of the front and back of the wall samples each, two displacement transducers on the loading axis and two units of displacement transducers in the vertical direction to the loading axis. Furthermore, two units of displacement transducers were placed on the front side of the sample in order to control the movement out of plane. The layout diagram and the illustration of the displacement transducers are given in **Figure 10**. Here, the direction of the arrows shows the approach direction to the panel consisting of the displacement transducers' measuring points.

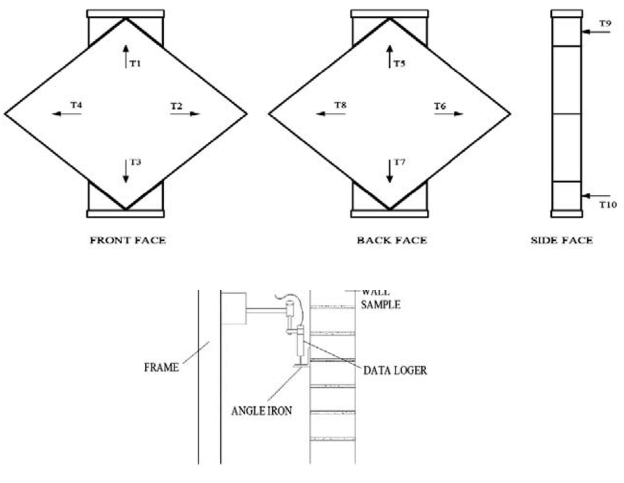

Figure 10: The layout diagram of the displacement transducers
Slika 10: Razporeditev transduktorjev premikov

The data read by the displacement transducers numbered T9 and T10 during the experiments are constantly controlled and the movement of the sample out of the plane is provided to be within the certain limits.

3.5 Experimental work

A total of 9 experiments – 3 from each bricking type – have been carried out in order to compare some of the bricking types in terms of horizontal load-bearing capacity and cutting force. The pictures of the samples before and after the experiment are given in **Figure 11**. The loading was accomplished with approximately 10 kN load steps and the displacement measuring was taken right after each step.

3.6 Modelling and numerical interpretation

For the finite-element modelling (FEM) of the masonry prisms, SOLID45 elements in the ANSYS element library were used for the 3-D modelling of the solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal *x*, *y*, and *z* directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. The element is defined by eight nodes and the orthotropic material properties. With using this element, the analysis cannot capture the bending behaviour with a single layer of elements. In the loading system of these studies there are no bending effects on the masonry infill and the SOLID 45 elements are suitable for the analysis [9].

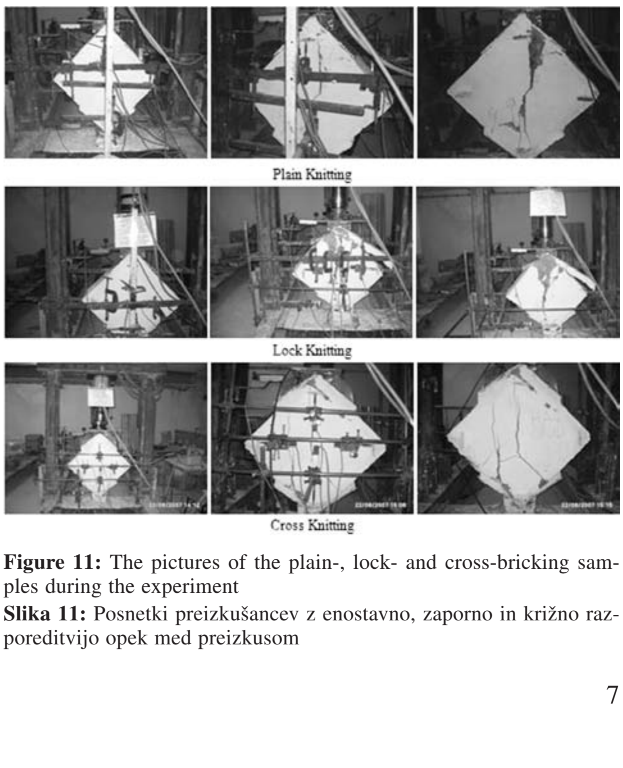

Figure 11: The pictures of the plain-, lock- and cross-bricking samples during the experiment
Slika 11: Posnetki preizkušancev z enostavno, zaporno in križno razporeditvijo opek med preizkusom

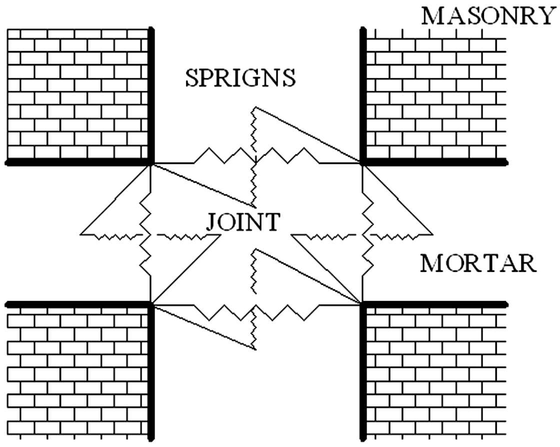

Figure 12: Mortar-brick joint interface modelling
Slika 12: Modeliranje povezave med opeko in malto

The masonry units and mortar layers are modelled independently and different material properties are obtained. In the elaborate FE model developed in this study, masonry units are linked to the mortar units by a series of nonlinear springs, which is also available in the ANSYS library. COMBIN39 is a unidirectional element with nonlinear generalized force-deflection capability that can be used in every analysis. The longitudinal option is a uniaxial tension-compression element with up to three degrees of freedom at each node: translations in the nodal *x*, *y*, and *z* directions. No bending or torsion is considered. The element has a large displacement capability for which there can be two or three degrees of freedom at each node.[10] The element is defined by two (preferably coincident) node points and a generalized force-deflection curve. The springs are introduced to handle the tensile and shear stress failure in the mortar joints, **Figure 12**.

The material model for the masonry panel was assumed to be orthotropic parallel and normal to the bed joints.[11] The material stress versus strain relationship is represented in **Figure 13**.

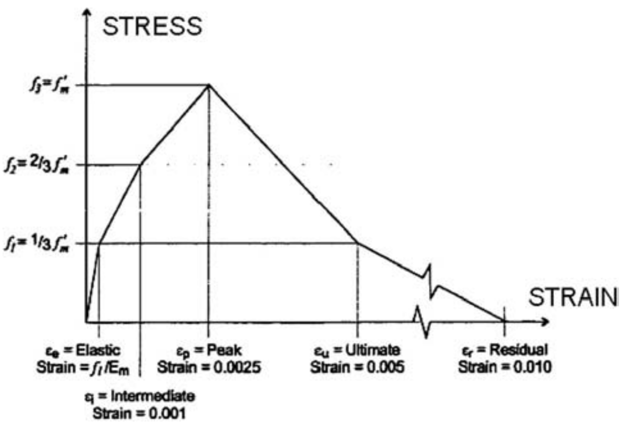

Figure 13: Stress versus strain relationship
Slika 13: Odvisnost napetost – deformacija

The incremental full Newton-Raphson iterative solution procedure was used in order to account for both large deformation effects and the material plasticity. In order to capture the complete load-deflection behaviour including the post peak response, the top node of the masonry prism was subjected to a vertical downward displacement.[12]

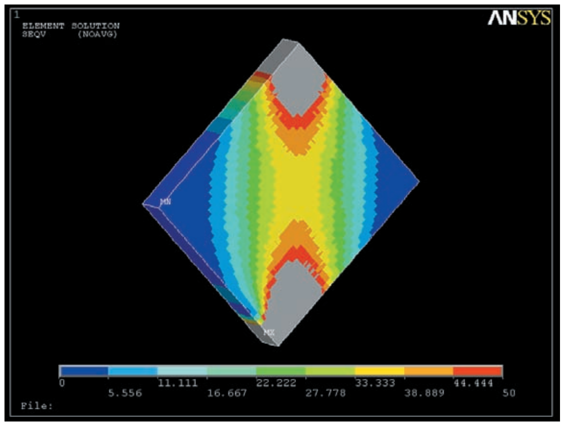

Figure 14: Von-Misses Stress distribution for specimen type 1
Slika 14: Von-Misesova razporeditev za vzorec 1

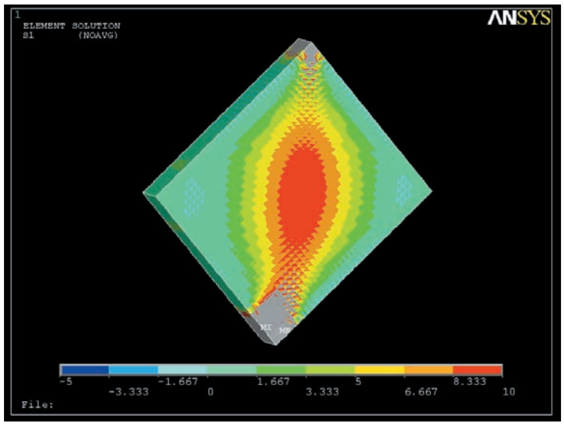

Figure 15: Principal Stress distribution for specimen type 1
Slika 15: Razporeditev glavnih napetosti za vzorec tipa 1

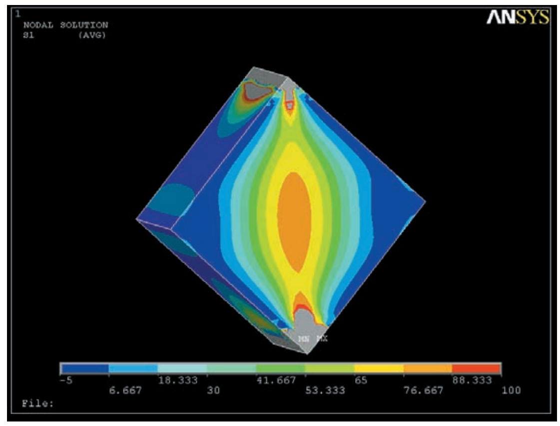

Figure 16: Von-Misses Stress distribution for specimen type 2
Slika 16: Von-Misesova razporeditev za vzorec 2

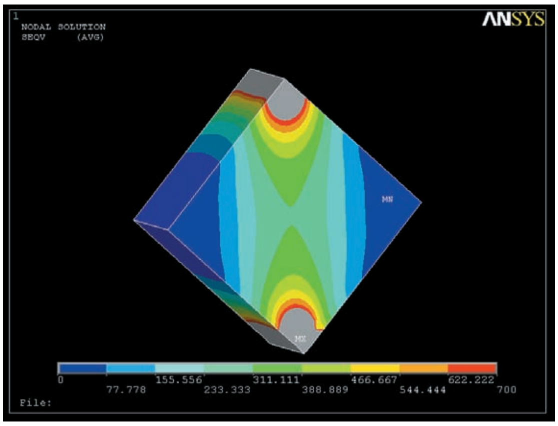

Figure 17: Principal Stress distribution for specimen type 2
Slika 17: Razporeditev glavnih napetosti za vzorec tipa 2

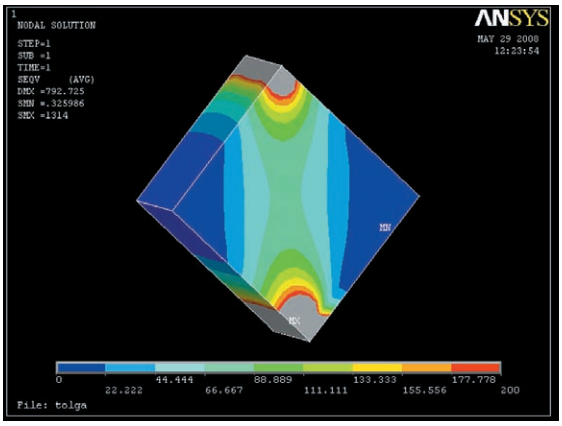

Figure 18: Von-Misses Stress distribution for specimen type 3
Slika 18: Von-Misesova razporeditev za vzorec 3

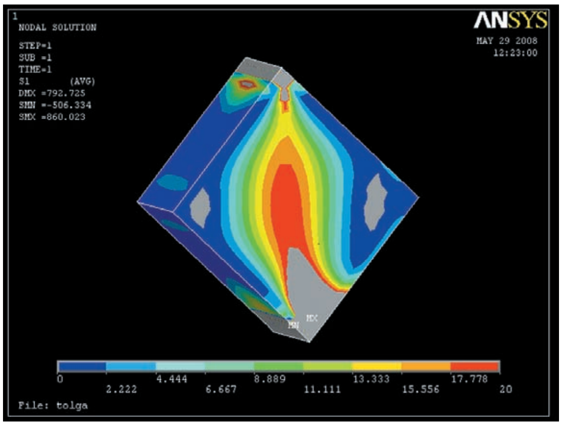

Figure 19: Principal Stress distribution for specimen type 3
Slika 19: Razporeditev glavnih napetosti za vzorec tipa 3

The Von-Misses stress distribution and principal stress graphics for the loaded masonry panels are represented in **Figure 14 through 19**. The applied maximum displacement level is chosen for comparison purposes. (Type 1: Plain Knitting, Type 2: Cross Knitting, Type 3: Lock Knitting).

3.7 Behaviours of the experimental samples and the experimental results

The first crack in the sample reached to the biggest collapsing load with the plain bricking samples occurred at around 40 kN. The first cracks started from the top-left side of the sample and continued downwards. The maximum collapsing load was monitored to be 60 kN and a break on the top-right of the sample is seen.

The first crack in the sample carried the biggest collapsing load with the lock-bricking samples occurred at 100 kN. This crack is formed on the right-bottom side of the sample. The loading was continued and the sample started not to carry the load at 160 kN and broke at the right-top side.

The first crack in the sample where the maximum collapsing load is obtained with the cross-bricking samples occurred on the right-top side of the sample at 170 kN. The collapsing load was determined to be 240 kN. The sample was broken from the right-top side.

The horizontal load-displacement graphics of the plain-, lock- and cross-bricking samples is given in **Figure 20**.

3.7.1 The comparisons among the bricking types

a) Comparison in terms of horizontal load-displacement

The samples reaching to the biggest collapsing load out of the plain-, lock- and cross-bricking samples were

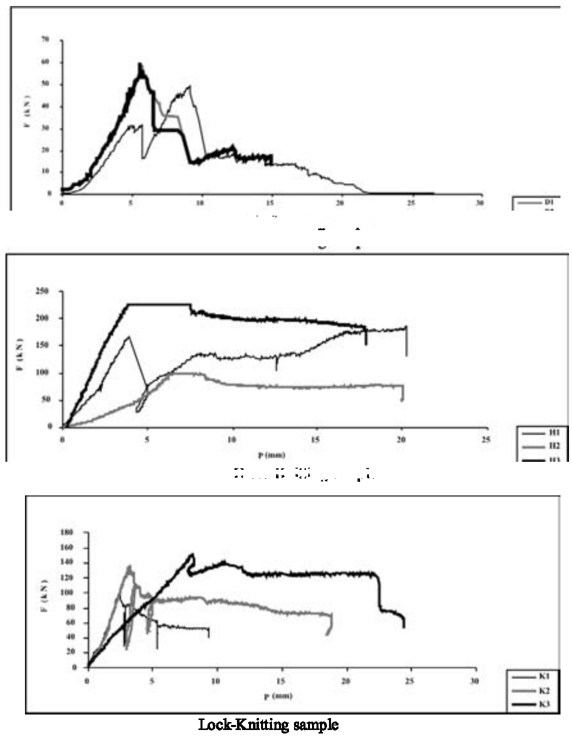

Figure 20: The horizontal load-displacement graphics of the plain-, lock- and cross-knitting samples
Slika 20: Odvisnost vodoravna obremenitev – premik za enostavno, zaporno in križno razporeditvijo opek

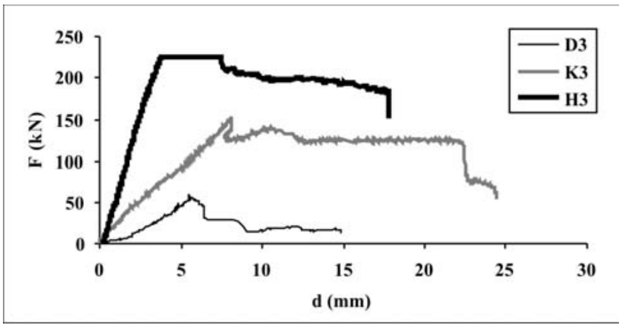

Figure 21: The comparisons of the horizontal load-displacement graphics
Slika 21: Primerjava največje rušilne sile za 3 vrste postavitve opek

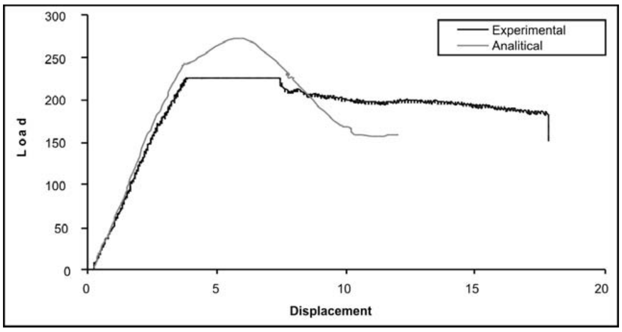

Figure 24: Load versus displacement comparison for specimen type 2
Slika 24: Primerjava breme – premik za vzorec tipa 2

compared in terms of the horizontal load-displacement. The comparisons of the horizontal load-displacement graphics obtained from the biggest collapsing load in 3 bricking types are given in **Figure 21**.

b) Comparison of the shear resistance-displacement

While the shear force is determined from the plain-, lock- and cross-bricking samples, the displacement values have been dictated finding out the average of the T1-T3 LVDT reading values and the T2-T4 LVDT values. The sliding resistance was obtained by taking the Cos45 value of the load and dividing it by the area. The shear resistance-displacement graphics obtained in this way are given in **Figure 22**.

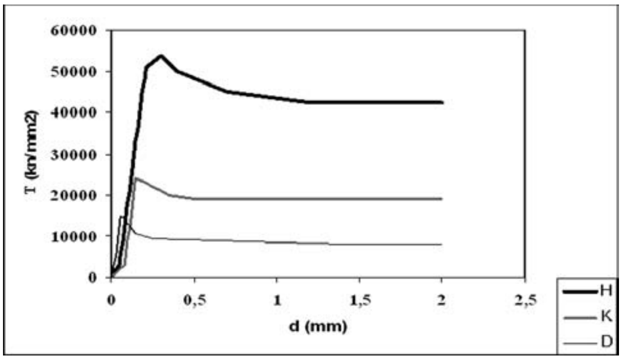

Figure 22: The shear resistance-displacement graphics
Slika 22: Odvisnosti strižna sila – premik

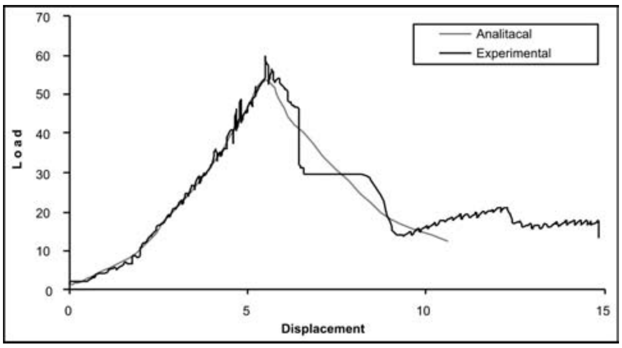

Figure 23: Load versus displacement comparison for specimen type 1
Slika 23: Primerjava breme – premik za vzorec tipa 1

c) Comparison related to the Numerical Modelling

The magnitude of this displacement was sufficiently greater than that observed in the actual test, after which a load-deflection plateau was attained indicating that the contribution of the infill almost entirely diminished and that no appreciable increase in the load resistance occurred. The three different masonry configurations are modelled and loaded in time steps, and the applied vertical load versus displacement values are obtained. The comparison of the analytical and experimental data is represented in **Figure 23, 24 and 25**.

4 DISCUSSION AND CONCLUSION

The total of 9 units of samples made up of three different bricking types to be used in the formation of a masonry building were compared in terms of the horizontal load and shear force using a standard sliding resistance experiment technique for the masonry-wall samples recommended in ASTM 1391-81, and the following outcomes have been obtained. The analytical results obtained by the solution with the finite-element method together with the results obtained as a result of the experiments were evaluated. The results are as follows:

The biggest collapsing load occurred with the cross bricking as per the horizontal loads. The collapsing load with this type of bricking is 240 kN. The collapsing load

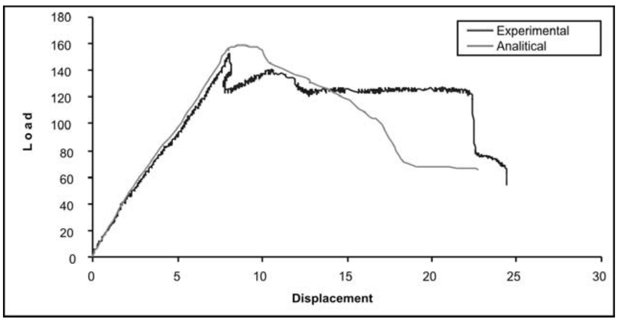

Figure 25: Load versus displacement comparison for specimen type 3
Slika 25: Primerjava breme – premik za vzorec tipa 3

with the lock bricking is 160 kN, and the plain bricking is found to be 60 kN.

It was determined that the strength of the shear stress formed in cross knitting is 2.25 times higher than lock knitting and 3.6 times more than plain knitting.

When horizontal load displacement graphs are taken into consideration, it was found that the energy-absorption capacity is 3 410 kN mm in cross knitting, 2 420 kN mm in lock knitting and 625 kN mm in plain knitting. It was concluded that cross knitting consumed 1.4 times more energy than lock knitting, whereas it consumed 5.8 times more energy than plain knitting.

According to the horizontal load-displacement graph, the displacement ductility of the cross-knitting wall was 19 mm, that of the lock-knitting wall was 23 mm and that of the plain-knitting wall was 14 mm.

The values obtained analytically by using the finite-elements method (ANSYS) were in accordance with the ones obtained as a result of the experiments.

5 CONCLUSIONS

When the results of both the empirical and analytical studies on the samples formed by using different knitting types were evaluated, a masonry construction with cross knitting is considered to be the most suitable knitting type in terms of collapse load, shear stress, and energy-absorption capacity. Although the collapse load of lock knitting is low, its displacement ductility is higher than other knitting types. It was observed that plain knitting has the lowest values among the other knitting types. These results show that different knitting types used in the masonry constructions of rural regions have an important role in the protection of the construction against earthquakes. Using a cross-knitting type in masonry constructions in rural regions that are especially at risk of earthquakes will make the construction more resilient to earthquake damage.

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