Session Schedule

Monday Keynote Address

Session 1A: Retrofitting

Session 1B: Historic Masonry Cases Studies 1

Session 1C: Unreinforced Masonry 1

Session 1D: Arching

Session 2A: Confined Masonry 1

Session 2B: Existing Masonry 1

Session 2C: Energy Transfer 1

Session 2D: Innovative Technology 1

Session 3A: Partially Grouted Masonry

Session 3B: Surface-Mounted Reinforcement

Session 3C: Material Properties 1

Session 3D: Numerical Methods

Tuesday Keynote Address

Session 4A: Material Innovations

Session 4B: Education and Codes

Session 4C: Energy Transfer 2

Session 4D: Non-Traditional Masonry 1

Session 5A: Seismic Analysis and Testing

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Session 6A: Confined Masonry 2

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Session 7A: Infill Masonry

Session 7B: Historic Masonry Cases Studies 2

Session 7C: Veneer 2

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Session 8A: Unreinforced Masonry 2

Session 8B: Reinforcement

Session 8C: Out-of-Plane Flexure 2

Session 8D: Non-Traditional Masonry 2

Keynote Address Presentations

There are no papers associated with the keynote addresses.

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From Whence to Here and Where?

Nigel G. Shrive
Professor
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ABSTRACT

The evolution of masonry will be examined to establish where the industry is today. Current pressures and influencers will be reviewed to consider how the industry needs to adapt to those pressures and influencers. The need for closer industry-researcher interaction will be exposed in order for the industry to be proactive in response to certain predicted inevitabilities. The intent of the presentation is to provoke thought, discussion, and debate.

BIOGRAPHY

Professor Nigel Shrive has researched in masonry for over 40 years. Based at the University of Calgary, he has collaborations with colleagues in Australia, Brazil, Europe and the USA. He has served on the Boards of Directors of The Masonry Society and the International Masonry Society and has been recognized for his contributions to the advancement of masonry through the Scalzi Award from TMS, the HWH (Timber) West Award from the IMS and the Outstanding Achievement Award of the Canadian Masonry Contractors Association. Nigel serves on four technical committees of the Canadian Standards Association – Structural design of masonry, mortar and grout, masonry construction, whilst also representing the masonry industry on the committee for structural applications of Fibre Reinforced Polymers. Nigel has been elected fellow of both the Canadian Academy of Engineering and the Royal Society of Canada for his contributions to engineering.

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Innovation in Masonry Today

Peter Roberts
Founder, CEO
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ABSTRACT

This talk will address the important role of innovation to the masonry industry in today's world. Different types of innovation will be described, including incremental, gradual changes; and revolutionary or disruptive innovation. Various sources of innovation will be explored, including linear focused research; interdisciplinarian research involving other fields; the psychology of innovation; biomimicry as a source of innovation; and the unexpected, "opened door" source of innovation. The challenges of innovation will be described: including fundraising, intellectual property, green technology, the importance of credentials, evangelizing new technology, converting others, establishing a technical standard and obtaining a critical mass. The speaker will address all of these considerations in the real-world context of his own experiences in the development of using specialty manufactured concrete block to build masonry roof arches, domes, spheres, flying buttresses, boats & ships, and much more. This talk will summarize the role of profitable innovation in the masonry industry relative to society, our country, and the wider needs of today's world.

BIOGRAPHY

Peter Roberts is Founder and Chief Executive Officer of innovative masonry systems at Spherical Block, LLC. Peter is a masonry designer entrepreneur inspired to develop profitable, sustainable and scalable solutions for expanding the use of manufactured concrete block into topological designs, using block to provide roofs, such as arches and domes. He is at the vanguard of this entirely new use of concrete block, creating new applications, uses and markets for concrete block at scale. Peter has earned a reputation for utilizing existing production methods and materials to provide a profitable new realm for manufactured concrete masonry products. His work is suitable for affordable, high-strength building designs viable for withstanding severe weather events, wildfires, tsunamis, seismic applications, infrastructure, kilns and more. Peter has been granted six awards from the National Science Foundation, and two awards from the New York State Energy Research Development Authority toward the development and characterization of this innovative masonry technology. Peter's work has been identified as a Cutting-Edge Technology by the American Concrete Institute. Peter has authored 18 US patents. He holds a Bsc in Masonry Science from Alfred University's New York State College of Ceramics. In his spare time, Peter is an avid outdoors enthusiast and devotes his time to pottery, sculpture, metal working, glass blowing and music. He is currently working to obtain a positive evaluation of his company's technology from International Code Council – Evaluation Services.

Technical Paper Presentations

Associated technical papers can be found in the conference proceedings.

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Air Content and the Performance of Masonry Cement Mortars

Paper 188

W. Mark McGinley[1], Bill Kjorlien[2], Jamie Farny[3], and Wayne Wilson[4]

ABSTRACT

Exterior masonry walls are a composite structure built using rigid masonry units and softer less rigid masonry mortar. As an assembly, exterior masonry walls rely on appropriate design and workmanship to function effectively in-situ. As masonry construction occurs in a wide range of climates and to perform adequately the plastic mortar characteristics must be adjusted to ensure the masonry assembly can be built and function in a wide range of conditions. Thus, manufacturers, designers and masons must work together to choose the best set of materials for each application so that a durable, attractive and functional masonry wall can be achieved.

In an effort to offer masons a more workable mortar in hot climate construction, mortar manufacturers have proposed increases in maximum allowable mortar air content for mortar cement mortar. Experience suggested that increased air content improves mortar workability and water retention. Thus, ASTM Sub-committee C01.11 on Masonry Cement, proposed and passed a maximum air content limit increase of 6% for C1329 Mortar Cements to facilitate the use of higher air content mortar in hot climates. Furthermore, in an effort to harmonize the C1329 air content change with the ASTM C270 mortar standard, Sub-committee C12.03.01 on Specifications for Mortar, investigated raising the maximum air content limits on mortars made with Mortar Cements. In support of the proposed change, a re-search investigation was conducted to determine the impact of higher air content Mortar Cement mortars on the water penetration resistance of masonry assemblies, as well as the bond between the units and mortar. The proposed paper summarizes the results of this investigation.

KEYWORDS: mortar, air content, water penetration

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Air Flow Within a Brick Veneer Cavity Wall

Paper 205

Nathaniel C. Huygen[1] and John P. Sanders[2]

ABSTRACT

In residential brick veneer cavity walls, there is an air space behind the brick that serves as a drainage plane. This study was carried out to definitively demonstrate the R-value and thermal mass benefit of brick veneer and air cavity in residential wall systems. Some authors argue that this open air cavity causes infiltration of exterior air, thus bypassing the brick veneer entirely. However, this air cavity can impact the thermal performance in non-trivial ways. The requirement of weeps at the bottom of the wall indicates the potential for air exchange between the exterior and the cavity. The aim of this study was to determine to what extent air movement within the air cavity impacted the overall thermal performance of the wall system. Several configurations were studied that included characterization with the weeps closed. This was considered best case as there was no exchange with the exterior environment. ANSYS Fluent was used to perform 3D fluid dynamics simulations of a typical residential brick veneer cavity wall system that has air exchange between the exterior environment and the air cavity behind the brick. In addition, a residential brick veneer cavity wall was tested using a hot box apparatus to give experimental verification to the model under similar conditions. The goal was to determine how significant this air exchange was and how it affected overall thermal performance of the wall system.

KEYWORDS: brick, fluid dynamics, weeps, air cavity, thermal performance

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An Alternative to Using Steel Beams Supporting Long Span Openings in Masonry Walls

Paper 272

Casey T. Moore[1] and Thomas M. Corcoran[2]

ABSTRACT

Reinforced concrete masonry beams are a standard design element when considering an opening in masonry walls. As wall opening spans increase, the beam is required to not only support gravity loads but also must meet code deflection requirements, which is typically achieved using steel for long, clear spans. Recently, however, a masonry beam was designed for a 48-foot clear span across a large proscenium opening in a new 900-seat Performing Arts Center as part of a new 325,000 SF high school/middle school project. This paper describes the approach used to design the largest masonry deep beam in the U.S., including consideration of simple-span versus fixed ends for supporting gravity loads, out-of-plane requirements for seismic and wind loads, and standard beam versus deep beam design methodology.

The MSJC (TMS 402) 2013 code was used for the beam design, along with consideration of the size effect on shear strength of the beam. High strength masonry blocks were used for both the 12-inch nominal masonry beam and the supporting 24-inch nominal jambs. The 24-inch jambs were not only designed to support the masonry beam gravity loads but also as special reinforced masonry shear walls. This paper also discusses challenges faced during the construction phase along with thoughts on the design approach for future masonry beams of similar scale.

KEYWORDS: reinforced, beam, deep beams, shear, out-of-plane

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Analysis of the Last Standing Arch of the Roman Aqueduct at Blaundos

Paper 213

Ece Erdogmus[1], Bora Pulatsu[2], Birol Can[3], and Kadir Ozkan[4]

ABSTRACT

Blaundos is an ancient site near the modern-day city of Usak in Turkey. The ancient city is rich with layers of history including its foundation in Hellenistic period and later during the Roman period. It appears that the city flourished during the first century AD, and to satisfy its water needs, a long aqueduct system was constructed to bring water from the springs in the Inay village, which is 8 km to the north of Blaundos. The aqueduct is constructed in dry masonry from travertine blocks, most likely obtained from the Blaundos canyon. The city also includes several other noteworthy structures constructed from marble and travertine, such as temples, a stadium, a theatre, a city gate, and a basilica.

Based on prior literature, in the first half of the 19th century at least a few of the arches of the aqueduct were standing. Later in the first half of the 20th century, only two were standing. Today, only a single arch remains, and it is in a damaged condition. In this paper, the stability of the last remaining arch is investigated un-der various scenarios: the idealized (undeteriorated) arch, and arch in its current state of geometrical imperfection (deteriorated). This is important as the geometrical impurity is expected to have a major effect on the stability of this arch that has lost the support of a series of arches. Discrete element modeling is used to assess the stability and seismic resistance of the arch structure in both conditions. Loss of capacity, due to loss of material and a poor intervention on the key stone from 1980s, is discussed. The level and type of seismic excitation that would cause the collapse of the deteriorated lone arch is studied. The paper concludes with preliminary design recommendations for the conservation of this historic arch.

KEYWORDS: arch, discrete element modeling (DEM), historic preservation, historic preservation, seismic, aqueduct

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Analytical Models for Shear–Displacement Curves of Unreinforced Masonry Panels With and Without Bending Moments

Paper 261

Kenan Michel[1]

ABSTRACT

In this study, the displacement will be determined for single wall in three limit states: decompression (elastic), yielding (cracked), and plastic, while the rotation will be determined in the first two limit states: decompression and yielding. The wall will be investigated under two loading cases: under normal and shear forces; and under normal force, shear force and a bending moment (or a normal load with eccentricity). The decompression (elastic) limit state will consider the shear force contribution in the displacement, i.e., Timoshenko beam theory. The yielding (cracked) limit state will neglect the shear force contribution, i.e., Euler theory.

KEYWORDS: shear walls, bracing elements, analytical methods, Timoshenko theory

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Application of Artificial Intelligence in Predicting the Behavior of Semi-Interlocking Masonry (SIM) Panels

Paper 181

Orod Zarrin[1] and Mohsen Ramezanshirazi[2]

ABSTRACT

The Semi Interlocking Masonry (SIM) system has been developed in Masonry Research Group at the University of Newcastle, Australia. The main purpose of this system is to enhance the seismic resistance of framed structures with masonry panels. In this system, SIM panels dissipate energy through the sliding friction between courses of SIM units during earthquake excitation. This paper aimed to assess the ability of Artificial Neural Networks (ANNs) to predict the displacement behavior of the SIM panel under out-of-plane loading. Moreover, the goal of the research is to development of efficient model based on the application of (ANN) to predict the behavior of SIM panel and focus on sensitive analysis to find most effective parameters on displacement behavior of the SIM panel by Sequential forward Feature Selection method (SFS). In conclusion, results of prediction, feature extraction, and model validation have been reported. The final results of the study proved the capability of aforementioned models to predict the displacement behavior of the SIM panel under out-of-plane loading as well as the optimization of time, cost and safety in laboratory.

KEYWORDS: artificial neural network (ANN), out-of-plane capacity, prediction, earthquake-resistant design, semi-interlocking masonry (SIM)

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Applied Element Modeling of the Dynamic Response of a Full-Scale Clay Brick Masonry Specimen with Flexible Diaphragms

Paper 021

Daniele Malomo[1], Rui Pinho[2], and Andrea Penna[3]

ABSTRACT

The seismic assessment of typical unreinforced masonry buildings in The Netherlands, recently exposed to low-intensity ground motions induced by gas extraction, is becoming the focus of both experimental and numerical research. Their design, originally not conceived for earthquake-resistance, often features the presence of both large openings and flexible diaphragms, and the lack of any specific seismic consideration or detailing further increases the associated vulnerability towards horizontal loading. In this paper, the Applied Element Method, which explicitly represents the discrete nature of masonry, is used to simulate the shake-table response of a full-scale building specimen representative of a typical Dutch detached house made of unreinforced clay brick masonry. Using this modelling strategy, the damage evolution, as well as both global failure mode and hysteretic behavior, are described. The results have shown a good agreement with the experimentally-observed response, confirming the capabilities of the Applied Element Method in reproducing effectively the large-scale response of masonry structures, whilst simultaneously keeping computational costs within acceptable limits for this time of detailed modelling.

KEYWORDS: applied element method (AEM), numerical modeling, shake-table testing, flexible diaphragm, unreinforced masonry (URM)

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Assessment of the Compressive Strength of Masonry Prisms Using the Eurocode 6 Approach

Paper 047

Julia Favretto Machado[1], Gihad Mohamad[2], André Lübeck[3], Fernando S. Fonseca[4], and Almir Barros da S. Santos Neto[5]

ABSTRACT

The Brazilian code establishes that prisms, wallettes or walls can be used to obtain the masonry compressive strength; for example, the Brazilian code allows the strength of the masonry to be estimated as 70% of the strength of the prism. In contrast to the Eurocode 6, which prescribes that only wallettes meeting the requirements of EN 1052-1 should be used. The goal of this work was to first determine the compressive strength of three types of concrete and clay units with different net and gross areas, as well as of prisms constructed with those blocks and mortars having different strengths. The results of the tests were then used to achieve the second objective of the research: develop a model having the same format as that of the Eurocode 6 to predict the compressive strength of masonry.

KEYWORDS: clay block, concrete masonry, mortar, strength

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The Behavior of Masonry-Infilled R/C Frames Under Horizontal Seismic-Type Loading

Paper 077

George C. Manos[1], Vassilios Soulis[2], and Lazaros Melidis[3]

ABSTRACT

Reinforced concrete (R/C) buildings are composed of multi-story multi-bay frames constructed by reinforced concrete structural elements (columns and girders). Usually, the bays of such frames are "infilled" with unreinforced masonry panels, considered as non-structural elements. These masonry "infills", due to their considerable in-plane stiffness, interact with the surrounding R/C frame during strong seismic ground motions leading to various forms of damage to the masonry as well as to the structural members of the R/C frame. Currently, several seismic design codes include provisions attempting to take into account such problems arising from the masonry infill – frame interaction in an indirect way. Moreover, different analytical and numerical approaches have been proposed by various researchers and regulators to determine the initial stiffness of the masonry "infills" towards attempting to form a realistic approach for the masonry infilled frame structure seismic performance. However, in the majority of these cases the influence of the peripheral mortar joint, that forms the contact boundary between the masonry infill and the surrounding frame, is ignored. It was observed that the increase of the stiffness and strength of the mortar joint interface between the masonry infill and the surrounding frame could result in the narrowing of this contact area, which in turn could lead to the premature crushing of the masonry infill at the corner regions where the R/C beam is joined with the column. For masonry infills with high compressive strength such a narrow zone may also lead to the crushing of the R/C joint at this region. The alternative mode of failure is the common diagonal failure of the masonry infill. The non-linear macro-model proposed by the authors that incorporates the simulation of this contact interface is a very good approximation of the horizontal masonry infill stiffness that yields positive agreement with observed behavior.

KEYWORDS: masonry infill, infill-frame interaction, contact interface, seismic loading, numerical simulation

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Best Practices for Masonry Resilience Based on Performance During the 2018 Wilkes-Barre Tornado

Paper 187

Heather A. Sustersic[1], Michael Kinzel[2], James E. Horting[3], and Mary E. Haynes[4]

ABSTRACT

Tornados can and have occurred in every state and across varied terrain, causing millions of dollars in damage. Due to the presumed low probability of occurrence, designing low -rise buildings for tornados is typically viewed as absurd and expensive. However, a low-level tornado ravaged an outdoor shopping complex in Wilkes-Barre, Pennsylvania on June 13, 2018. The potential for any building to experience this intense phenomenon is real and design solutions may be simpler than imagined.

Using photographic evidence taken shortly after the Wilkes-Barre tornado, this report will review the performance of multiple construction types, including masonry structures. Historic evidence of masonry performance from other tornado events will also be summarized, highlighting susceptible details and the simple solutions that could have prevented failure during a low-level (EF-0 to EF-2) tornado. Cladding failures observed after the Wilkes-Barre tornado support the need for new, cross-disciplinary approaches to estimate tornado wind pressures; we identify areas where further research is required. Finally, steps for the practicing engineer to make informed decisions regarding tornado design and detailing of masonry structures will be presented.

KEYWORDS: tornadoes, computational fluid dynamics, fluid-structure interaction, failure, resiliency rating, masonry detailing

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Case Study on URM Parapet Bracing: Research and Application

Paper 225

David G. Sommer[1], Cale R. Ash[2], Dmytro Dizhur[3], and Jason M. Ingham[4]

ABSTRACT

The main campus of a large public university in Washington State is undergoing a seismic retrofit project to seismically brace or eliminate all URM parapets. Many parapets on campus feature varying conditions such as terra cotta capstones, through-wall flashing, sloped slate roofs, and discontinuities at the roof level. Unreinforced masonry parapets have long been recognized as a falling hazard in seismic events, and recent research has focused on recommended bracing techniques. Summarized herein are conclusions gleaned from recent research in New Zealand on securing of unrein-forced masonry parapets. Parapet securing recommendations considering architectural and constructability concerns are made to the university parapet bracing project.

KEYWORDS: parapet, seismic, bracing, unreinforced masonry (URM), retrofitting

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Challenges of Stabilization and Adaptive Re-Use of Historic Unreinforced Masonry Buildings

Paper 215

Katarzyna Burzynska[1], Charu Chaudhry[2], Ali Ashrafi[3], and Jenny Sideri[4]

ABSTRACT

Nowadays, New York City is a place where new architecture meets the old – often face to face. As a result, historic masonry, which is frequently exposed to vibrations caused by construction related activities, may encounter a loss of soil stability undermining the existing foundation system in case of adjacent demolition. Various non-destructive and in-place methods of unreinforced masonry stability evaluation, such as Surface Penetrating Radar testing, borescope investigation, vibration analysis, movement and crack monitoring, are used to determine the structural capacity of unreinforced masonry.

This paper describes the challenges for adaptive re-use of masonry buildings, including methods of evaluation, temporary protection (shoring) and structural emergency response (stabilization) in New York City. A range of methods for strengthening and bracing that engineers have at their disposal have been described.

KEYWORDS: unreinforced brick masonry, emergency response, masonry stabilization, shoring, bracing

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Characteristics of One- and Two-Way Arching Behavior of Masonry Infills Under Out-of-Plane Loading

Paper 082

Ehsan Nasirikhaneghah[1] and Yi Liu[2]

ABSTRACT

This paper presents the results of a finite element study to investigate both one-way and two-way arching behavior of concrete masonry infills bounded by RC frames subjected to out-of-plane loading. Arching action, enabled by the restraint provided by the bounding frame, has been attributed to as a main factor resulting in a much higher out-of-plane strength of masonry infills than their flexural wall counterparts. The original arching model was proposed decades ago and largely based on experimental observations on masonry bricks where compressive failure of masonry was the governing failure mode. To gain a better understanding of the out-of-plane behavior of masonry infills made of concrete masonry units (CMUs), a three-dimensional nonlinear finite element model capable of simulating the load-deflection response and capturing potential failure modes for masonry infills was developed. A parametric study was conducted using the model to investigate one-way arching, two-way arching, and correlation of the two covering a wide range of geometries of infills and stiffness of bounding frames. Results showed that for CMU infills, shear failure through the webs of the CMUs is the predominant failure mode. A significant difference between the horizontal and vertical arching was observed where the vertical arching leads to a much higher strength than the corresponding horizontal arching. The vertical arching strength is highly sensitive to the frame stiffness and the horizontal arching strength, on the other hand, was found to be barely affected by the stiffness of the bounding frame. The existing analytical methods for calculating out-of-plane strength of infills was also examined using the finite element results and the discrepancies were discussed.

KEYWORDS: out-of-plane, masonry infill, arching, concrete masonry infill, finite element analysis (FEA), RC frame

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Clogging Progression of Permeable Interlocking Concrete Pavers

Paper 135

Jody T. Scott[1] and Jennifer Drake[2]

ABSTRACT

The primary function of permeable interlocking concrete pavers (PICP) is to reduce stormwater runoff and remove unwanted pollutants from stormwater, however, over time a pavement's ability to infiltrate stormwater can be limited by sediment clogging the system. As sediment accumulates within the pavement joints, the PICP's capacity to infiltrate stormwater in a timely manner decreases. The process of sediment accumulation is dependent upon the source, amount and size of sediment introduced to the surface. Clogged pores are a detriment to permeable pavement, as it reduces their lifespan and allows for sub optimal runoff mitigation. Thus far, there has been limited research on the progression of clogging in PICPs. Studies assessing restorative maintenance practices for PICP present mixed results and standardized restoration practices are needed to improve the longevity of permeable pavements.

This study investigates how sediment gradation and quantity affect infiltration rates through clogging of PICPs. Two laboratory scale plots of PICP systems were constructed identically, and dry sediment was incrementally applied to both systems to examine the decrease in surface infiltration rates over time. The sediment used on both plots was a non-organic blend adhering to the New Jersey Stormwater Particle Size Distribution, however, on one plot, a portion of the gradation was removed to add organics. Results showed that the organic addition had a drastic impact on the reduction of surface infiltration rates compared to the non-organic sediment. The non-organic blend plot applied a total of 72 grams which corresponded to an overall surface infiltration decrease of 43%. In comparison the organic blend plot applied a total of 28 grams which corresponded to an overall surface infiltration decrease of 89%.

Results of this work can be used to better understand the conditions that limit the effectiveness of restorative maintenance and develop best management practices for the PICP sector.

KEYWORDS: clogging, operations and maintenance, particle-size distribution, interlocking concrete pavers, permeable pavement, infiltration

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Cohesive-Frictional Interface Fracture Behavior in Soft-Brick Masonry: Experimental Investigation and Theoretical Development

Paper 076

Mehar Babu Ravula[1] and Kolluru V. L. Subramaniam[2]

ABSTRACT

An experimental program to investigate the shear transfer across the brick mortar interface at different levels of applied compression is conducted. Direct shear tests were performed in the triplet test configuration on masonry made with brick with a soft brick. The failure across the brick-mortar interface is produced by a crack in the soft brick-mortar interface which propagates in a thin layer where the mortar penetrates the soft brick. A cohesive-frictional interface failure which combined cohesive bond failure and frictional resistance is proposed. The maximum shear resistance is found to follow a Mohr-Coulomb type relationship. The residual frictional resistance increases linearly with an increase in the applied compression.

KEYWORDS: cohesive, failure mechanism, dilatancy, interface, soft brick, mohr-coulomb theory

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Compressive Strength of FRP-Confined Concrete Masonry With and Without Longitudinal Steel Reinforcement

Paper 133

Khalid Saqer Alotaibi[1] and Khaled Galal[2]

ABSTRACT

Using Fiber Reinforced Polymers (FRP) to confine concrete masonry columns has been a proven strengthening technique to enhance the axial capacity and ductility of concrete masonry columns. This paper presents an experimental investigation of the interaction between existing internal longitudinal steel reinforcement and external FRP wraps. The test matrix was designed to measure the effect of the presence of longitudinal steel reinforcement in the columns on the compressive strength of FRP-confined concrete masonry (f_{mcd}). Six half-scale concrete block masonry specimens strengthened with Carbon FRP jackets were tested under monotonic uniaxial compressive load. The tested specimens were built using pilaster units and were fully grouted. The result showed that the effect of existing internal longitudinal steel reinforcement on the compressive strength of FRP-confined masonry was limited. The findings would support the assumption that the compressive strength of FRP-confined masonry can be obtained from compression tests of specimens without longitudinal steel reinforcement.

KEYWORDS: column, fiber reinforced polymer (FRP), strengthening, compression, pilaster, half-scale

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Confined Masonry: The Current Design Standards

Paper 162

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ABSTRACT

Confined Masonry (CM) is a structural system composed of horizontal and vertical reinforced concrete confining elements cast around masonry wall panels. CM construction technology is used in several countries and regions across the world including high seismic- and hurricane-prone regions and has demonstrated good performance in earthquakes. The purpose of the paper is to present results of activity of a recently formed working group by members of the Masonry Society and the Earthquake Engineering Research Institute (TMS-EERI) related to a survey and analysis of global seismic design provisions for CM buildings. As a part of the initiative, the authors have identified the current codes and guidelines governing the structural/seismic design of CM buildings and have analyzed the relevant design provisions in order to identify any needs or gaps in the current documents. The authors will focus on the overview and comparison of the code design provisions. The paper will be relevant for engineering academics and professionals interested in seismic design of CM buildings.

KEYWORDS: confined masonry, structural practice, seismic design, design code

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Correlating Brick Compressive Strength to Its Fundamental Transverse Natural Frequency

Paper 192

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ABSTRACT

Several ASTM standards use the principle of sonic resonance and resonant frequencies to determine or estimate mechanical properties such as Young's modulus, shear modulus, Poisson's ratio of refractory materials and concrete specimens. However, such studies do not exist which relate the fundamental natural frequency corresponding to transverse flexural vibration of bricks to its compressive strength. This paper reports the results of a study conducted to find a correlation between the frequency of elastic waves of vibrating brick prisms and the soundness of brick material, as natural frequencies are directly related to modulus of elasticity of the material. Twelve bricks were first tested for their natural frequency and then tested destructively to evaluate their compressive strength. Brick specimens were set in the fundamental mode of transverse vibration and an IEPE accelerometer was used to measure the acceleration time history. A simple Fast Fourier Transform (FFT) of recorded accelerometer signal time history gives the resonant frequency of the brick specimen. The bricks tested in this study ranged from 15–30 MPa (21 MPa on average), which is typical of bricks found in northern India. The modulus of elasticity was found to vary between 5000-7500 MPa (with an average of 6100 MPa) which is about 150-500 times compressive strength and about 300 times compressive strength on average. The experimental dataset so developed can be evaluated for acceptability for a given target strength and bricks can be classified into categories such as very good, good, fair or poor. Therefore, an objective assessment of brick quality is possible by measuring fundamental transverse natural frequency of bricks using accelerometer sensors. This assessment procedure can be extended to smartphones, utilizing its on-board sensor capabilities.

KEYWORDS: quality, brick, frequency, vibration

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Critical Analysis of Codes and Standards of Structural Fire Design of Masonry Structures

Paper 088

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ABSTRACT

Currently, in Brazil, the current structural masonry standards are divided into clay block structural masonry standards and concrete blocks structural masonry standards. The study committee ABNT / CE-002: 123.010 recently proposed the unification of these standards which is expected to be published this year. It is observed that, even with the unification of the standards, there are gaps regarding the fire behavior of structural masonry. Faced with this, this same commission of studies intends to launch in the next two years a code that meets this need. In Brazil, structural masonry is widely used in the construction of high-rise residential buildings, and it is important to be attentive to the building's ability to resist fire. Because of this, the Fire Department of the State of Sao Paulo recommends sizing the masonry structures in a fire situation according to the instructions of Eurocode 6 or a similar international standard. In this article, the adoption of structural fire masonry design procedures of the United States, Australia and Europe standards for a typical structure of Brazilian structural masonry is critically examined. The applicability of these codes to the Brazilian context, due to the differences in the materials of the blocks and finishing was verified, in order to subsidize future discussions on Brazilian standardization, as well as to compare the different approaches to each standard.

KEYWORDS: building code, fire design, Brazilian masonry, structural masonry

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Cyclic In-Plane Testing of Simulated Australian Historical Perforated URM Walls

Paper 055

Milon K. Howlader[1], Mark J. Masia[2], and Michael C. Griffith[3]

ABSTRACT

Historical unreinforced masonry (URM) buildings in Australia are vulnerable to damage during earthquakes. This was highlighted by the 1989 Newcastle earthquake, which caused extensive damage in older URM construction, despite being of only moderate magnitude (M5.6). Based on the importance of the historical URM buildings, this study was conducted to investigate the global in-plane behavior of the old URM walls by placing emphasis on both the pier and spandrel geometry, whereas previous testing considered only the performance of the piers. Experimental pseudo-static cyclic in-plane testing of walls which represent old Australian unreinforced masonry construction was conducted to assess the in-plane shear behavior by investigating the shear strength, failure behavior, ductility and displacement capacity. The ongoing testing program consists of eight full-scale perforated wall specimens with arched openings. The walls are 2630 mm long, 2400 mm high with a two-leaf thickness of 230 mm using American or common bond. Two different geometries are considered by varying the spandrel depth and two levels of vertical pre-compression stress were selected. In this paper, the results are presented for those walls already tested, consisting of the first four walls (shallow spandrel geometry) of the eight-wall experimental program. The test results show a significant effect of the pre-compression load on the load-displacement behavior and the failure mode of the walls. Also, the results show that for the same configuration of the walls, the failure mode varied between specimens.

KEYWORDS: unreinforced masonry (URM), perforated walls, experimental testing, cyclic in-plane shear

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Cyclic Load Behavior of Confined Masonry Walls Using Silica Lime 11H Bricks

Paper 083

Daniel R. Quiun[1] and Elizabeth Y. Villanueva[2]

ABSTRACT

An experimental research was performed using a relatively new product for structural walls: 11H silica lime solid bricks, with eleven holes in the bed area. The holes cover about 29% of the brick bed area and were designed to accomplish the maximum 30% holes limit for solid bricks of the Peruvian Masonry Code (Norma E.070, 2006).

A series of tests on the new 11H brick units is presented: plain masonry tests and a cyclic load test on a confined masonry wall. The objective is structural evaluation of masonry that uses these bricks. The 11H brick becomes an alternative to clay bricks as in Peru, solid clay bricks are usually produced under request by very few producers. Many popular constructions are built with hollow clay bricks which are cheaper than solid ones but are not allowed for use in structural walls because they have too many holes in the bed area (45-50%) or are horizontally hollowed.

One full scale confined wall was built using 11H bricks for cyclic load testing under displacement control, simulating seismic loads. The test had 10 steps, and results include lateral load capacity, initial stiffness, failure mechanisms, and critical wall zones.

Additionally, small specimens using 11H bricks were built and tested to study masonry properties. Three prisms were subjected to axial compression and three small walls were subjected to diagonal compression. The axial resistance f'_m and the shear resistance v'_m, were obtained and used to estimate the 11H wall behavior analytically.

Finally, conclusions and recommendations are given to show the ability of the wall made with 11H silica lime bricks to comply as a structural wall under seismic loads, according to the Peruvian Masonry Code requirements.

KEYWORDS: silica-lime, confined masonry, 11H bricks, solid brick

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Damage Analysis of an Early 20th Century Masonry Church Due to Soil Settlement

Paper 136

Giuliana Cardani[1], Dario Coronelli[2], and Nicole Cortinovis[3]

ABSTRACT

The case presented in this study concerns a building that has just passed through its first century of life, it is the parish church of San Bernardino in Sesto Calende in the province of Varese (Italy), where the Ticino river forms at the end of Lake Maggiore. The Church was built in 1905 following the demolition of the ancient church dating back to the XV century, due to serious cracks attributed to strong soil settlements.

The objective of this study concerning the new Church is to determine and analyze the causes that led to the current damage situation after only 100 years, verifying the static safety conditions. The results of the analysis can be used to assess the foundations.

An integrated approach was adopted, combining visual observation with structural calculation using the Limit Analysis method. The results obtained are the result of a process that has involved and correlated various disciplines including historical research, architectural representation, geological analysis and engineering analysis, all necessary in order to understand the complexity that distinguishes architectural heritage.

KEYWORDS: church, masonry structure, soil settlement, historic masonry structures, crack pattern, limit analysis

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A Decade of Deterioration: Evaluation of Limestone Cladding at the Daily Planet

Paper 189

Emma Cardini[1] and Nikki Baldvins[2]

ABSTRACT

Originally known as the Industrial Trust Tower, the 111 Westminster Street building is the tallest building in the city of Providence and the state of Rhode Island. Standing at 428 feet and comprising 28 floors, it was the tallest building in New England for over twenty years after completion in 1928 and is most well known locally for its similarity to the Daily Planet building in the Superman comics. The building has also been featured on the Providence Preservation Society's Most Endangered Properties List multiple times (2014, 2016, 2017, 2018, and 2019). Constructed between 1927 and 1928, the building was designed by Walker & Gillette in the Art Deco style popular at the time. The majority of the facades of the building are constructed of grey Indiana oolitic limestone.

The author has performed regular close-up inspections of the building facade since 2006; initially investigating the causes of limestone spalls and subsequently performing annual close-range inspections to monitor deterioration. Early project tasks included reviewing historical construction documents, observing underlying conditions at inspection openings, performing close-range facade surveys, and performing laboratory analysis of original building materials. Annual inspections have continued with only emergency stabilization repairs performed. It is a rare opportunity to observe a building of this significance and size over the course of twelve years while being left to deteriorate. 111 Westminster provides tangible evidence of what can happen to natural stone and embedded steel if moisture is trapped by sealant in a marine climate. It is a canvas of past repairs that have illustrated cause and effect.

KEYWORDS: limestone, art deco, steel corrosion, endangered property, spalling, sealant

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Design Procedure for Confined Masonry Walls Subjected to Uniform Out-of-Plane Loads

Paper 059

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Luis Fernandez-Baqueiro[3]

ABSTRACT

A procedure to determine the design out-of-plane strength of confined masonry walls subjected to uniform loads is presented. This procedure considers that confined walls are divided into an unreinforced masonry wall panel and a flexible reinforced concrete frame. The frame is formed by the two vertical and the top confining elements. The out-of-plane strength can be governed by failure of the wall masonry panel or failure of the confining elements. Type of failure depends mainly on the selected properties of wall masonry panel and reinforced concrete confining elements. The out-of-plane strength of confined walls governed by wall masonry panel failure is calculated using an analytical model called the Bidirectional Strut Method. This method is based on two-way arching action. Alternatively, the out-of-plane strength of confined walls governed by failure of confining elements is calculated performing a linear elastic structural analysis of the frame of confining elements and corresponding concrete design of those elements. The structural analysis is carried out using in-plane forces obtained from the Bidirectional Strut Method and corresponding torsional moments. For practical purposes, design tables were developed using the Bidirectional Strut Method. The out-of-plane strength governed by wall masonry panel failure, the in-plane forces transferred to the frame of confining elements and the type of wall masonry panel failure can be obtained from those tables, depending on geometric and mechanical properties of confined walls. In general, design tables can be used for confined walls with different axial compressive strength of masonry, slenderness ratio, axial load, stiffness of confining elements and wall openings.

KEYWORDS: confined masonry, out-of-plane loading, design procedure

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The Design and Construction of the City Creek Center Masonry Façade

Paper 281

John G. Tawresey[1]

ABSTRACT

Located in the heart of down town Salt Lake City, just blocks from the 13th North American Masonry Conference, City Creek Center is a premier shopping experience with hundreds of stores, a fully-retractable glass roof, fountain shows, waterfalls and a creek running through the project. But, for those interested in masonry, City Creek Center is much more. City Creek Center serves as an example of modern structural masonry design and construction. With its geometrically complex brick and precast concrete facades, located in a seismically sensitive area, the masonry exterior wall design and construction was a challenge. The design solutions, extending over a two-year period, drew heavily upon this author's design experience and resulted in new and unique applications of structural masonry.

The scope of the project included six buildings and two large retail malls. Masonry systems used included Structural Brick Veneer (SBV), Reinforced Brick Veneer (RBV), Laid-in-Place Brick Panels, Brick Veneer on Steel Studs, and unique building attachments. Additionally, unlike the normal bidder-designed facade delivery method, a design-bid delivery method was used. The masonry facade was designed concurrently with the design of the architectural, structural and mechanical systems. The resulting cooperation between consultants provided opportunities for material and labor cost savings, and performance enhancements that would not have been possible in the more conventional bidder-design delivery method.

KEYWORDS: structural, design, façade, brick, precast, curtainwall

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Development of Enclosure Masonry Walls Made with Improved Thermal Performance Blocks

Paper 049

Rui Sousa[1], Hipólito Sousa[2], Luísa Sousa[3], and Luís Silva[4]

ABSTRACT

Energy savings/efficiency and environmental sustainability in building construction are motivating the development of new masonry products with these concerns in the last decade.

This paper describes the development of a new masonry wall with improved thermal and mechanical behavior, made under the scope of a national/Portuguese research project. One of the main challenges of this project was to conciliate/maximize the thermal resistance of the wall without significantly impairing its mechanical strength. Since the blocks have the most important/influential role in the behavior of the masonry walls, the work performed was focused on the development of a new block with limited width (250 mm), however with improved thermal insulation and enough mechanical strength.

An experimental campaign, involving factory productions, lab tests and numerical/optimization simulations, was made to support/validate the thermal/mechanical characteristics of the new block, including masonry assemblies made with these blocks. Several mixtures of lightweight concrete, with dry densities between 700 to 1100 kg/m3, and different proposals for the internal geometry of the block were developed in order to achieve the best possible thermal/mechanical behavior for the block.

The final solution obtained was a vertical perforated block with an optimized internal geometry, made with an open structure lightweight concrete with dry density (near 800 kg/m3) and low thermal conductivity. The results obtained from lab tests and numerical simulations demonstrated that this new block has a high potential to constitute masonry walls with improved thermal behavior and enough mechanical strength. However, some adjustments are still needed, highlighting a better stabilization of the concrete thermal/mechanical properties after being submitted to the manufacturing/casting process of the blocks (vibration/compression).

KEYWORDS: energy efficiency, masonry walls, thermal block, lightweight concrete, numerical optimization, laboratory testing

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Development of Light Transmitting Mortar

Paper 061

Jason Lampton[1] and Frederick R. Rutz[2]

ABSTRACT

Translucent concrete is a relatively new concrete-based building material with light-transmissive properties due to optical fibers embedded into normal cement mix. This paper reports on research done at the University of Colorado Denver, applying this concept to masonry and successfully developing Light Transmitting Mortar (LTM). Like translucent concrete, where light is conducted through concrete blocks from one side to the other through fiber optics, optical fibers are introduced within the mortar joints of masonry units to create a composite material that could be used by any mason without any extra specialized training. Although LTM was developed with architectural applications in mind, tests demonstrate that it increases the strength of the overall assemblages and does so significantly. The added strength benefits, combined with the many possible eye-catching patterns that can be created by placing lights behind or within the cavity of masonry structures, will open the door to new and stimulating possibilities for architects and engineers.

KEYWORDS: translucent, mortar, fiber, optics, light transmitting, transmitting

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The Development of a Standard Masonry Bond Wrench for International Use

Paper 245

John M Nichols[1]

ABSTRACT

There are three distinct bond wrenches in use currently in the USA, Europe and Australia. A decade long study at Texas A&M University (TAMU) using the US and the Australian bond wrenches has investigated the bias and precision for the two wrenches using a standard brick and mortar type commonly used in Texas construction. Two new simpler bond wrenches were developed at TAMU, termed the balanced and unbalanced TAMU bond wrenches. These wrenches are significantly cheaper to build, safer to use and provide a consistent set of results that has been compared to the other wrenches and the standard US masonry beam tests. The purpose of the paper is to provide a set of standard plans for the two wrenches and outline some of the critical results differences to the US and Australian wrenches. The objective is to ultimately align all major masonry standards to one wrench type.

KEYWORDS: bond wrench test, standard

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Diagnosis of Damage in Masonry Structures: Repair for Non-Destructive Geometric Restitution

Paper 277

Manuel Fortea[1], Julio Jesus Palomino Anguí[2], Antonio Sousa Gago[3], Mark Sarkisian[4], Neville Mathias[5], and Samantha Walker[6]

ABSTRACT

Masonry structures do not collapse because of material overstress. They do not collapse because tensile stresses exceed maximum allowable stresses. They collapse simply because of loss of equilibrium. When an arch built of stone voussoirs collapses, the voussoirs typically end up on the floor in one piece without any breaking, which makes it possible for them to be used again. Before collapse, masonry structures undergo considerable geometric deformations while still maintaining their stability, deformations which other types of structures such as concrete are not capable of withstanding. The reason behind this is that masonry structures do not have elastic behavior (in which deformations are proportional to stresses). They exhibit plastic behavior, i.e. collapse occurs when the amount of joints formed is sufficient to turn the structure into a mechanism. This has direct effects when it comes to working with them: First, there's no concern related to the maximum working stresses of the material. Second, attention must be paid to equilibrium. Since working with tensile stresses in the material is of no concern, it is possible to easily work with lightweight materials. By paying attention to equilibrium, it becomes possible to achieve geometries that are responsible for stability. This paper explores solving structural problems in masonry arches and vaults by adding masonry units in order to restore them to their original shape and arch structure load. This methodology works because strength is not an issue in those structures. Several successful examples will be presented in the paper. The paper also includes an extended theoretical explanation of the problem.

KEYWORDS: masonry structure, reinforcement, arch, seismic loading, structural damage, thrust line

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Discrete Element Analysis of the Seismic Behavior of an Ancient Roman Temple Façade

Paper 226

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ABSTRACT

In this research, the seismic behavior of an ancient Roman temple façade, dating back to late 2nd to early 3rd century AD, is investigated by means of three-dimensional (3D) discrete element modeling. The temple is in the ancient city of Antioch ad Cragum, near the modern-day town of Gazipaşa on the southern coast of Turkey.

The entire façade, composed of four columns, the architrave, frieze, pediment, and walls, is examined in depth by modeling them as rigid blocks based on the discrete element method (DEM). Mortar in the joints is not considered as the original construction is dry stack masonry. The block sizes are determined from the measurements during the site visits. Non-linear static and dynamic analyses are performed using discrete element models. Furthermore, as a parametric investigation, the influence of the number of drums on the seismic response of the façade is studied. The seismic behavior and the damage state of each structural configuration is discussed under different earthquake excitations. The results provide a prediction of the seismic performance of future reconstruction in two possible scenarios: a) just the superstructure, and b) the entire façade. The investigation also provides a better understanding of the original collapse mechanism of the façade.

KEYWORDS: discrete element modeling (DEM), ancient temple, seismic behavior, pushover

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Displacement Demand Equations for the Non-Linear Static Analysis of Short-Period Masonry Structures

Paper 140

Stylianos Kallioras[1], Gabriele Guerrini[2], Stefano Bracchi[3], Andrea Penna[4], and Francesco Graziotti[5]

ABSTRACT

This paper discusses the accuracy of four established methods and proposes two improved formulations for calculating earthquake-induced displacement demands, to be used for the assessment of masonry structures in conjunction with non-linear static analysis procedures. All predictions make use of codified elastic displacement spectra, which are modified to account for inelastic effects following different approaches. Focus is placed on systems with fundamental periods between 0.1 and 0.5 s, for which the inelastic seismic displacement amplification is usually more pronounced. The accuracy of the predictive equations is assessed based on the results from nonlinear time-history analyses, carried out on single-degree-of-freedom oscillators with hysteretic force-displacement relationships representative of masonry structures; the same analyses are also used to calibrate the proposed formulations. Two independent sets of ground-motion records are employed to evaluate the methods under tectonic and induced-seismicity scenarios. First, the study demonstrates some limitations of two established approaches based on the equivalent linearization concept: the capacity-spectrum method of the Dutch guidelines NPR 9998-18, and its version outlined in FEMA 440, both of which overpredict the maximum displacement. A non-iterative procedure, making use of an equivalent linear system with an optimal stiffness, is then proposed to overcome some of the problems identified for the two established methods. Two codified formulations relying on inelastic displacement spectra are also evaluated: the N2 method of Eurocode 8 and the displacement-coefficient method of ASCE 41-17. The former proves to be significantly unconservative, while the latter is affected by excessive dispersion. A recently developed modified N2 formulation is shown to improve the accuracy while limiting the dispersion of the predictions for both suites of ground motions.

KEYWORDS: capacity-spectrum method, equivalent linear system, inelastic displacement spectra, structural assessment, nonlinear static analysis, seismic displacement demand

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Ductility of Confined Masonry Walls: Results from Several Experimental Campaigns in Mexico

Paper 116

Juan Jose Pérez-Gavilán[1]

ABSTRACT

Displacement capacity and ductility of confined masonry walls are evaluated. Data from several experimental studies in which full scale, confined masonry walls were subjected to cyclic lateral loads was reviewed. Specimens include walls made of traditionally-crafted clay bricks, extruded clay units and multi-perforated concrete blocks. The walls included different amounts of horizontal joint reinforcement. The ductility of the specimens was reevaluated using a standardized procedure to make them comparable. The lateral displacements, obtained from pseudo-dynamic tests, were scaled to take into account experimental observations made in shaking table tests that show that the lateral displacements obtained in the shaking table are much larger than the observed ones in pseudo-static tests. Considering that in a multi-story masonry structures, plastic displacements concentrate in the first floor, the ductility demand in the first story can be estimated given the global ductility and the number of stories of the structure. In this study, the number of stories that a structure, with walls similar to those tested, may have is calculated, so that the walls in the first floor may develop the calculated ductility demand for that number of stories and a given global ductility. A recommendation for the drift and ductility limits for masonry structures with and without joint reinforcement and for solid and hollow units is given. The results are valuable to have a clearer view of the expected global ductility of masonry structures and its relation to their number of floors.

KEYWORDS: confined masonry, ductility, displacement, demand

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Durability of Brick Masonry and the Absorption Alternate

Paper 117

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ABSTRACT

Durability, or the resistance to damage as a result of cycles of freezing and thawing, is an important characteristic of brick masonry, especially in northern climates. One widely accepted means to predict a brick unit's resistance to freeze-thaw cycles is to determine its saturation coefficient as defined by ASTM C216 Standard Specification for Face Brick and ASTM C62 Standard Specification for Building Brick. However, ASTM C216 and ASTM C62 have an "Absorption Alternate" that indicates the saturation coefficient requirement does not have to be met as long as the 24-hour cold water absorption of five brick units does not exceed 8.0 percent. Some architects and engineers choose to exclude the Absorption Alternate and provide more strict restriction on the saturation coefficient when specifying brick masonry to be used in climates with more significant freeze-thaw cycling due to their past experience with failures of Grade Severe Weathering (Grade SW) brick. The intent of this paper is to explore the history behind of the current methods to determine the durability of brick masonry, decipher the requirements of the ASTM specifications, raise awareness for specifying and using brick masonry, outline procedures utilized by manufacturers to provide durability improvements, discuss potential issues that can arise from accepting the Absorption Alternate, and outline recommendations for potential situations where using more strict requirements than those provided in ASTM C216 and ASTM C62. Case studies are also presented relating to the durability of brick masonry.

KEYWORDS: durability, freeze-thaw, absorption, saturation, brick, silicone

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Dynamic Analysis of the Bell Action on the South Tower of the National Palace of Mafra

Paper 268

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ABSTRACT

Slender structures like ancient masonry bell towers are subjected to various types of static and dynamic actions, such as self-weight and earthquakes. In this work, the forces produced by the swinging of bells were evaluated, which can cause local damage. The dynamic behavior of the south bell tower of the National Palace of Mafra, in Portugal, was analyzed under forced vibration generated by the motion of four bells located at a height of 49 m, which rotate in full circle according to the Spanish system. For this purpose, a Finite Element model was built and calibrated using the results from the in-situ tests, and the dynamic forces of the bells were calculated as function of time. Two approaches were adopted to evaluate the structural response of the tower. The first set of analyses were focused on the frequency content of the excitations induced by the bells, in order to assess possible interactions with the natural frequencies of the structure (resonance effect). The second approach consisted of several time-history analyses assuming different load combinations, aiming at evaluating the global dynamic performance of the tower over time and assessing the damage on the masonry close to the supports of the bells. According to the results, the tower has an appropriate overall dynamic response when the bells are swinging. Moreover, these forces do not represent a source of local damage for the masonry elements.

KEYWORDS: tower, bell, Spanish system, Mafra

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Dynamic Behavior of Box Type Scaled Stabilized Earth and Fired Clay Block Masonry Building Models

Paper 125

Nanjunda K. S. Rao[1]

ABSTRACT

The paper discusses the outcome of the experimental investigations conducted on five scaled box type masonry building models with various kinds of earthquake resistant features for the purpose of evaluating their effectiveness in reducing their vulnerability during earthquakes. Two of the building models were of one-fourth scale and remaining three were of half scale. The one fourth scale building models were without roof slab, while the half scale models were with rigid roofing system. One each of the one-fourth scale and half scale models had all round RC horizontal bands at lintel and roof levels. The one-fourth scale model also had vertical reinforcing steel at corners as suggested by the Bureau of Indian standards (IS 4326:1993). The other building models had all round RC horizontal bands at sill, lintel and roof levels and vertical steel hugging the masonry walls on both faces at corners and adjacent to door and window openings. The vertical steel was connected discretely through bed joints of masonry using steel wires. The base motion to the building models was provided through a shock table test facility which was designed and developed as a simple and cost-effective alternative to the conventional shake table. Based on the investigations conducted the following conclusions are drawn:

1. The shock table test protocol developed has been successful in evaluating the dynamic behavior of scaled masonry building models and in simulating the failure patterns as observed in damage surveys after the earthquakes.

2. The earthquake resistance features suggested by the Bureau of Indian standards (IS 4326:1993) are found to be inadequate in preventing collapse of masonry buildings during severe ground shaking.

3. The provision of vertical reinforcement hugging the masonry wall in addition to RC band at sill level is effective in limiting damage and ensuring seismic safety.

KEYWORDS: masonry structure, model, horizontal band, seismic vulnerability, reinforced masonry, earthquake resistance

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Dynamic Thermal Performance Measurements of Residential Wall Systems Part II, with Numerical Validation of Steady-State Performance

Paper 200

Nathaniel C. Huygen[1] and John P. Sanders[2]

ABSTRACT

Real-world thermal performance of wall systems cannot be accurately characterized by simple steady-state R-value measurements. This is because real-world conditions are never stable and are constantly changing, thus requiring thermal mass to be taken into account. In this study, a hot box apparatus was used in order to determine steady-state R-value measurements, as well as dynamic thermal performance. By using heat flux transducers in the hot box apparatus, the energy transfer through the wall was measured and characterized under cyclic thermal loading. This study aimed to produce both steady-state and dynamic thermal characterization of a variety of typical residential wall types. In addition, 3D finite element simulations in ANSYS were carried out under steady-state conditions in order to provide numerical verification of hot box results and create a model capable of producing results for other wall systems without needing to perform lengthy hot box testing. Part I of this study was focused on the calibration of the hot box as well as characterization of four residential wall systems. These included a reference wood stud wall, fiber cement board siding, vinyl siding, and a brick veneer cavity wall. Part II added more wall systems to this list: insulated vinyl siding and Exterior Insulation and Finish System (EIFS) with insulation thicknesses of one inch, one-and-a-half inches, and two inches. The brick veneer wall had an R-value 14.7% higher than the reference stud wall, but under dynamic testing performed over 50% better, highlighting the importance of thermal mass.

KEYWORDS: brick, thermal performance, R-value, thermal mass, hot box, finite element modeling (FEM)

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The Effect of Fire Temperatures on the Mechanical Performance of Concrete Masonry Materials

Paper 017

Hamish Pope[1] and Ehab Zalok[2]

ABSTRACT

Concrete Masonry has been known to have excellent fire protection properties. Its large thermal mass helps to keep the fire contained and reduces the temperature at the core of the masonry assembly which allows for a longer time for the loads to be carried. This is important because the mechanical properties of concrete blocks and mortar begin to deteriorate as the material heats up. The main properties that effect the stability and temperature profile of masonry exposed to fire are its thermal expansion, density, thermal conductivity, and specific heat capacity. There can be a large difference in the properties between two concrete mixes, based on factors such as aggregate type, mix design, moisture content, and the addition of supplementary cementitious materials. This technical paper aims to outline the (a) effects of temperature on the mechanical properties of masonry materials and (b) effects of different concrete types on the performance of concrete masonry at fire temperatures. This is done by explaining the chemical and physical changes that concrete undergoes when it is heated, as well as outlining the results of several different researchers. In conclusion, thermal expansion is an important factor that needs to be taken into account when deciding which materials to use in concrete masonry to reduce negative effects at elevated temperatures and keep the residual compressive strength high. The residual compressive strength of concrete is usually unchanged below 400C. Above 400C the strength starts to decrease due to a combination of moisture loss, micro cracks, chemical decomposition, and thermal stresses. The strength loss can be mitigated by using thermal stable aggregate such as lightweight aggregates or certain recycled aggregates. Supplementary cementitious materials can also be used to reduce micro cracking and improve the mechanical properties of concrete at elevated temperatures.

KEYWORDS: fire temperatures, concrete masonry, thermal properties, mechanical properties, mix design, aggregates

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Effect of Gap Between Column and Masonry Infill on the Response of Masonry-Infilled Reinforced Concrete Frames

Paper 124

Ashutosh Sonpal[1], Manish Kumar[2], and Hrishikesh Sarma[3]

ABSTRACT

Reinforced concrete (RC) frames with an unreinforced masonry infill constitute the primary lateral force resisting system in a large number of buildings across the world. The lateral force-displacement response of infilled RC frames is a function of the geometrical and material properties of the frame and infill, and the interaction between the two. The interaction is affected by the gap between columns and masonry infill. This paper presents a study on the effect of column-infill gaps on the lateral force-displacement response. A finite element model of a masonry-infilled RC frame is developed, calibrated, and validated against experimental studies on one-bay-one-story infilled RC frames (with and without column-infill gaps) subjected to lateral in-plane loads. A parametric study using the finite element model revealed that the presence of a column-infill gap does not affect the peak strength of the infilled frame substantially but leads to a considerable reduction in the initial stiffness. The load shared by the frame decreases significantly with an increase in the gap. The extent of reduction may be a function of specimen, however. Therefore, a gap between the columns and the masonry panel may help contain the damage to the frame.

KEYWORDS: masonry infill, RC frame, column-infill gap, finite element modeling (FEM)

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The Effect of Impact Energy Loss in Seismic Response of Unbonded Post-Tensioned Rocking Masonry Walls

Paper 091

Dimitrios Kalliontzis[1], Arturo E. Schultz[2], and Sri Sritharan[3]

ABSTRACT

Previous research studies investigated the use of vertical unbonded post-tensioning for rocking masonry walls as it leads to re-centering with minimal damage. Most of those studies employed quasi-static tests to characterize the seismic behavior of the walls, ignoring that additional energy loss results from dynamic impacts at the rocking interface. This paper employs a previously validated dynamic analysis approach pertaining to rocking walls to show that neglecting impact energy loss may overestimate their seismic displacements and underestimate their damping capabilities. Contribution of the impact and other mechanisms to the seismic responses of the walls is quantified in terms of equivalent damping ratio. It is shown that a simple relationship can be developed to estimate this ratio as a function of the maximum seismic responses of rocking masonry walls.

KEYWORDS: unbonded, rocking, impact energy loss, dynamics, post-tensioned masonry, damping

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Effect of Interior Vertical Reinforcement on the Performance of Partially Grouted Masonry Shear Walls

Paper 159

Amr Ba Rahim[1], Jeffrey Hung[2], Clayton Pettit[3], and Carlos Cruz-Noguez[4]

ABSTRACT

Partially grouted (PG) masonry shear walls are a cost-effective and efficient choice as a lateral force resisting system due to their low cost and ease of constructability. However, the behavior of these PG walls is complex, due to the inherent anisotropic properties of the masonry materials and the nonlinear interactions between the mortar, blocks, grouted and non-grouted cells, and reinforcing steel. As a result, the shear strength of PG walls is still not well understood, and recommendations from codes of practice often lead to uneconomical designs – while being unconservative in some cases. One parameter that has a non-negligible influence on the shear strength of PG walls is the influence of the vertical reinforcement. Although theorized to play a contribution through dowel action and resisting crack openings, North American codes do not account for the influence of vertical web reinforcement. In this paper, an investigation of the effect of vertical web reinforcement on the shear capacity of PG shear walls using finite element (FE) methods is presented using a macro-modelling technique. An analysis model for the in-plane shear strength of PG walls was developed and validated with experimental tests. A parametric analysis of the vertical web reinforcement was conducted to quantify the influence it has on the overall shear capacity of the wall. The results revealed that the web (interior) vertical reinforcement contributes to the shear strength of PG walls. This contribution is depicted in a linear trendline that best fitted the relationship between web vertical reinforcement and shear strength.

KEYWORDS: partially grouted masonry, shear walls, vertical reinforcement, shear strength, macro modeling, parametric analysis

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Effect of Side-Wall Openings on Out-of-Plane Behavior of Dry Stack Brick Walls

Paper 126

Barış Erdil[1] and Fırat Kıpçak[2]

ABSTRACT

Out-of-plane behavior of brick walls are affected by several factors two of them being mortar type and presence of side walls. Although, historical mortars are usually the main part of brick walls, due to their lack of durability and strength, they may deteriorate by time and in some cases total loss can also be visible. Side walls are also important because they add strength to the main wall serving as restraints through its high in-plane rigidity. However, the effect of that restraint may reduce due to the openings owing to the reduction in in-plane stiffness. Concerning these two aspects, dry-stack walls were built with side walls having different type of openings. Tested walls had several configurations: L-shaped walls (one side wall) without openings, side wall with window or door opening; U-shaped walls (two side walls) without openings, one side wall with door or window openings, one side wall with door and the other one with window opening. In all cases, main front walls did not have openings. All tests were performed by a specially designed tilting-table and the front walls were equipped by 15 LVDT's located at each height and width to record the out-of-plane deformation profile. Besides 2 LVDT's were used to have vertical displacements of the table which was then used to relate with pushover force. It was realized that as the size of openings increased, the pushover capacity of L-shaped walls decreased. As for U-shaped walls, the worst behavior was observed with door openings, but all other cases showed insignificant effects from the openings.

KEYWORDS: brick, dry stack masonry, openings, out-of-plane, tilting table

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Engineering Judgment for Historic Building Façades

Paper 029

Edward A. Gerns[1] and Rachel L. Will[2]

ABSTRACT

Do the structural provisions in modern building codes dictate methods of evaluation that are inappropriate for historic buildings? Various structural masonry components, including exterior facades, in many older buildings do not meet current structural code provisions and yet the vast majority have been in service for decades in the United States and centuries throughout the rest of the world. Building codes, especially the structural provisions written into these documents, have evolved due to construction experience, engineering and architectural research, material and system testing, the ability to model intricate structural systems, and lessons learned from various building and structural failures. Yet does this evolution suggest that the application of the current codes is always appropriate for buildings constructed without all of this additional knowledge? Does the lack of meeting current standards automatically designate a portion or component of a building as unsafe? Moreover, what does it mean if a building is "not up to code"?

Building code requirements triggered by significant alteration of existing structures can have dramatic economic impact on rehabilitation projects, of which the masonry facades are generally a large percentage of the cost and risk. Absence of rational/practical engineering judgment with regard to the code regulations relative to the existing structures often results in unnecessary upgrades. Furthermore, current regulatory approaches relying extensively on the judgment of local building officials, can lead to unpredictable and inconsistent results, unwarranted loss of historic fabric, and excessive expense for conservative structural retrofits.

This paper provides an overview of some of the common components and systems, specifically related to the facades of historic masonry buildings that do not strictly comply with current code requirements. Representative examples will be included ranging from smaller detailing support elements for facades, wall systems and the integration of the facade support with the building structure.

KEYWORDS: façade, code, structural, rehabilitation, retrofitting, historic masonry

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Ergonomic Assessment of Standard vs. Heavy-Weight CMU Lifts

Paper 066

JuHyeong Ryu[1], Lichen Zhang[2], Mohsen Diraneyya[3], Carl T. Haas[4], Eihab Abdel-Rahman[5], and Bennett Banting[6]

ABSTRACT

Handling concrete masonry units (CMU) may lead to adverse effects on masons, such as work-related musculoskeletal disorders to the back and shoulders. This study evaluates the compression forces and joint moments acting on the lower back during handling two types of CMUs. Eight journeymen, each with more than 20 years of work experience, completed five-courses of pre-built lead walls with two types of CMUs weighing 16.6 kg (36.6 lb) and 23 kg (50.7 lb). Whole-body motion data was collected using wearable inertial measurement unit (IMU) suits to estimate the biomechanical loads. The experimental results indicate that lifting heavy CMUs results in approximately 30% higher lower back compression force than standard CMUs. Joint moments acting on the upper limb joints showed proportionately elevated values. Lifting standard and heavy CMUs generated the highest and lowest back compression forces during work in the second (lowest) and fourth courses, respectively. In particular, back compression force during laying of heavy CMUs in the fourth course was similar to the compression force when laying standard CMU in the second course and both were less than the safety limit (Action Limit) recommended by NIOSH. We also found that the shoulder moment when lifting a heavy CMU to the fourth course was lower than that when lifting a standard CMU to the sixth course. These findings indicated that worksite design to enable lifting and laying CMUs at an optimal height can safely expand the use of heavy CMUs.

KEYWORDS: masons, ergonomics, lifting, biomechanics, low-back loading, shoulder loading

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Evaluation of Construction Provisions to Avoid Cracking in Masonry Partitions Affected by Structural Deformations of Concrete Slabs

Paper 074

Hipólito Sousa[1] and Rui Sousa[2]

ABSTRACT

Partitions walls can be damaged and crack when affected by the deformation of structural elements during their use in buildings. Masonry is the most common solution used for partitions. However, giving their brittle behavior, construction provisions to avoid cracking may have to be evaluated and implemented in these walls.

In this paper, a numerical study was conducted to evaluate the susceptibility of cracking of traditional Portuguese masonry partitions affected by vertical deformations of concrete slabs during serviceability conditions (with and without creep effects). Two different modeling approaches were used: simulation of a concrete structure interacting with the unreinforced masonry partitions constructed with lateral or top movement joints, and another simulation of isolated masonry deep beams constructed with and without reinforcements. The most common construction solutions used in Portuguese buildings for structural systems, partition walls and reinforcement techniques (reinforcement of mortar bed joints and mortar coatings) were used in these simulations.

To simulate the behavior of masonry panels, a non-linear model calibrated with experimental results was used, a linear elastic model was assumed for the concrete structure and an elastic-plastic model was used for the steel reinforcements. The effect of creep in the masonry and concrete was calculated according to European standard calculation methodologies.

The results obtained demonstrated that the use of reinforcement techniques can be a solution to increase the strength and deformation of these walls in order to avoid cracking, as well as the use of movement joints and a proper control of structural deformations. Some recommendations are suggested.

KEYWORDS: masonry partitions, masonry partitions, cracking, numerical simulation, construction provisions

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Evaluation of Macro Models for Masonry-Infilled Reinforced Concrete Frames

Paper 168

Rajdeep Ghosh[1] and Manish Kumar[2]

ABSTRACT

Masonry-infilled reinforced concrete (RC) frame buildings are widely seen in India and around the world. The presence of the masonry panels leads to a complex lateral force-displacement response of the infilled RC frames due to an uncertain and brittle behavior of the masonry wall, and the interaction between the wall and the surrounding frame. Simplified macro models are often used to simulate the response. These models differ primarily in the number and orientation of the struts, and corresponding constitutive model. This paper presents an evaluation of 56 macro models (eight strut models coupled with seven constitutive models). These models are used to simulate the lateral force-displacement response of 35 one-bay-one-story masonry-infilled RC frames tested experimentally. The response is quantified in terms of the ratios of analytically calculated to experimentally observed values of initial stiffness, peak strength, and "residual" strength. The analytical determination of the flexural and shear failures in the RC members is also compared with the corresponding experimental observations. A single strut model can be used to simulate the response, if shear failure in RC members is not important. Two-strut models with off-diagonal struts only led to a poorer estimation of the peak strength and the post-peak response compared to the one-strut and the three-strut models. Macro models with three struts can be used to simulate the lateral force-displacement response. Placement and orientation of the struts in a three-strut model did not affect the calculated response considerably. Of the seven constitutive models considered, different models led to "best" estimation of the parameters under consideration (e.g., initial stiffness, peak strength). A new constitutive model comprising the "best" features of the existing models can be developed.

KEYWORDS: strut, constitutive model, experimental specimens, lateral force-displacement response, pushover analysis

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Evaluation of the Adherence Between Clay Blocks and Grouts

Paper 148

Gustavo Sipp[1], Guilherme A. Parsekian[2], and Marcio R. S. Correa[3]

ABSTRACT

The behavior of masonry elements is influenced by the properties of the materials used and their interface characteristics. This research intends to evaluate the adherence properties between grout and clay blocks applied in structural masonry. For this purpose, push-out tests were used to evaluate the adherence strength between 5 types of clay blocks and 2 types of grouts. As a result, it became clear that the grout compressive strength influences the bond strength and blocks with grooved cell geometries provide greater adherence strength. Therefore, what can be stated by this research is that the use of blocks with grooved surface cells can be more suitable for the use in masonry structures, since their capacity to transmit forces and deformations tends to be greater than the smooth surface blocks.

KEYWORDS: block, grout adherence, push-out test

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Experimental Determination of the Behavior of Lag Screws in Masonry Veneer Shelf Angles

Paper 044

Clayton Pettit[1], Jesus Salazar[2], Carlos Cruz-Noguez[3], and Mark D. Hagel[4]

ABSTRACT

Masonry building envelopes (veneers) are an architecturally pleasant, efficient system for protecting structural members against moisture penetration and heat loss. An integral part of the design of masonry veneers is the shelf angle, which supports the outer brick layer and is bolted or secured to a floor system. A typical detail in mid-rise wood-frame buildings is the use of thru-bolts to secure the angle to the rim board. Although effective, this type of connection can be time-consuming and expensive to install. The penetration to the building envelope due to the thru-bolt also requires additional sealing for the system to retain its thermal efficiency. As a result, lag screws are becoming a common alternative within the industry to the thru-bolt system, but there is a scarcity of test data regarding lag screw performance. In this paper, an experimental program developed to determine the performance of lag screws as an alternative option to attach shelf angles to wood floor systems is presented. The experimental program involved six specimens. Each specimen consists of a steel angle bolted into the side of a typical timber floor system using lag screws. The spacing of the lag screws was varied to reflect current industry practices. The load-displacement response and failure modes of the connections are presented and discussed. The main conclusions from the work presented herein are that the lag screws are a feasible alternative to thru-bolts to attach shelf angles in timber floor systems. Lag screws do not withdrawal from the rim joists and provide a significant margin of safety when comparing the ultimate load to service load.

KEYWORDS: masonry veneer, lag screws, experimental testing, timber slab

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Experimental Evaluation of an Unreinforced Masonry Building Strengthened with Steel Bands

Paper 194

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ABSTRACT

Strengthening of unreinforced masonry (URM) buildings has become an important issue because of huge URM building stocks in different parts of the world including India. Application of steel bands over URM buildings has been a practice in some seismically active regions of India. However, the strengthening measure was adopted more or less in a non-engineered manner as an ad-hoc measure to reduce the damage to URM buildings during earthquakes. In the present experimental study, slow-cyclic tests were carried out on three full-scale, single-bay, single-story masonry buildings, out of which two were strengthened using steel bands to evaluate the effectiveness of the strengthening scheme. In one of the buildings, single band at lintel level was provided using steel flats on both sides of the walls, while in the other, both horizontal and vertical steel bands were provided at critical locations observed during testing of the un-strengthened building. The application of steel bands over URM buildings exhibited promising results with significant improvement in the lateral load behavior. Use of the steel bands for strengthening vulnerable URM buildings can be an inexpensive and efficient way without modifying the architecture of the buildings.

KEYWORDS: unreinforced masonry (URM), cyclic in-plane shear, strengthening, steel bands

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Experimental Investigation of the Capacity of Masonry Beams with Different Aspect Ratios and Quantities of Steel

Paper 152

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ABSTRACT

The overall behavior of masonry beams is largely dependent on the aspect ratio and quantity of flexural steel in the beam. The objective of this study was to evaluate how aspect ratios and longitudinal reinforcement affects the behavior of six experimental masonry specimens. It also served as a class project to introduce students to experimental testing. As a result, a set of three beams with aspect ratios ranging from 0.67 to 1.5 was conducted. The quantity of steel remained constant to isolate effect of aspect ratio. Another three beams were tested with varying levels of steel to observe the failure mode transition from flexure to shear. Capacities were predicted based on the Strength Design Provisions of the 2016 TMS code. This paper presents the failure patterns, cracking sequence, mid-span deflections, and ultimate loads that the beams resisted.

After testing of the beams, the experimentally observed capacities of the beams exceeded the predictions determined based on the TMS code. In addition, the mid-span deflection increases as the aspect ratio, a/dv, increases. Finally, the ultimate capacity increases, as the aspect ratio decreases. The beams with varying levels of flexural steel revealed a transition from flexure-dominated behavior to shear-dominated as the quantity of steel increased.

KEYWORDS: flexure, shear capacity, aspect ratio, masonry beam

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Experimental Investigations on the In-Plane Shear Behavior of Unreinforced and Reinforced Masonry Panels

Paper 037

Nanjunda K. S. Rao[1] and Joshi Amrut Anant[2]

ABSTRACT

The paper addresses the issue of in-plane shear resistance of unreinforced and reinforced masonry walls. Investigations have been conducted on (1) triplet masonry shear specimens, (2) unreinforced masonry panels subjected to monotonic diagonal compression loading and (3) masonry panels reinforced with near surface mounted galvanized iron (GI) wires subjected to monotonic and cyclic diagonal compression loading.

The masonry triplet specimens were subjected to shearing load along the mortar joint while simultaneously being subjected to compression load normal to the joint. Totally 30 specimens were tested at 6 levels of compression stress in the range of 0.004 to 0.9 MPa. Nine square shaped masonry panels of size 710 mm and thickness 110 mm were subjected to diagonal tension (shear) test as per American Standards for Testing Materials (ASTM E519-15) recommendation. Three specimens were unreinforced while six specimens were reinforced with two numbers of 4 mm diameter GI wires on both faces of the specimen. From the tests conducted on triplet masonry specimens, cohesion and friction angle were estimated to be 0.46 MPa and 45 respectively.

Tests conducted on masonry panels subjected to monotonic diagonal compression showed that shear modulus of unreinforced and reinforced masonry was 2160.0 MPa and 2410.0 MPa respectively. Reinforced masonry showed 60% enhancement in non-hysteretic energy dissipation compared with unreinforced masonry. Cyclic load tests on reinforced masonry panels showed 65% stiffness degradation up to 20% normalized displacement (normalized with respect to maximum displacement). The hysteretic damping was found to increase almost linearly up to 40% normalized displacement and there after remained fairly constant at about 11%.

The present study shows that by modestly reinforcing masonry it is possible to considerable enhance energy dissipation capacity and thereby reduce seismic vulnerability of masonry buildings.

KEYWORDS: reinforced, stiffness, damping, energy dissipation, cyclic in-plane shear, shear modulus

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Experimental Study of Out-of-Plane Behavior of Timber Retrofitted Masonry Prisms

Paper 100

Jamiu A. Dauda[1], Ornella Iuorio[2], and Paulo B. Lourenço[3]

ABSTRACT

Typical unreinforced masonry (URM) walls have little strength to withstand out-of-plane loads. Under severe out-of-plane loading, URM walls failure is likely to be sudden and severe, producing devastating damages and death. Since out-of-plane failure mode has been identified as the most critical failure mode of URM walls, this study thus focuses only on investigating the out-of-plane behavior of URM wall. This paper presents a small-scale testing program to evaluate the out-of-plane load capacity and deformation of masonry prism subjected to out-of-plane loading. This is the first stage of a multi-phase experimental and numerical investigation into the possibility of retrofitting URM walls using timber-based panels.

In this research, flexural bond strength in form of four-point bending test was obtained from nine different masonry prisms (615 x 215 x 102.5mm), three of which are tested as plain specimens. The remaining 6 specimens were retrofitted with an 18mm thick Oriented Strand Board (OSB) timber panel using two different types of connection (C1: adhesive anchor and C2: mechanical connection). Based on the results of the experimental tests, the out-plane load capacity and displacement of both plain and retrofitted specimens were assessed in order to highlight the performance of the proposed retrofit technique. It was observed that the application of OSB panel at the back of masonry greatly influences the flexural behavior of the test specimens preventing sudden failure of masonry prisms.

KEYWORDS: flexural strength, four-point bending test, masonry prism, OSB panel, out-of-plane loading, retrofitting

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An Experimental Validation of a Procedure to Distinguish Global and Local Modes of Masonry Structures

Paper 182

Daniele Brigante[1], Carlo Rainieri[2], and Giovanni Fabbrocino[3]

ABSTRACT

Earthquakes have shown the inherent vulnerability of the masonry buildings, in particular those belonging to architectural complexes in the form of building aggregates. Building aggregates are identified as the result of an articulated, but not unitary growth of the construction, in a way that structural units (growth cells) are added to existing ones often sharing the same boundary wall. Due to uncertainties from material characterization and structural behavior, prevention and preservation have be-come a complex task in seismic regions. The issues related to the definition of an appropriate structural and dynamic model often jeopardize the reliability of seismic analysis. A primary concern is the discrimination between the local response of selected macro elements and the global response of the structure. This paper describes an original approach to solve the problem in the case of large architectural complexes. The approach relies on the computation and spatial analysis using the Modal Assurance Criterion; moreover, the approach can be purely numerical or take advantage of dynamic testing of the investigated structure. Results from application of the pro-posed procedure to a case study, indicating how the proposed approach can guide engineers towards the selection of the most appropriate numerical analysis procedure in the seismic assessment, are presented in this paper.

KEYWORDS: modal assurance criterion (MAC), mode shape classification, dynamic identification, local modes, global modes, seismic analysis

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Experimental and Computational Study of the Influence of Pre-Damage Patterns in Unreinforced Masonry Crack Propagation Due to Induced, Repeated Earthquakes

Paper 052

Paul Korswagen[1], Michele Longo[2], Edwin Meulman[3], and Jan G. Rots[4]

ABSTRACT

Induced seismicity in the north of the Netherlands has recently exposed unprepared, unreinforced masonry structures to considerable earthquake risk. While the ultimate-limit state capacity of the structures is vital to assess the individual's risk, their behavior during more frequent, lighter earthquakes, leading to 'lighter damage', has shown to be strongly linked to economic losses and societal unrest. When observing the light damage caused by minor earthquakes, the existing state of the structure appears to be highly relevant for the final damage intensity and configuration: earthquakes that may have otherwise caused no apparent damage, may intensify existing damage. In particular, incipient damage due to settlements is common in the baked-clay and calcium-silicate brick masonry structures of the region.

This paper details the study of full-scale laboratory walls, pre-damaged following typical (crack) patterns caused by settlements and tested with quasi-static lateral loads. The aggravation of the damage during a relevant number of load cycles is monitored using full-field digital image correlation. The damage is quantified objectively using a purposely-developed damage parameter.

The tests are used (together with previous studies) to further calibrate computational finite element models, which coupled with detailed soil-structure interaction boundary conditions, are then employed to assess a larger number of structural geometries and pre-damaged configurations exposed to (repeated) induced earthquake acceleration histories.

Both experimental and computational approaches show that settlement pre-damage in masonry structures increases the likelihood and the amount of further damage. This is more easily observed when some initial, yet limited, damage exists and the masonry wall is exposed to moderate earthquake vibrations in the order of 30 mm/s.

KEYWORDS: unreinforced masonry (URM), induced seismicity, light damage, damage aggravation, crack propagation

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Experimental and Numerical Study of Uniaxial Compression Behavior of Compressed and Stabilized Earth Blocks

Paper 203

Erika L. Rengifo-Lopez[1], Nitin Kumar[2], Fabio Matta[3], and Michele Barbato[4]

ABSTRACT

The compressive strength of earth masonry blocks is an important analysis and design parameter and quality indicator. The sustainability advantages of compressed and stabilized earth block (CSEB) masonry have prompted its use in structural applications in developed countries worldwide. However, there is no consensus on specimen geometry, size, and boundary conditions for the experimental characterization of the compressive strength. This knowledge gap is relevant since CSEBs are manufactured in a wide variety of sizes, and compressive strength inevitably depends on specimen geometry (i.e., aspect ratio, cross-sectional area).

This paper reports on a study of the uniaxial compression behavior of CSEB specimens. The scope of the study was two-fold. First, cylindrical CSEB specimens with different aspect ratio were load tested to characterize experimentally the axial stress-strain response. Second, the test data were used to define detailed continuum micro-models for finite element (FE) analysis. The prototype CSEB was manufactured using a mixture of local South Carolina medium-plasticity in-organic-clay soil, water, and 6% (by weight) of ordinary Portland cement. Three-dimensional digital image correlation (3D-DIC) was enlisted to perform full-field non-contacting strain measurements, and better understand axial strain distribution and constraining (loading platen) effects as a function of cylinder aspect ratio. The load-displacement data served to validate the detailed FE model. Finally, the FE model was used to gain a preliminary insight into the uniaxial compression response of cylindrical CSEB specimens with different aspect ratios.

KEYWORDS: aspect ratio, compression test, compressive strength, constitutive model, earth block, finite element modeling (FEM)

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Failure Mechanism of Top Corner in Unreinforced Masonry

Paper 232

Kyle Lerch[1], Logan Cayton[2], and Sara Ganzerli[3]

ABSTRACT

The failure of the top corner in an unreinforced masonry building is evident in many earthquake occurrences. However, this failure mechanism has not received much attention in the literature. In areas populated by older construction, the masonry structures are typically unreinforced. After an earthquake event, it has been observed that an inverted prism located at the top corner of a building separates from the rest of the structure. The plane of failure is inclined, and the angle of inclination has been previously investigated with the assumption that the height of the prism corresponds roughly to the height of a story. The approach taken was graphical and iterative, which is similar to an approach used in soil mechanics. The adaptation of this method to unreinforced masonry is a novel concept. In this paper the work is carried further, assuming different heights for the failing prism and introducing more load cases to encompass a larger realm of possibilities. This method is easy to implement, yet effective and constitutes a way to address a complex problem in a simplified manner. This paper represents a contribution in the area of historic construction and should be informative for engineers and architects involved in the retrofitting of older buildings located in earthquake-prone areas.

KEYWORDS: corner, failure mechanism, unreinforced masonry (URM)

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The Failure of Partially Grouted Masonry Walls Subject to In-Plane Shear Is Affected by the Stiffness of the Grouted "Frame"

Paper 090

Huina Pan[1], Andrea C. Isfeld[2], and Nigel G. Shrive[3]

ABSTRACT

Masonry subject to in-plane shear typically fails in one of three independent modes: sliding, diagonal cracking or flexural failure. Combinations of these modes also occurs, typically sliding combined with diagonal cracking or diagonal cracking with flexure. When partially grouted masonry is considered, the wall can fail as a wall in one of the possibilities above, or the wall can fail as a series of panels, each typically failing with diagonal cracking. In previous tests on two walls, each with three panels with aspect ratio near 1, one wall failed in a whole wall mode, while the other failed as three panels. The objective of the work presented was to determine if the difference in failure mode could be due to differing stiffnesses of the "frame" of grouted cores and bond-beams encompassing the panels. Two different approaches with the finite element method were used to show that the stress distribution in the panels is distinctly affected by the stiffness of the grouted core and reinforcing bar. As the stiffness of the "frame" surrounding the unreinforced panel (the stiffness of the grouted column and the bond beam above) increases, so the failure mode shifts from a wall response with failure in one of the well-established modes to a panel response, where the wall fails as a series of panels. The failure load for a multi-panel wall is not a simple multiple of the failure load of a single panel. We conclude that the stiffness of the "frame" in partially grouted masonry needs to be taken into consideration when assessing the potential failure mode and strength of such masonry subject to in-plane shear.

KEYWORDS: blockwork, partially grouted masonry, in-plane shear, reinforcement stiffness, panel failure

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Finite Element Analysis of Hollow Concrete Block Masonry Walls

Paper 085

Andrea C. Isfeld[1], Mark D. Hagel[2], and Nigel G. Shrive[3]

ABSTRACT

The Canadian Masonry Design Standard, CSA S304-14, requires that walls having a slenderness ratio greater than 30 meet design provisions beyond those required of less slender walls. Such walls must be designed with pinned end connections at the top and bottom of the wall and the axial load must not exceed 10% of the factored axial strength of the effective cross section, amongst other requirements. Pinned end conditions are required to account for the effects of snap-through and other factors which may reduce the effects of end restraints, while limitations are placed on the axial load to prevent buckling. Previous testing of reinforced concrete masonry walls has focused primarily on walls with pinned-pinned boundary conditions under eccentric and concentric axial loads precluding the observation of realistic in-situ behavior. Under these idealized test conditions buckling has rarely been observed. More recent testing has examined the ability of reinforced masonry walls actually to form a pinned connection at the base under eccentric axial and out-of-plane loading. Results from testing of these walls and the constituent materials were used to calibrate finite element models. Models were developed of pinned-fixed and fixed-fixed hollow, unreinforced, concrete block masonry walls using the detailed micro-modeling approach, modeling units and mortar as separate contacting parts. Displacement controlled loading was modeled at varying eccentricities for pinned-fixed walls having slenderness ratios between 5 and 60 to identify the slenderness at which failure transitions from compressive material failure to buckling at each eccentricity. Results of the modeling show that for hollow concrete block walls buckling initiates at a slenderness above 40 when a load eccentricity of t/10 is considered. Expansion of such modeling to partially grouted, reinforced walls may be applied to reexamine the approach used in the CSA S304-14 standard.

KEYWORDS: buckling, out-of-plane failure, slender walls, concrete masonry wall, finite element modeling (FEM)

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Finite Element Simulation of Confined Semi-Interlocking Masonry Walls

Paper 098

Mehdi Hemmat[1], Yuri Z. Totoev[2], and Mark J. Masia[3]

ABSTRACT

The semi-interlocking masonry (SIM) has been under study and development in the Centre for Infrastructure Performance and Reliability at The University of Newcastle, Australia. High displacement ductility, as well as significant earth-quake energy dissipation, were observed during in-plane tests on frames with SIM infill panels. Hence, combining semi-interlocking masonry with other systems could be of interest. Confined masonry is a typical masonry system with the proven track record in many earthquake-prone regions. It is simple and cost effective. Any additional improvements in its earthquake performance would be welcomed. It is proposed in this paper to combine SIM with confined masonry to form a new earthquake-resistant system which is called confined semi-interlocking masonry (or CSIM) and investigate the structural performance of CSIM walls using numerical pushover analysis. Gradually increasing in-plane horizontal displacement was applied on simulated CSIM walls using a detailed micro-modeling FE approach. Results were assessed in terms of strength, cracking, and displacement. In addition, the effect of vertical pre-compression load, as the representative of the weight of walls at higher stories; together with the effect of shear toothing existence between the confining elements and the SIM panel were investigated.

KEYWORDS: semi-interlocking masonry (SIM), sliding joints, numerical simulation, micro modeling, shear toothing

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Flexural Testing of a Concrete Masonry Unit Wall with Near-Surface Mounted Steel Reinforcement

Paper 104

Adrien Sparling[1], Dan Palermo[2], and Fariborz Hashemian[3]

ABSTRACT

In conventional concrete masonry unit wall construction, reinforcing bars are positioned in the center of the grouted cells of the masonry units. Such positioning limits the out-of-plane stiffness of walls built using this technique, and therefore the height to which they can safely be constructed. Near-Surface Mounted (NSM) steel reinforcement allows reinforcing bars to be placed near the extreme tension fiber of completed walls, resulting in increased flexural stiffness. This paper out-lines the construction and testing procedure for a 1.2m long by 3.2m tall hollow masonry wall with a gross reinforcement ratio of 0.25%. Flexural testing demonstrated that the hollow wall with NSM steel reinforcement had a comparable strength but smaller ductility than that of one reinforced conventionally; however, the stiffness of the wall prior to yielding of the NSM reinforcement was approximately 2.2 times greater than that of the conventional wall.

KEYWORDS: flexure, stiffness, concrete, near-surface-mounted (NSM) reinforcement, out-of-plane, walls

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Flexure Behavior of Reinforced Masonry Assemblages Under Monotonic and Cyclic Loading

Paper 150

Nanjunda K. S. Rao[1] and Joshi Amrut Anant[2]

ABSTRACT

The primary reason for collapse of unreinforced masonry buildings during earthquakes is out-of-plane flexural failure of walls which jeopardizes the gravity load carrying capacity. Reinforcing masonry in the vertical direction along with continuous horizontal bands for establishing integral connection of various walls of the building will ensure overall stability of the building. This paper addresses the issue of flexural behavior of reinforced masonry assemblages under monotonic and cyclic loading. Flexure studies have been conducted on (1) Stretcher bond (110 mm depth) and English bond (230 mm depth) masonry beams with near surface mounted reinforcement consisting of galvanized iron (GI) wire of 4 mm diameter and high yield strength bars of 5.35 mm and 10.0 mm diameter and (3) Rat-trap bond masonry beams of 230 mm depth reinforced at the middle of the depth with GI wires of 4 mm diameter. Totally twenty beams were tested, ten under monotonic four point bending and remaining under reverse cyclic three-point bending. The cyclic loading was of sinusoidal pattern with increasing displacement amplitude and decreasing frequency (1.0 Hz to 0.2 Hz). The parameters considered were yield tensile strength of reinforcement and percentage area of reinforcement. However, for all the beams the percentage area of reinforcement provided was a fraction of the area of reinforcement required for balanced section. The primary purpose of reinforcing masonry was to enhance ductility and energy absorption capacity and not strength.

From load-displacement and moment-curvature response, displacement ductility and curvature ductility were found to be in the range of 1.1 to 14.5 and 1.3 to 12 respectively. The equivalent hysteretic damping at failure was found to be in the range of 5% to 20%. It was observed that there is steep reduction in stiffness (degradation) up to 10% of normalized displacement and remains fairly constant thereafter till failure.

KEYWORDS: flexure, cyclic in-plane shear, reinforced masonry, ductility, hysteretic damping, stiffness degradation

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Force-Displacement Response of Semi Interlocking Masonry Panel Under Large In-Plane Displacement: An Experimental Study

Paper 097

Md. Akhtar Hossain[1], Yuri Z. Totoev[2], and Mark J. Masia[3]

ABSTRACT

An innovative masonry building system is being developed in the Centre for Infrastructure Performance and Reliability at The University of Newcastle, Australia for seismically vulnerable regions as an alternative to traditional masonry panels. This system consists of mortar-less masonry panels made of semi-interlocking masonry (SIM) units capable of relative sliding in-plane of a panel and inter-locked to prevent sliding out-of-plane of a panel. These special panels have significant energy dissipation capacity due to friction on sliding bed joints between the SIM units during a seismic event. As SIM is a new masonry system, it is important to study the load-displacement behavior. In this study, a new approach is developed to idealize the load-displacement response of SIM infill panels. The force-displacement response of SIM panels can be described by two equivalent bilinear relationships. In order to evaluate the seismic behavior of framed SIM panels, a series of three SIM panels were built with topological SIM units and have been tested by subjecting them to cyclic in-plane displacements up to 100mm. It has been shown for the current study that besides shear displacement and energy dissipation capacity, the initial slope of bilinear relationship should be taken into account as a governing parameter when evaluating the force-displacement response of SIM panels in large displacement.

KEYWORDS: semi-interlocking masonry (SIM), idealized force-displacement curve, sliding joints, energy dissipation, large in-plane displacement

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A Homogenized Distinct Macro-Block (HDM) Model for Simulating the In-Plane Cyclic Response of URM Walls

Paper 102

Daniele Malomo[1], Matthew J. DeJong[2], and Andrea Penna[3]

ABSTRACT

The interaction between in-plane and out-of-plane actions, often neglected by simplified numerical approaches, significantly affects the overall seismic response of URM structures. The use of advanced numerical modeling, on the other hand, often entails a relatively high computational cost, limiting applicability to the analysis of local mechanisms. In this work, to combine the efficiency of macro-element strategies with the benefits of discrete element methods, a new macro-element approach to model in-plane cyclic behavior of URM panels is presented. Shear damage is accounted by a homogenized Finite Element macro-block, while flexural and sliding phenomena are represented through equivalent interface spring layers between discrete elements. The methodology is evaluated through comparison with both micro-modeling results and experimental outcomes on full-scale wall specimens characterized by different aspect ratios, boundary conditions and overburden pressures. In particular, the abilities of the proposed method to predict stiffness and strength degradation, energy dissipation and P- effects, are quantified. Moreover, contrarily to most of the macro-elements presently available in literature, the damage propagation can be reproduced directly. Being implemented in an explicit Distinct Element code, naturally suitable for large-displacement analysis, out-of-plane modes and collapses can also be considered by modeling each unit separately. The employment of this hybrid modeling strategy is demonstrated through an initial application, leading to adequate results within a reasonable timeframe.

KEYWORDS: finite-distint element method, numerical modeling, in-plane, unreinforced masonry (URM)

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The Impact of Green Codes and Standards on the Masonry Industry in the US

Paper 013

Christine A. Subasic[1]

ABSTRACT

Energy efficiency of buildings has been a focus of federal energy policy in the United States for many decades. In the last 15 years, interest in energy efficiency of buildings has grown and expanded to include other aspects of "green" or sustainable design and a wider audience. This paper examines the impact the green building movement has had on the masonry industry, including masonry products. Specifically, model energy codes, carbon footprint, and LEED® are analyzed for their influences.

Increasingly stringent model energy codes have led to a decrease in single-wythe masonry construction in certain parts of the US, increases in cavity width to accommodate more insulation, and other changes in masonry wall design. Energy codes have also influenced masonry products, with new materials, unit requirements, and designs. The focus on carbon footprint has led to changes in ingredients and manufacturing techniques used to make masonry products and spawned much research on the subject. Green programs such as LEED® and other green standards have also impacted masonry products and accessories, especially related to their raw ingredients. As these green codes and standards continue to evolve so too does the masonry industry to meet the demands.

KEYWORDS: masonry industry, energy code, green building, carbon footprint, LEED, manufacturing

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Impact of Moisture Curing Conditions on Mechanical Properties of Lime-Cement Mortars in Early Ages

Paper 134

Meera Ramesh[1], Miguel Azenha[2], and Paulo B. Lourenço[3]

ABSTRACT

Blended lime-cement mortars, which are frequently used in masonry construction, mature as a result of two different phenomena, namely lime carbonation and cement hydration. At any given temperature, these two processes require different moisture conditions for optimal contribution to the mechanical performance of mortar. Since mortars have an impact on the non-linear behavior of masonry from the time of application, it is necessary to optimize their performance with regard to composition and curing conditions. It is expected that a suitable choice of mortar in conjunction with the unit will provide better performance of masonry by reducing risk of cracking and facilitating durability of masonry.

This work aims at studying the impact of environmental relative humidity (RH) in the curing process of lime-cement mortars, focusing on their early age behavior. Two mixes with 25% and 67% lime in the binder (by volume), binder-aggregate ratio of 1:3, and target workability of 17510 mm were chosen for the study. Mechanical properties like compressive strength, flexural strength, open porosity and density have been studied at 2, 4 and 7 days of curing age. Temperature was kept constant at 20C while three distinct environmental humidity conditions were tested: sealed environment, 90% RH, and 60% RH. Results have been explored to understand how the evolution of basic mechanical properties changed as a function of curing RH. Curing in sealed conditions and 90% RH did not result in similar values of strength, in either of the two blended mixes. For the mix with 25% lime - 3C1L12S (25%), hardening appeared to be guided by cement hydration. For the mix with 67% lime - 1C2L9S (67%), curing in RH of 60% and 90% resulted in almost the same strength at day 7, demonstrating that lime carbonation may be important earlier than 7 days.

KEYWORDS: mortar, moisture curing conditions, early curing age, mechanical strength, lime and cement, relative humidity

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Improving Performance of Unbonded Post-Tensioned Masonry Walls with the Use of Rubber Interface

Paper 146

Dimitrios Kalliontzis[1], Sri Sritharan[2], and Arturo E. Schultz[3]

ABSTRACT

Using thin rubber pads underneath the compression toes, seismic performance of structural masonry walls with unbonded post-tensioning was investigated. The intent of the proposed system was to enhance the seismic performance of masonry walls, while minimizing structural damage and improving their self-centering capability. This research study investigated the experimental behavior of a one-story concrete masonry wall with the proposed features. To accurately capture the effect of impact and hysteretic energy loss, the wall was subjected sequentially to dynamic and quasi-static excitations. Throughout the tests, the wall exhibited resilient behavior with stable responses, which included negligible strength degradation and no virtual damage to the masonry up to lateral drifts of 4.7%. The different energy dissipating mechanisms and displacement components experienced by the wall were quantified at various levels of responses. The rocking mechanism dominated the lateral wall behavior, followed by small sliding movements at the wall-to-foundation interface and flexure deformations within the masonry wall panel. Experimental findings also showed that hysteretic action was concentrated within the rubber pads, providing about one-half of the energy dissipation in the wall, with the rest being attributed to dynamic impacts of the wall at the foundation surface.

KEYWORDS: resiliency, rubber, rocking, impact energy loss, hysteresis, post-tensioned masonry

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In-Plane Loading Tests for Confined and In-Filled Masonry Panels in RC Frames with Eccentric Door and Window Openings

Paper 062

Yi-Hsuan Tu[1], I-Ting Tung[2], Ting-Wen Yang[3], and Tsung-Chih Chiou[4]

ABSTRACT

This paper presents a sequential series of the tests for confined and in-filled masonry panels with eccentric openings. The specimens included two confined and two in-filled masonry panels surrounded by identical RC frames. Each construction type has a specimen with eccentric door and window openings, respectively. All specimens were tested with displacement-controlled cyclic lateral in-plane loading in a double-curvature manner. Constant vertical force was applied during the tests. The test results showed that the specimens had asymmetric behavior under cyclic loading. Because of the lack of confinement around the openings, the confined and in-filled panel acted similar when they were pushed by the column. The difference between the two construction types only showed when the loading was pulling back. The windowsills in these tests did not appear to affect the panel behavior but caused short-column effect to the frame and decreased the deformation capacity.

KEYWORDS: confined masonry, masonry infill, openings, eccentric openings

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Influence of Brick and Mortar Properties on the In-Plane Lateral Behavior of Partially Grouted Reinforced Masonry Shear Walls

Paper 255

Sebastián Calderón[1], Cristián Sandoval[2], and Oriol Arnau[3]

ABSTRACT

During last years, several researches have studied how the in-plane lateral behavior of partially grouted reinforced masonry (PG-RM) shear walls is influenced by design properties. In general, masonry compressive strength, horizontal reinforcement ratio, height-to-length ratio, and axial compression stress have been the most researched design properties. However, only few studies have addressed this issue by studying the influence of the constituent materials' strength, such as compressive strength of brick and mortar.

This paper presents the results of a numerical study focused on determining the influence of compressive and tensile strengths of brick and mortar on the in-plane lateral behavior of PG-RM shear walls. For this purpose, a previously validated detailed micro-model of a full-scale square wall tested in laboratory is employed as reference wall. The material properties of three bricks and three mortar are used as input parameters for calculating the reference wall and analyzing the effects on its response.

The results obtained are analyzed in terms of lateral deformation, lateral capacity and displacement ductility, leading to significant conclusions about the influence of brick and mortar compressive and tensile strengths on the masonry walls' performance. Finally, it is pointed out that the employed methodology can be extensively used to determine the influence of other material properties and other un-studied geometrical properties (e.g. joint thickness) on the shear response of PG-RM walls.

KEYWORDS: micro modeling, partially grouted masonry, shear walls, parametric study

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Influence of Distributed Fiber Reinforcement on Concrete Masonry Ductility

Paper 105

Joshua T. Hewes[1] and Jeff Hamlin[2]

ABSTRACT

A new type of ductile fiber reinforced concrete masonry (FRCM) is proposed to improve the seismic performance of reinforced concrete masonry shear wall construction. The current US masonry design specification limits maximum compression strain in concrete masonry shear walls to 0.0025 and requires boundary elements and verification testing for some designs in order to achieve the wall ductility implied by the code. It is theorized that a delay in onset of concrete masonry unit splitting can be achieved by inclusion of small amounts of randomly distributed reinforcing fibers, thereby improving the seismic behavior of shear walls dominated by flexure.

Twelve fully grouted, three course tall concrete masonry prisms were tested in uniaxial compression to investigate the improvement in falling branch characteristics when masonry units contain varying amounts of distributed synthetic fiber reinforcement. Fiber percentages by volume included 0% (control), 0.15%, 0.30%, and 0.45%, and a decreasing post-peak compression stress – strain response slope was observed as fiber percentage increased. However, peak compression strength of prisms was also observed to decrease with increasing fiber percentage as compared to the control without fiber.

Moment – curvature analyses were performed for the control and 0.15% fiber FRCM for a sample reinforced concrete masonry shear wall, and large increases in curvature ductility were observed for axial force ratios varying between 2.5% and 10%. Graphs of curvature ductility versus flexural reinforcement ratio were created to investigate the overall ductility of FRCM, and improvements in ductility averaged between 40% and 50% compared to conventional masonry. Finally, maximum flexural reinforcement ratios are calculated for varying levels of extreme fiber compression strain to illustrate the potential increase in reinforcement amount while maintaining code prescribed minimum ductility levels.

KEYWORDS: ductility, seismic, fiber reinforced, shear walls

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Influence of Ductile Shear Wall Ratio on the Seismic Performance of Reinforced Concrete Masonry Shear Wall Buildings

Paper 130

Nader Aly[1] and Khaled Galal[2]

ABSTRACT

The structural system of reinforced concrete masonry buildings typically involves load bearing walls. Therefore, the reinforced masonry shear walls are resisting both vertical and lateral loads. It is well-known that as the axial load increases on the walls, the lateral drift capacity and ductility are adversely affected. This paper is proposing and investigating component and system level solutions to enhance the overall seismic performance of reinforced masonry buildings. At the component level, it was proposed to utilize end-confined shear walls to reduce the compression zone and enhance the compression strain capacity. At the system level, a hybrid structural system composed of ductile and gravity walls was proposed. This hybrid structural system would allow using various ductile shear walls' arrangements and ratios (i.e. ratios of ductile shear walls' area in one direction to total floor area). A series of linear dynamic, nonlinear static and nonlinear time history analyses were performed to quantify the enhancements from the proposed solutions on the overall response. The study aims at recommending shear wall ratios that optimize the design and the overall structural response. It targets mid-rise reinforced concrete masonry buildings in locations with moderate seismicity. The results of the study demonstrated that the utilization of the proposed structural system with reinforced concrete masonry shear walls with boundary elements (i.e. end-confined) as the ductile walls resulted in significant improvements in the seismic behavior and optimization of the design. Hence, this would promote ductile reinforced concrete masonry shear wall buildings as a competitive structural system for mid-rise buildings in zones of moderate seismicity.

KEYWORDS: ductility, boundary element, shear wall ratio, hybrid structural system, seismic response, reinforced masonry shear walls

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Influence of Soil Backfill Depth on the Strength and Behavior of Masonry Arch Bridges in the Transverse Direction

Paper 132

Bora Pulatsu[1], Ece Erdogmus[2], and Paulo B. Lourenço[3]

ABSTRACT

Inspection and assessment of masonry arch bridges indicate that the depth of backfill material has a significant influence on the damage state and failure mechanism of masonry arch bridges. Although, soil backfill provides a positive influence on the strength of arch barrels, it causes lateral (out-of-plane) pressure on the spandrel walls which may lead to spandrel wall failures. In this research, a nonlinear three-dimensional (3D) mixed discrete-continuum modeling strategy is used to assess the transversal strength and behavior of deep medium span masonry arch bridges. Structural components of masonry arch bridges, including spandrel walls, arch barrel and abutments, are simulated via rigid discrete blocks whereas the soil backfill is replicated by a deformable continuum. The representative geometrical properties for the numerical models are taken from a database obtained by a comprehensive survey in Northwestern Iberian Peninsula. Furthermore, collapse mechanism and load bearing capacity of masonry arch bridge models are investigated under different boundary conditions. The results of the analyses demonstrated the importance and the impact of the depth of soil backfill and the interaction of the backfill with the structural components of masonry arch bridges.

KEYWORDS: discrete element modeling (DEM), mixed discrete-continuum approach, discontinuum analysis, masonry-arch bridges, spandrel-wall failure

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Influence of Water Content and Cure-Time of Factory-Made Mortar on Mortar Properties and Bond Strength to Clinker Brick

Paper 080

Jan Kubica[1], Iwona Galman[2], and Kamil Kozdron[3]

ABSTRACT

The problem of water dozing in preparation of the fresh mortar mix is important from the mechanical properties point of view. Nowadays there is the most popular using of ready premixed or ready factory-made mortars, especially mortars with some specific additions, like pozzolans or trass, dedicated for bricklaying using clinker units. In this paper, the results and analysis of laboratory tests on the problem of water content in preparation of fresh factory-made mortar on mortar flexural strength and bond strength to clinker units is presented.

The mortar flexural strength was tested based on the regulations specified in European standard EN 1015-11 whereas the mortar bond strength to the surfaces of the clay clinker hollow units was determined by the "wrench test" method, according to EN 1052-5. Mortar specimens were prepared from the mortar mix with 4.0, 4.5 and 5 dm3 of water per 25 kg bag of ready dry mortar mix. All specimens were tested in 4 series, after 9, 14, 21, 28 days of the samples' seasoning.

Based on the results of the laboratory tests the influence of water content in preparation of fresh factory-made mortar on mortar flexural strength and bond strength was obtained. Moreover, the significant difference between mortar flexural strength in relation to the seasoning period was recorded. The similar situation was observed also for changing of bond strength. Whereas, the shape and character of these two relationships was completely different. The explanation of this phenomenon is also presented and discussed.

KEYWORDS: water-content, mortar flexural strength, mortar flexural test, bond wrench test, clinker unit, curing time

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Influence of the Multi-Layer Bed Joint on the Crack Distribution in Masonry Walls Subjected to Static-Cyclic Loading

Paper 053

Nebojsa Mojsilovic[1], Milos Petrovic[2], and Bozidar Stojadinovic[3]

ABSTRACT

A series of static-cyclic shear tests on full-scale unreinforced masonry walls with a multi-layer bed joint have been performed as a part of a research project on the seismic behavior of unreinforced masonry walls with a soft layer membrane placed in the bed joint. Walls were built using typical perforated Swiss clay blocks and standard cement mortar and a multi-layer bottom bed joints, which comprise a core soft layer protected by two layers of extruded elastomer and placed in the middle of the bottom mortar joint. The preliminary testing phase aimed at choosing the most suitable core soft layer type among the four types considered: rubber granulate, cork, cork-rubber granulate and bitumen. The main testing phase comprised five tests on story-high specimens with rubber granulate core soft layers performed to investigate the influence of the size, the pre-compression level and the aspect ratio on the seismic behavior of walls. Sliding occurred in all specimens tested. However, the final failure mode as well as the displacement capacity of test specimens were governed by the extent of shear and tensile (vertical) cracks that developed from the bottom course.

This paper reports in detail on the development and extent of the developed vertical cracks, which eventually led to the disintegration of the walls, i.e. the reduction of the effective shear-transferring wall area. Further, a model, which is capable of predicting the position of the vertical cracks is presented and its predictive response compared with the experimental findings. One of the recommendations from this study is that engineers must carefully consider the distribution of the shear stresses along the bottom of the wall

KEYWORDS: cracking, multi-layer bed joint, rubber granulate, soft layer, static-cyclic shear loading, unreinforced masonry (URM)

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Integrated Approach for Unreinforced Masonry Stabilization in Historic Buildings of New York City

Paper 201

Katarzyna Burzynska[1], Charu Chaudhry[2], and Marguerite Pinto[3]

ABSTRACT

It has been recently estimated that the majority of existing masonry buildings were designed to resist only axial loads and gravity, without taking into account lateral loads or other factors, which is especially common in historic buildings. One of the causes of this are building codes, which were insufficient at the time some of the structures were built, and since then have been updated to meet the needs of a fast-developing city.

The need for masonry stabilization of existing buildings, especially unreinforced, is a common aftermath of this notion in New York City. Factors, such as settling or vibration occurring due to new construction or excavation works, frequently result in incidents of out-of-plane (bulging and arching, separation at collar joints or between wythes, wall or wythe displacement perpendicular to the plane of the wall) masonry failures.

Masonry stabilization aims to improve the statics of such structures and strengthening them to provide safety of their users while assuring a minimal interference with their aesthetics, especially when dealing with historic or landmark buildings. The approach of emergency interventions varies, depending on the type of failure and particular case of each building.

This paper reviews methods of preventing loss and providing repair and strengthening of unreinforced masonry buildings, i.e. providing stiffness to improve lateral and shear resistance via post-tensioning or grout injection, including examples of successful implementation of said methods in field.

KEYWORDS: unreinforced brick masonry, strengthening, masonry stabilization, historic preservation

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Interface Parameters Between Masonry Concrete Blocks and Mortar for Modeling of Masonry Structures

Paper 101

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ABSTRACT

In order to simulate the behavior of masonry structures accurately using finite elements, the interface between the units and the mortar needs to be represented. A set of 30 samples was tested to obtain the tensile strength of the mortar and the normal stiffness (K_{nn}) of the block-mortar system. To obtain the tangential stiffnesses (K_{ss} and K_{tt}) and the coefficient of friction, 29 samples, subdivided into three levels of pre-compression, were tested. The analytical procedures that allow the block-mortar interface parameters to be determined from the experimental data are presented. Numerical models were developed and are also presented. The material models for the simulations were calibrated using the experimental results. The calibrated interface parameters can be used in more complex numerical models, such as those simulating walls subjected to lateral action.

KEYWORDS: masonry structure, half-scale, unit-mortar interface, bond strength

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An International Perspective of Masonry Promotion

Paper 260

John Chrysler[1] and Elizabeth McIntyre[2]

ABSTRACT

There are many facets of the masonry industry, including research, design, material production and construction, but one overlooked and important component is advertising and promoting the most durable material system since the beginning of habitable structures.

Through collaboration and participation on an international scale, the promotion arm of the masonry industry is coming together by sharing resources, technology and information distribution systems that are beneficial on a global scale.

Australia and the Continental United States share nearly the same land area, but the demographics are significantly different, and this paper will show how different promotion groups over 7,500 miles (12,000 km) apart are sharing their experience for the benefit of not only each other, but also the entire masonry industry.

KEYWORDS: promotion, international collaboration, technical resources, advertising

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Investigating the Role of Masonry Typology Using a Detailed Micro-Modeling Approach

Paper 185

Shenghan Zhang[1] and Katrin Beyer[2]

ABSTRACT

The mechanical behavior of the masonry elements is determined by the properties of the constituents, i.e., block, mortar and interface, and the masonry typology, which depends on the shape and size of the blocks, the mortar thickness and the arrangement of the blocks. The masonry typology varies widely between construction periods and regions but its influence on masonry mechanical properties is not yet well understood.

This study investigates the role of masonry typology using our recently developed tools, i.e., a detailed micro-modeling approach based on cohesive zone model and a versatile masonry typology generator. In this paper, we briefly reviewed the masonry typology generator and different geometrical indexes, i.e., the Line of Minimum Trace (LMT) and the block area ratio. Typical samples obtained from the masonry typology generator are then simulated under compression and shear-compression loading conditions. The correlation between the geometrical indexes and the masonry strengths is further studied. LMTs and block area ratio are shown to be correlated with material strengths for certain failure types, i.e., compressive failure and shear failure. Block area ratio shows a stronger correlation with the masonry strengths than the LMTs, which is further confirmed by numerical investigations on different bond types and different block shapes.

KEYWORDS: masonry typology, typology generator, force capacity, line of minimum trace, block-area ratio, micro modeling

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Investigation and Assessment of the Early Phrygian Gate Complex at Gordion, Turkey

Paper 128

David T. Biggs[1] and Semih Gonen[2]

ABSTRACT

The fortress city of Gordion in central Turkey (modern-day Yassıhöyük) was constructed by the Early Phrygians (ca. 950-800 BCE) and is now renowned as the seat of the most famous Phrygian king, Midas of the Golden Touch, and also for being the spot where history records Alexander the Great cutting the Gordian knot in 333 BCE.

Large-scale excavations that uncovered the fortress city and the Early Phrygian Gate Complex were begun by the University of Pennsylvania in the 1950s. Archeologists believe the gate walls were originally as much as 16 m tall, even though the exposed remains are now less than 10 m. They comprise the best-preserved Iron Age gate building in the entire eastern Mediterranean and ancient Near Eastern worlds and are thus of inestimable cultural-historical significance.

In 1999, Turkey experienced two major earthquakes (Mw=7.4 and Mw=7.2 respectively) along the North Anatolian fault in the northwest, causing widespread damage and the loss of thousands of lives. Although those earthquakes were nearly 230 km from Gordion, they caused an existing bulge in the Gate Complex to increase. Since then, the bulge enlarged to the point where a partial collapse was likely.

Condition assessment of the south gate wall revealed that the problem was the separation of the wall facing leaf from the fill material. In 2014, a site conservation project was begun to conserve and stabilize the bulging wall.

This paper is the companion to "Strengthening and conservation of the early Phrygian gate complex at Gordion, Turkey". Together, the two papers address the assessment and conservation of the South Court walls. This paper describes the investigation and assessment of the project including i) description and investigation of the site, ii) condition assessment of the gate wall via hand calculations and verification with FE analysis.

KEYWORDS: investigation, stone masonry, heritage site, case study, historic preservation, structural assessment

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An Investigation of the Canadian Code-Based Shear Strength Equation of Partially Grouted Masonry Shear Walls

Paper 160

Karren Hudson[1], Clayton Pettit[2], Amr Ba Rahim[3], Jeffrey Hung[4], and Carlos Cruz-Noguez[5]

ABSTRACT

Masonry shear walls are commonly used in multi-story masonry buildings to provide lateral stability against lateral loads such as wind and earthquake. Recent studies have shown that the design code equations regarding the shear capacity of partially grouted walls do not reflect the true behavior consistently, potentially leading to unsafe or uneconomical designs. The shear strength equation for masonry walls presented in the current Canadian design code (CSA S304-14) was investigated to assess its accuracy and determine what improvements could be made to the equation by optimizing the equation coefficients. High-quality data from 27 independent studies were analyzed using non-linear regression. The analysis showed that there is a great need for the accuracy of the CSA shear strength equation to be improved, but this cannot be achieved simply by calibrating the equation coefficients. A new model for the shear strength of masonry is required in order to resolve the errors in the current form of the equation.

KEYWORDS: partially grouted masonry, shear walls, in-plane, shear strength equation, statistical analysis, Canadian code

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Limit States of Unreinforced Masonry Shear Walls: Discussion on Standards Approaches and Regulations

Paper 079

Jan Kubica[1]

ABSTRACT

The analysis of shear (stiffening) walls, especially Unreinforced Masonry (URM) walls is usually based on the shear behavior of masonry. Each shear wall in real construction is subjected to complex states of stress and strain corresponding with the complex state of loading, mainly shearing with pre-compression and, in case of shear walls resisting wind action, in-plane bending too. Such states of loading produce the complex state of stress and strain. Practically there are two main cases of loading:

- shearing in the horizontal direction (mainly with vertical pre-compression and in-plane bending) – as the effect of wind loads and/or seismic influences;

- shearing in the vertical direction (also mainly with vertical pre-compression and sometimes with in-plane bending) – connected with irregular vertical ground movements below the foundations of the building (e.g. irregular settlements or human activity, like mining activity or tunneling works)

Up to now in most of European masonry standards (including Eurocode 6) the problem of unreinforced (as well as reinforced) masonry shear wall calculation (determination and verifying of limit state conditions) is still not so well explained. Simple procedures and/or formulae specified in some standards are not so precise and give different results.

Based on the regulations given in selected masonry standards: EN 1996-1-1:2005 (Eurocode 6-1-1); EN 1996-3:2005 (Eurocode 6-3); Russian national masonry standard II-22-81:2004; former Polish standard PN-B-03002:2007; Swiss Code SIA 266 and American TMS 402/602-16 comparative calculations of example URM stiffening walls were done. The results of calculations of an example shear wall, subjected to horizontal and vertical in-plane shearing will be compared with experimental data. Some remarks, comments and suggestions are formulated and presented.

KEYWORDS: unreinforced masonry (URM), shear walls, stiffening walls, complex stress state, design procedure, masonry standards

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Macro-Model for Steel Frames with Reinforced Masonry Infill Walls

Paper 087

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ABSTRACT

In this article, a new analytical modeling approach is proposed to predict the in-plane behavior of reinforced masonry infill walls. The proposed finite element model for masonry infill walls is comprised of a rectangular frame made of corner-hinged rigid bars and nonlinear springs. Groups of springs are used to model the shear, flexural and shear transfer (including friction) behavior of the infill wall system. In addition, the model separately considers the effect of embedded reinforcements (if present). In the model, interaction between in-fill walls and the building frame is also taken to account. The proposed macro-model facilitates accurate modeling of reinforced masonry walls.

In this paper, a description of the model development is given. Also given is a comparison of model predictions to full sized reinforced infill wall testing. This comparison showed that the proposed model is able to describe all major failure modes of reinforced masonry infill walls and the gradual degradation of the system under loads with an acceptable degree of accuracy.

KEYWORDS: finite element modeling (FEM), masonry infill, openings

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Masonry Structures Using Lightweight Materials

Paper 276

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ABSTRACT

Throughout history, the construction of vaulted masonry structures, such as cathedrals, mosques, castles, palaces, bridges and even self-constructed homes, have been made with similar materials, such as stone, brick, gypsum and clay. This paper presents a pilot study that explored the possibility of using different lightweight materials, such as wood wool board and cellular glass panels, to build timbrel vaults. These materials are low cost and are manufactured in small brick-sized pieces. They can be placed together using lime or plaster mortar. Timbrel vaults can be constructed safely using these materials because they are self-supporting and lightweight. They do not require formwork; therefore, they can be easily and rapidly built with little additional equipment. The results of this pilot study show that the use of these lightweight materials is promising for safe and low-cost construction as well as for new and modern designs, either alone or in combination with other materials. While past research has focused on using steel or fiber reinforced polymer materials to repair damaged masonry structures, the use of lightweight materials may also be an effective solution in their repair or reconstruction. In addition, the lower mass of the structure reduces demands on the foundations and leads to lower seismic demands on the mortar joints holding the bricks together. These materials can also provide improvements in comfort, thermal and acoustic insulation and environmental sustainability compared to traditional ceramic materials. Further research, however, is needed to validate these hypotheses.

KEYWORDS: masonry structure, timbrel vault, wood wool board, lightweight structure, seismic behavior, brick

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Masonry Wall Partitions Acoustic Performance: Components and Thickness Contributions

Paper 010

Alberto Lordsleem Junior[1], Fabia K. Andrade[2], Pedro H. Rosa[3], and Jose Victor Verissimo[4]

ABSTRACT

The performance assurance is the main recent challenge in the residential building construction industry, mainly due to the new Brazilian performance standard NBR 15575. One of these requirements is the wall acoustic performance, which can cause acoustic discomfort when deficient. The purpose of the work is to evaluate the internal and external masonry wall compliance in relation to the Brazilian acoustic performance criteria. The wall acoustic performance research approach analyzes the 4 component types (brick; ceramic, concrete and gypsum blocks) and different coating thicknesses in 15 multi-floor buildings. The major findings indicate that only 25% of internal walls are in compliance with the Brazilian standard; while the external walls were only 10% conform to Brazilian criteria. Although most of the results are below the required level, it is possible to show that the concrete block was the best component in relation other types and it can perform better with the increase thicknesses, but there is a limit thicknesses for this maximum performance acoustic. This specification - concrete block - presents to its more constant behavior in the frequency range of 100 to 3150 Hz, which can reduce variations in acoustic insulation.

KEYWORDS: acoustic performance, masonry walls, brick, block, coatings

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A Mechanical Model for the Cyclic In-Plane Force-Displacement Response of URM Walls

Paper 259

Bastian Valentin Wilding[1] and Katrin Beyer[2]

ABSTRACT

The in-plane displacement-based seismic design of unreinforced masonry (URM) walls in current codes is based on approximating the non-linear force-displacement responses of walls with bi-linear curves. To construct these simplified curves, a prediction of the wall's effective stiffness and drift limits is required. These parameters, however, are determined with empirical models that often do not perform well in predicting the results of tests. The models usually only depend on very few parameters such as, for drift capacity models, the aspect ratio of the wall multiplied by a constant basis drift. They often do not capture observed trends in URM walls with regard to static and kinematic boundary conditions. An analytical model, the Critical Diagonal Crack (CDC) model, was developed recently to simulate the monotonic in-plane force-displacement response of URM walls with clay units, normal strength mortar and bed joints of normal thickness. This article introduces an extension of the model to capture the full response of URM walls subjected to a cyclic loading protocol. It considers the evolution of damages in the wall throughout the loading history derived from analytical considerations and uses it to simulate stiffness degradation and residual drifts. Concluding, the model is compared to quasi-static tests of walls that were subjected to cyclically increasing drifts and varying boundary conditions from literature. It shows a good agreement in capturing the force-displacement loops including drift and force capacity, residual drifts and stiffness degradation.

KEYWORDS: unreinforced masonry (URM), analytical model, force-displacement behavior, cyclic response

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Most Common Myths for Masonry Mortar and Grout

Paper 016

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ABSTRACT

Masonry construction has been used for centuries, even millennia, yet is often misunderstood. Many designers are not exposed to masonry until they are in practice. As a result, some common myths persist. In part, these are due to confusion with concrete construction, which is more widely used and understood. This paper addresses the following common misunderstandings about masonry mortar and grout: selecting a high-strength mortar when a lower strength would suffice; requiring testing for field-sampled mortar and trying to apply a compressive strength requirement to it; not understanding that retempering mortar—adding water and remixing—is typically good practice; limiting the selection of cementitious materials for mortar; and limiting the water content of grout. Best practices for design, quality assurance, and construction are offered.

KEYWORDS: mortar, grout, compressive strength, mix proportioning, quality assurance, quality control

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The Need to Improve Standard Test Methods to Determine CO_2 Sequestration in Cementitious Units for Carbon Footprint Changes

Paper 221

Canan D'Avela[1] and Jason Thompson[2]

ABSTRACT

While it has been assumed for nearly a century that mineral-based materials, especially cementitious-based materials, can absorb (sequester) atmospheric carbon dioxide (CO_2), methods to accurately quantify the net amount of initial carbon dioxide content as well as the amount absorbed after manufacturing (sequestered) has remained problematic. Sensitivity, precision, as well as accuracy have been less than optimum using typical test methods. This paper presents a simplified review of preliminary analyses and reporting protocols attempting to document the amount of carbon dioxide content found in a variety of mineral and cementitious-based materials such as concrete masonry units (CMU). Test methods measuring CO_2 as a gas volume seem to have the greatest difficulties. Sensitivities to the nearest whole percent are typically reported yet are not nearly sensitive enough for today's applications requiring a sensitivity of 0.01% or less. Relative precision ranges (repeatability as relative variations) around 25.6% were not uncommon for intra-laboratory results (same lab, same equipment, same technician) for certain standard test methods. Standard deviations of about 4% or more were also observed. Accuracy approximating +/- 11.4% no longer suffices for today's needs. Yet when analyzing cement's CO_2 mass changes within a concrete, it may only indicate a CO_2 change of 0.00083%, as an example. Test method history along with details regarding the challenges faced by 14 professional laboratories/organizations and 15 researchers involved with this research are explored. Exceptionally detailed analyses of stable mineral crystals were used to add to existing internal calibration. When including those results with test methods incorporating specific CO_2 analyzers, improved cost-effective analyses resulted.

KEYWORDS: sequestration, carbon, chemical, cement, footprint, concrete masonry unit (CMU)

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A New Penetrometric Test for in Situ Mechanical Characterization of Historic Mortar: Preliminary Results on Different Hydrated Lime Mortar Specimens

Paper 198

Giuliana Cardani[1], Roberto Felicetti[2], and Giuseppe Pappadà[3]

ABSTRACT

Some existing non-destructive tools are used to characterize on site the lime-based mortar of historical buildings from a mechanical point of view. Those devices are not only based on the surface hardness but are able to inspect the mortar joints up to a few millimeters' depth. Historical mortar joints are normally too thin to extract representative samples for mechanical characterization and often too weak and without sufficient cohesion, due to a hard significant surface decay. Mortar "sanding" in historic building (lack of cohesion in bedding mortar, reducing it to grains) can penetrate from 20 to 40 mm, without compromising the overall masonry mechanical behavior. This makes it difficult to obtain reliable data on their real consistency.

A new device has been realized to analyze in situ mortar joints, adapting the rebound hammer with a pointy probe (conical tip, 4mm diameter) and able to reach a depth of penetration of 60-70 mm inside the test specimen. The system is based on the automated measurement of the penetration rate at each hammer blow, allowing to discriminate the effect of the most degraded and powdered external mortar. Thanks to a low-cost electronic data acquisition system connected to the hammer, all measurements carried out on site are recorded and made available for processing.

The paper presents a first series of preliminary laboratory tests on different samples of lime mortar made ad hoc for a Round Robin Test. Two different methods were compared on laboratory samples of known compressive strength: static and dynamic penetrometric tests, correlated with the compressive strength obtained in the laboratory and supplied by another university. The resulting correlation between the two methods was promising enough to start a first experience on a historic building where previous diagnostic investigations were carried out and a stratification of mortar joints was detected.

KEYWORDS: mortar, penetrometric test, mechanical properties, lime mortar, correlation curve, mortar joint

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A New Simplified Truss Model of Semi-Infilled Frames Based on Behavior Predicted by Finite Element Analysis

Paper 273

Asok K. Ghosh[1] and Amde M. Amde[2]

ABSTRACT

An extensive investigation into the behavior of semi-infilled frames were carried out by non-linear finite element analysis of various semi-infilled frames. The interaction at the interface between the exterior steel frame and the interior concrete masonry was modeled using a new interface element capable of modeling a non-associated dilatant interface behavior observed in actual laboratory tests. A simple von Mises plane stress plasticity model with an associated flow rule and an isotropic strain-hardening/softening is adopted to model the uncracked masonry. A smeared crack modeling approach has been adopted to model the cracked masonry.

Based on the understanding of the behavior of the semi-infilled frames of various geometry, a "strut-and-tie" model has been proposed for simplified analysis of semi-infilled frames. The load displacement plots of the simplified model with those of the finite element analysis have been compared and a good agreement between the two sets of results was observed. Additionally, the load displacement plots for bare frame were included to observe significant stiffness improvement of bare frame in the presence of infill.

KEYWORDS: interface, mortar joint, plasticity, semi-infilled masonry, strut-and-tie modeling (STM)

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Nonlinear Finite Element Analysis of Unreinforced Masonry Veneer Wall Systems Under Out-of-Plane Loading

Paper 093

Imrose Bin Muhit[1], Mark J. Masia[2], and Mark G. Stewart[3]

ABSTRACT

This paper presents part of a research project that aims to develop an improved understanding of the structural behavior of unreinforced masonry (URM) veneer and facade systems considering the variability of strength and stiffness of the brick, mortar, and wall ties. It is imperative to develop a deterministic nonlinear FEA model prior to establishing a stochastic nonlinear FEA model of veneer walls with flexible backup systems. In this paper, a nonlinear FEA model is developed for a full-sized single-story non-loadbearing veneer wall with ties and flexible timber stud framing as a structural backup. The brick URM wall has dimensions of 2400 mm (h) 2400 mm (w) 110 mm (t) with the inclusion of four vertical lines of ties, and four timber studs as an internal layer of the wall system, spaced as per Australian standards. Both inward and outward acting uniform out-of-plane pressure, which represents earthquake and windstorm loadings, are applied to the masonry veneer wall system. The structural response along with tie force distributions are explicated for both uncracked and cracked veneer. Additionally, the load transfer mechanism for a multistory veneer is also analyzed, and tie force distributions across the height are quantified.

KEYWORDS: unreinforced masonry (URM), masonry veneer, nonlinear numerical modeling, wall ties, out-of-plane loading, tie-force

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Numerical Analysis of Capacity Interaction of Brick Masonry Wallettes Strengthened with Geosynthetic

Paper 178

Hasim Ali Khan[1], Radhikesh P. Nanda[2], and Diptesh Das[3]

ABSTRACT

An un-reinforced masonry wall is subjected to simultaneous in-plane and out-of-plane activities under seismic loading. In this paper, the results of a group of tests with different strengthening patterns using geosynthetic of simultaneous in-plane and out-of-plane loadings on brick wallettes are illustrated. The wallettes were strengthened on one side with various geometric pattern viz parallel, and diagonal. This study showed that strengthening of geosynthetic enhanced the load carrying, deformation, stiffness and ductility with higher increase when using the diagonal pattern for both in-plane and out-of-plane loading. Strengthening effect due to bidirectional loading is also carried numerically with capacity interaction curves. The curve shows a strong interaction effect and gives out-of-plane load on the in-plane shear capability, the minimum for un-strengthened while the maximum for the wallettes with a diagonal pattern.

KEYWORDS: strengthening, geosynthetics, masonry wallette, bidirectional loading, capacity interaction

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Numerical Modeling of Controlled Rocking Post-Tensioned Fully-Grouted Masonry Shear Walls With and Without Energy Dissipation

Paper 023

Ahmed Yassin[1], Mohamed Ezzeldin[2], and Lydell Wiebe[3]

ABSTRACT

Controlled rocking post-tensioned wall systems represent an excellent alternative to conventional reinforced masonry shear walls (i.e. fixed base walls) as a seismic force resisting system because of their low damage and self-centering capability after a seismic event. When a controlled rocking wall experiences a lateral load, a horizontal base crack initiates at the wall-foundation interface, allowing the wall to uplift followed by a reduction in the wall lateral stiffness. Vertical unbonded post-tensioned tendons provide a re-centering force to the wall and hence prevent residual drifts. The reduction in the wall lateral stiffness due to rocking limits the corresponding base shear demands without damage, leading to an essentially nonlinear elastic system. In this research study, a numerical macro model is introduced based on a Multi-Spring modeling approach using OpenSEES. The model is experimentally validated using the results of six fully grouted masonry walls with unbonded post-tensioning tendons tested under cyclic loading, as reported in the literature. These walls include examples of supplemental energy dissipation devices and rocking toe confinement. The results show that the introduced model can capture to a good extent the cyclic force-displacement, hysteresis loops, cyclic stiffness degradation, post-tensioning force variation and strength degradation of the wall. Such a simple macro model provides sufficient accuracy to be used to evaluate controlled rocking post-tensioned masonry walls, while also providing more computational efficiency than advanced finite element micro models.

KEYWORDS: self-centering, controlled rocking masonry wall, fully grouted masonry walls, numerical modeling, unbonded post-tensioning

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Numerical Simulation of the Lateral Behavior of Partially Grouted Reinforced Masonry Shear Walls

Paper 199

Sebastián Calderón[1], Oriol Arnau[2], and Cristián Sandoval[3]

ABSTRACT

Several analysis techniques and approaches have been proposed with the aim of predicting the lateral resistance of partially grouted reinforced masonry (PG-RM) shear walls. Most recent efforts are mainly based on non-linear finite elements method applications, promoted by its versatility and last advances in computers hardware and software. However, it is still difficult to establish procedures and techniques that ensure a reasonable degree of accuracy when predicting the lateral behavior and damage patterns observed in walls tested in laboratory. This fact is produced by the difficulty to adequately consider the several complex phenomena governing the structural response of the reinforced masonry, and also due to numerical issues related to its computational simulation.

This paper presents a detailed micro-modelling strategy focused on reproducing in the most direct way the local mechanisms and phenomena that can be observed and measured in laboratory tests of PG-RM shear walls. A real scale test of a PG-RM square wall subjected to cyclic lateral loading is numerically reproduced with this approach, providing satisfactory results in terms of envelope curve, maximum load, ultimate deformation, and damage pattern.

Different numerical configurations and parameters controlling the iteration and solver method are investigated, obtaining important conclusions as well as recommendations on what should be taken into account when using nonlinear analysis of reinforced masonry and particularly through micro-modelling approach.

KEYWORDS: micro modeling, nonlinear analysis, partially grouted masonry, shear walls, reinforced masonry

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Out-of-Plane Load and Displacement Capacities of SIM Infill Panel with Mechanical Interlocking of Bricks: Experimental Investigation

Paper 078

Orod Zarrin[1], Yuri Z. Totoev[2], and Mark J. Masia[3]

ABSTRACT

The Semi Interlocking Masonry (SIM) system has been developed in the Centre for Infrastructure Performance and Reliability at The University of Newcastle, Australia. The main purpose of this system is to enhance the seismic resistance of framed structures with masonry panels. In this system, SIM panels dissipate energy during earthquake excitation through the friction on sliding joints between courses of brick units. A number of tests have been carried out to evaluate the in-plane load capacity of different framed masonry panels. However, there was only two out-of-plane tests performed on SIM panels (both made of topologically interlocking SIM bricks). The main objective of this study is to investigate experimentally the out-of-plane capacity of a SIM panel with mechanical bricks that was already damaged in previous in-plane tests. This paper presents the results of a full-scale test on a SIM panel made of bricks with mechanical interlocking. The panel was 19802025 mm (length height) respectively and 110 mm thick with full contact to the frame. A lateral load was applied by a hydraulic jack over the small area in the center of the panel. The load and displaced shape of the panel were recorded at regular increments during testing. The results show that this type of SIM panel has significant out-of-plane load and displacement capacity.

KEYWORDS: semi-interlocking masonry (SIM), interlocking masonry, out-of-plane capacity, masonry infill, sliding joints

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An Overview of Masonry Cleaning Techniques for Historic Masonry

Paper 030

Edward A. Gerns[1] and Rachel L. Will[2]

ABSTRACT

This paper focuses on the methodology and rationale for cleaning of historic masonry facades. Cleaning can be performed as a part of a maintenance program or included as part of a larger restoration project. Masonry is susceptible to damage and subsequent accelerated deterioration due the improper selection of the appropriate cleaning materials and methods. Therefore, care is necessary in the determination and implementation of an appropriate cleaning procedure. This paper outlines the authors' methodology in designing a cleaning project including survey, investigation, trials, implementation and evaluation. Additionally, the paper introduces current masonry cleaning systems, describing the general performance, applications and limitations of each. Specific attention will be paid to water soaking, steam, micro-abrasives, chemicals and laser cleaning systems

KEYWORDS: masonry cleaning, water soaking, steam cleaning, chemical, micro-abrasives, laser cleaning

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Parametric Study of the Behavior of Perforated URM Walls Under In-Plane Loading and Comparison with NZSEE Strength Prediction Formula

Paper 068

Milon K. Howlader[1], Mark J. Masia[2], and Michael C. Griffith[3]

ABSTRACT

The reliable prediction of strength and failure modes of perforated URM walls are important in the seismic assessment of URM buildings. These walls form part of the primary lateral load resisting system in URM buildings and have frequently suffered damage in previous earthquake events throughout the world. Due to the anisotropic characteristics of the masonry material, it is sometimes difficult to predict the behavior under seismic loading. The work reported in this paper focused on parametric studies using validated nonlinear finite element modeling (FEM) to improve the understanding of the in-plane behavior of URM walls. The FEM results were compared with the New Zealand Society for Earthquake Engineering (NZSEE) predicted maximum lateral strength and the probable failure modes to assess the reliability of the NZSEE provisions. The parameters considered in this study are the aspect ratio of the wall (pier and spandrel) and vertical pre-compression load. From this study, it is shown that there is a significant effect of the wall geometry on the failure modes and the load resistance capacity. Also, with the variation of vertical pre-compression load, the lateral load resistance capacity and ductility changed. In most of the cases investigated, the NZSEE equations for maximum shear strength and failure modes agree well with the FEM results.

KEYWORDS: unreinforced masonry (URM), in-plane lateral loading, perforated walls, finite element modeling (FEM), aspect ratio, pre-compression load

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Partially Grouted Reinforced Brick Masonry Wall Specimens Made in Greece Subjected to In-Plane Seismic Loading: Experimental Observations and Numerical Predictions

Paper 106

George C. Manos[1], Lampros Kotoulas[2], Lazaros Melidis[3], and Kostas Katakalos[4]

ABSTRACT

The main features of a study dealing with partially grouted reinforced clay brick masonry wall specimens are summarized here. A first objective was to validate the local materials and construction practices used towards building earthquake resistant low-rise partially grouted reinforced clay brick masonry structures in moderate seismic areas of Greece. A second objective was to numerically simulate the observed behavior. The experimental campaign studied the in-plane behavior of such partially grouted wall specimens, built using clay bricks with vertical holes manufactured by a local industry. All wall specimens were partially grouted at specific locations hosting vertical steel reinforcement. Horizontal (shear) steel reinforcement was also included at the mortar bed joints. These specimens were rigidly attached at a reaction frame and were subjected at their top to a constant vertical load together with a horizontal seismic-type cyclic load. The mechanical properties of all used materials were measured through laboratory tests. For the tested walls, with a height over length ratio equal to 1 and for horizontal reinforcing ratio values larger than 0.085%, the rather ductile plastic rotation response at the bottom of the specimens appeared to dominate the observed behavior when the maximum horizontal load was reached. A micro-modeling numerical simulation was performed with the bricks simulated by elastic plane finite elements separately from the mortar joints which were represented with non-linear links aimed to simulate the cut-off tensile capacity normal to the mortar joint -brick interface. The vertical reinforcement was simulated explicitly with non-linear links having mechanical properties based on the measured tensile characteristics of the actual reinforcement. The observed behavior was successfully reproduced by this micro-modeling numerical simulation featuring all the geometric and construction detailing together with the measured non-linear mechanical characteristics of the mortar joints and the vertical reinforcement of one tested specimen.

KEYWORDS: reinforced clay masonry, in-plane behavior, partially grouted masonry, cyclic in-plane shear, experimental observations, numerical simulation

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Performance of Reclaimed Waste to Energy Aggregates as Lightweight Sand in Concrete Masonry Units

Paper 058

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ABSTRACT

In the United States, solid waste is being disposed of in landfills at a rate of 50 – 60% due to a lack of existing recycling infrastructure. Waste-to-Energy facilities offer an alternative means to process solid waste through combustion, which leads to a volume reduction of 80 – 90%. Incinerator ash is produced as a by-product of this process, and is traditionally disposed of in landfills, at a tipping cost of $ 30 - $ 50 per ton. Alternatively, in recent years a refinement process has been developed to extract a lightweight sand-like material, known as reclaimed sands, from incinerator ash. This work investigates the use of reclaimed sands in concrete masonry units. Reclaimed sands are a Department of Environmental Protection approved construction material, and a 100% recycled product which qualifies for Leadership in Energy and Environmental Design credits. The structural performance of reclaimed sand concrete masonry units is assessed per American Society of Testing Materials (ASTM International) C90 and C140 standards, where it is found that the blocks meet physical properties and strength requirements. The environmental performance of the blocks is assessed through a Synthetic Precipitation Leaching Procedure analysis with respect to beneficial use permit requirements.

KEYWORDS: waste, lightweight aggregates, recycled, ash

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Practical Construction Detailing for CMU Special Shear Walls: A Student's Experience

Paper 033

Rachel Garcia Chandler[1]

ABSTRACT

The California Polytechnic State University, San Luis Obispo (Cal Poly) curriculum, provides numerous ways where students have opportunities to learn-by-doing, and further their education past the classroom. Through a special project course, students can further their classroom curriculum and gain hands on experience with masonry design. This special project course created the opportunity to explore the topic of reinforcement steel (rebar) detailing in concrete masonry unit (CMU) special shear walls. These special shear walls (the end segments) were constructed by students, and detailing was documented in three common shear wall configurations: wall without pilaster, a flush face pilaster wall, and a pilaster centered wall. During the construction of these walls the students were able to experience common construction issues in masonry wall construction. It was an opportunity that developed the classroom knowledge of students through the learn-by-doing. This special project enhanced the classroom learning of the masonry theory course (ARCE 305) and design laboratory course (ARCE 451). In furthering the masonry education, students were able to be aware of types of questions that should be thought about during masonry design on paper. This paper includes is-sues (e.g. dowel vs. wall rebar alignment/locations, cleanouts, and knockouts) and les-sons learned beyond the classroom by students constructing the walls. This paper will talk about how valuable this type of experience is for students. It is important for engineering students to have these opportunities to question what they are designing, and how they are designing. Being able to think critically and creatively in the design field is a valuable skill. This specific project is different from most because of its unique benefits for the engineering student to grasp 3-D concepts in masonry detailing. This experience would benefit others who have the ability to create similar opportunities for engineering students or engineers in the field.

KEYWORDS: student, concrete masonry unit (CMU), detailing, design, construction, shear

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Predicting the Strength of Masonry Beams with Openings and Varying Vertical Reinforcement Using the Strut-and-Tie Method

Paper 165

Joshua Ring[1], Eduardo Alexis Ramírez Sánchez[2], Fayez Almutawa[3], Md. Tarik Hossain[4], and Jennifer E. Tanner[5]

ABSTRACT

The strut-and-tie method has been proven to conservatively predict the strength of specialty concrete structures such as corbels, dapped ends, and beams with openings. The objective of this study is to determine if this method can be used to predict the strength of masonry beams with openings. To this end, a suite of 14 tests were conducted on masonry beams with openings of various sizes and locations. Specimens were loaded with two- or four-points to and ensure that the load path traveled through openings of the beam. Results are compared to predictions made with the strut-and-tie method to validate that this lower-bound solution is a reasonable and conservative method for evaluating the capacity of masonry beams with openings.

KEYWORDS: strut-and-tie modeling (STM), beam, capacity, openings

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Preliminary Results on Surface Coating Strengthening Concrete Block Masonry with Eco-Friendly Ductile Cementitious Composite

Paper 149

Guilherme A. Parsekian[1] and Nigel G. Shrive[2]

ABSTRACT

"Eco-Friendly Ductile Cementitious Composite" (EDCC) is an engineered composite material recently developed at the University of British Columbia. EDCC is a combination of Portland cement, fly-ash, sand, and silica fume mixed with polyvinyl alcohol and polyester fibers. The investigation reported here is part of the collaborative research program exploring new possibilities for masonry retrofit and rehabilitation, with emphasis on the behavior of composite concrete masonry-EDCC elements. Preliminary results from the experimental program are reported. Concrete block masonry was surface-coated with different EDCC thicknesses (5, 10, and 20 mm). Compressive strength was evaluated for both plain walls and walls strengthened with EDCC coating on both sides. Results indicate that the vertical load capacity is increased in proportion to the strengthening material thickness, but with the EDCC stress being limited by the masonry deformation. In other tests, walls with the EDCC coating on one (the tension) side, either 5 or 10mm thick, were tested under lateral loading. Walls were tested in two directions, parallel and normal to the bed joint. Separate four-point load tests were performed to evaluate the flexural capacity of the assembly. Results indicate that the application of EDCC produces a ductile behavior, different to plain masonry, and increases the flexural capacity proportional to the EDCC thickness. Three-point load tests were used to evaluate the effect of EDCC coating on shear behavior, with results indicating that the coating causes a distinct increase in the shear capacity. The research campaign was concluded with the testing of a full 4 m long by 3 m high wall panel under lateral load and numerical modelling that will be reported later.

KEYWORDS: concrete, cementitious composite, ductility, strengthening

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Preliminary Study of Galvanic Corrosion on Veneer Anchors

Paper 003

Patrick B. Dillon[1]

ABSTRACT

Metals are widely used in the construction of modern masonry veneers for the fabrication of veneer anchors, flashings, and joint reinforcement. Corrosion of veneer anchors is a common problem that affects many existing buildings. The potential for galvanic corrosion of veneer anchors due to the formation of a galvanic cells with dissimilar metal flashings has not been adequately considered in the masonry literature. An initial study was conducted to investigate the potential for the creation of a galvanic cell within the veneer assembly and severity of the risk of the resultant galvanic corrosion to veneer anchors. Two brick panel specimens were constructed on copper through-wall flashings and with embedded galvanized steel veneer anchors. The specimens were periodically saturated with water and the galvanic current between the veneer anchors and flashings was continuously measured and recorded. The galvanic current from each anchor rapidly increased with the application of water to the specimens and gradually decreased as the specimens were permitted to dry naturally. Veneer units with higher porosity had higher initial rate of corrosion when wetted but the rate decreases faster because the units dried more quickly. The corrosion rate was higher at the anchors nearest the flashings. The results indicate that galvanic corrosion can significantly increase the corrosion rate of galvanization from veneer anchors and lead to full consumption of the protective coating from steel veneer anchors well within the intended lifespan of a building. Methods are discussed for preventing galvanic corrosion of veneer anchors due to galvanic cell formation. Recommendations are made for further research.

KEYWORDS: masonry veneer, anchored veneer, flashing, veneer anchors, galvanic corrosion

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Preliminary Test Results of Seismic Response of Reinforced Concrete Masonry Shear Walls with C-Shape Block Boundary Element

Paper 020

Mohammed Albutainy[1] and Khaled Galal[2]

ABSTRACT

Recently, there is a global trend of promoting higher building performance with lower cost and lower environmental impact. Reinforced masonry (RM) systems have the inherent benefits of high fire protection, structural durability, energy efficiency, and cost-effectiveness. Recent research efforts toward enhancing the lateral performance of RM walls are reflected in the current Canadian national building code and masonry design standards by introducing a new ductile RM walls category with a lateral force reduction factor of 3.0. Consequently, promoting RM shear walls as a potential seismic force resisting system (SFRS) alternative in mid-rise buildings. One way of increasing the wall ductility is by introducing boundary elements to the walls' end zones to enhance the ultimate compressive strain and wall curvature ductility by increasing the confinement level at wall end zones. In this study, six half-scale RM walls with boundary elements specimens, flexural dominated, were constructed in two phases to be tested under a reversed cyclic top moment and lateral loading. These walls represent the plastic hinge zone located in the lower one-and-a-half story of a 10-story RM shear wall building. The wall's boundary elements are varied in size as well as vertical and transverse reinforcement ratios. This paper presents the experimental work, and the preliminary results of one of the tested RM walls. The results showed that the RMSW with C-shape block boundary elements could overcome the limitations arising from using stretcher units to form the boundary elements and provide the lateral strength and the ductility required to resist earthquake events.

KEYWORDS: confinement, seismic ductility, boundary element, shear walls, C-shape block

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Preventive Conservation Efforts and a Preliminary Preservation Management Plan for the Roman Temple at Antioch Ad Cragum

Paper 222

Ece Erdogmus[1], Joshua Freedland[2], Michael Schuller[3], Mine Turan[4], Rhys Townsend[5], and Michael Hoff[6]

ABSTRACT

The Roman Temple at Antioch ad Cragum, dating back to the late 2nd to early 3rd century AD, has been under excavation since 2005. During the past decade, over 700 marble blocks have been drawn, photographed, and inventoried; and the Temple's platform has been carefully investigated. As a result, several discoveries have been made about the structure, including its plan and facade; as well as later interventions, such as a wine press on the side of the temple and graves on top of the platform. The conservation and maintenance efforts along with these investigations have been thoughtful and cautious in order not to create irreversible changes or damage to this historic structure. In this article, the interdisciplinary team discusses the preventive conservation trials undertaken at the site for short-term preservation to reduce the rate of deterioration, followed by the potential paths for a more substantial preservation plan including reconstruction efforts. The article highlights the successful attempt to combat lichen growth on the blocks and conservation interventions on small cracks and open joints around the Temple's platform. In addition, solutions to control the drainage of rain water around the temple and a temporary walkway to climb up and down the temple are proposed.

KEYWORDS: conservation, historic preservation, temple, dry stack masonry, monument management

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Proposal of Simplified Design Methods to Evaluate Second-Order Effects in Tall Reinforced Masonry Walls

Paper 223

Marco Donà[1], Massimiliano Minotto[2], Nicolò Verlato[3], and Francesca da Porto[4]

ABSTRACT

A previous experimental campaign has demonstrated the good behavior of tall rein-forced masonry (RM) walls, with vertically perforated clay units, when subjected to lateral actions. The samples tested represent typical construction systems of commercial and industrial single-story RM buildings provided with deformable roofs.

However, to date, EN1996 does not have a consistent approach to check the second-order effects due to out-of-plane loads in such structures, providing requirements for RM walls which are too restrictive.

This paper firstly discusses some of the major results of a recent numerical parametric study which implements fiber FE models calibrated from the above tests, as the actual slenderness limits for RM walls, also on the basis of experimental evidences. Then, more rational simplified approaches than that provided in EN1996 for evaluating second-order effects in tall RM walls are proposed, starting from the design methods of the Model Column (MC) and the Nominal Curvature (NC) generally used for RC structures; details on how these general methods were adapted to be used for RM tall walls are given in the paper. Finally, their reliability is assessed with respect to the numerical results of the previous parametric study, as well as that of the Moment Magnifier (MM) method proposed by the American (TMS 402) and Canadian (CSA S304) standards.

KEYWORDS: reinforced masonry, slender walls, out-of-plane behavior, second-order effects, model column method, nominal curvature method

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Proposed Changes to the TMS 402 Anchored Veneer Provisions

Paper 072

Richard Bennett[1], John Hochwalt[2], Jason Thompson[3], G. Andy Dalrymple[4], Brian Trimble[5], and Charles B. Clark[6]

ABSTRACT

A comprehensive review is undertaken of the anchored design provisions in the TMS 402 Building Code Requirements for Masonry Structures. The proposed revisions include a section on general design for anchored veneers that applies to all anchored veneers. This section includes such things as limitations on external loads on veneer, out-of-plane stability of the veneer, and seismic design requirements. The prescriptive design provisions are simplified and a primarily tabular format is proposed for ease of use. Two engineered design methods are pro-posed, one being based on tributary area of the veneer tie, and the other a full engineered design method. The tributary area method specifies a design force for each veneer tie based on a factor times the tributary area load. The factor is based on the tie stiffness. A methodology for determining tie strength and stiff-ness is also proposed.

KEYWORDS: masonry veneer, anchored veneer, building code, design, TMS 402/602

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Proposed Changes to the TMS 402/602 Adhered Veneer Provisions

Paper 073

Jason Thompson[1], Richard Bennett[2], G. Andy Dalrymple[3], Charles B. Clark[4], John Hochwalt[5], and Brian Trimble[6]

ABSTRACT

A comprehensive review was undertaken of the adhered design and installation provisions contained within TMS 402, Building Code Requirements for Masonry Structures and TMS 602, Specification for Masonry Structures. A prescriptive method is proposed that has limitations on its use but does not require shear bond testing when more contemporary installation practices are used. However, a polymer modified mortar is required for the setting bed mortar when using the prescriptive method. A full engineered design method is also proposed for materials, applications, or installation practices that fall outside of the prescriptive constraints. Major changes are proposed to TMS 602 as the prescribed installation method in TMS 602 is out-of-date and no longer being used.

KEYWORDS: masonry veneer, adhered veneer, design, building code, TMS 402/602

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Proposed Design Provisions for Post-Tensioned Masonry Beams

Paper 121

Arturo E. Schultz[1] and David T. Biggs[2]

ABSTRACT

The advent of post-tensioned masonry in the USA was focused primarily on vertically post-tensioned walls, and current design provisions are limited to walls loaded either out-of-plane or in-plane. However, post-tensioned masonry was initially proposed and studied outside of the USA as a reinforcing technique for beams and lintels beams. Recently, design provisions for horizontally post-tensioned masonry members have been proposed for inclusion in the masonry design standard in the USA (TMS 402). This paper reviews the proposed provisions, including the technical basis for the provisions. Supporting evidence from recent research on the design and performance of post-tensioned concrete block masonry and clay brick beams is summarized. Highlights from the design of a post-tensioned masonry lintel are presented and compared with an equivalent design of a reinforced masonry lintel.

KEYWORDS: beam, code, design, post-tensioned masonry

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Reflections on Writing a Building Code

Paper 145

Richard Bennett[1] and David Pierson[2]

ABSTRACT

In this paper, the Chair and Vice-Chair of the 2016 TMS 402/602 Committee reflect on various aspects of writing a building code. The reasons for and successful effort to go to a six-year cycle are discussed. Thoughts on the ever-increasing length and complexity of codes is given, with the fact that the 2016 TMS 402 has slightly fewer pages than the 2013 TMS 402 being highlighted.

The authors provide a philosophical discussion of what makes a good code change. The cost of the code, and how that cost should be borne are discussed. They also provide interesting results of feedback solicited anonymously from Code Committee Members, related to application of the code.

KEYWORDS: TMS 402/602, masonry code, design

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Reinforcement of Masonry Dome Structures for Seismic Loading

Paper 143

Mark Sarkisian[1], Julio Jesus Palomino Anguí[2], Neville Mathias[3], Alessandro Beghini[4], Samantha Walker[5], and Laélia Vaulot[6]

ABSTRACT

Masonry structures are common worldwide, from low-cost homes in developing countries to architectural heritage buildings in Europe. However, these structures are not typically designed to resist seismic loading and have historically performed badly in earthquake events, leading to major losses of human lives and of cultural heritage. It is urgent to develop a simple and practical way to reinforce masonry buildings so that they can withstand seismic loading. Non-invasive and economical systems that do not alter the character of ancient buildings and that can be easily implemented in poor countries are needed. Previous research by the authors has shown that reinforcing masonry vaults using synthetic fabric with high tensile strength can be a simple, low-cost and effective way to improve their seismic performance. This paper expands on that research and presents the results of physical shake table tests on a masonry dome structure. The specimen was tested in the following states: (1) unreinforced, (2) reinforced using a tension tie and (3) reinforced using a synthetic fabric. These tests demonstrate how these simple reinforcement techniques could be implemented easily and cost-effectively to improve the seismic performance of a small masonry shelter.

KEYWORDS: brick, earthquake, shake table, fabric, fiber grid, tension tie

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Reinforcing Bar Splice Performance in Masonry with Self-Consolidating Grout

Paper 114

Aaron B. Roper[1] and Fernando S. Fonseca[2]

ABSTRACT

The use of self-consolidating grout (SCG) in reinforced masonry construction provides various advantages such as reduced labor, faster construction, decreased noise pollution and better structural response. SCG is a relatively new building material however, and little research on the structural properties of SCG has been conducted. The purpose of the study was to analyze the bond of steel reinforcing bar splices in masonry with SCG.

Twelve masonry panels, approximately 40 in. wide and 32 in. tall, were constructed with Type S mortar, SCG, and No. 5 steel reinforcing bars with splice lengths as determined by the current design equation and splices that were slightly shorter. Test Group 1 consisted of six panels with the code required lap length while test Groups 2 and 3 had splices two and four inches shorter, respectively. The lap-splices were tested in direct tension to determine if they would develop the code mandated stress of 125% of the specified yield strength of the reinforcing bars. More samples were tested with the code required development length to verify if the current provision was adequate for design while the other two groups were used to explore if the required capacity could be achieved with shorter lengths.

All splices tested developed the code required stress. For masonry with SCG containing No. 5 bars, the current design equation was shown to be adequate for calculating its development length. The results also indicated that a reduction in re-quired splice length for masonry with self-consolidating grout is possible.

KEYWORDS: development length, self-consolidating grout, bond strength, lap splice, reinforcement, tension tests

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Relationship Between Compressive Strength and Modulus for Existing Masonry Construction

Paper 235

Nicholas Cargill[1], Shan Wo[2], and Michael Schuller[3]

ABSTRACT

Strength/stiffness relationships are useful when evaluating older masonry construction to estimate masonry compression modulus when strength is known or to estimate compressive strength when modulus is measured following the flatjack method or through laboratory tests. For design purposes, building codes and industry guidelines calculate masonry compression modulus E_m as a multiple of the specified masonry compressive strength f'_m. This relationship has been established through research and quality assurance testing for modern concrete and clay masonry construction as included in general analysis and design considerations of TMS 402, Building Code Requirements for Masonry Structures. For existing masonry construction, ASCE 41-06, Seismic Rehabilitation of Existing Buildings, contained a provision for calculating the default lower-bound masonry compression modulus as 550 times f'_m; this relationship does not exist in the current ASCE 41-17, Seismic Evaluation and Retrofit of Existing Buildings. A database of in situ test results compiling data from over 250 compression tests on older brick masonry construction is presented, and data is analyzed to develop a relationship between f'_m and E_m based on statistical analysis of test data. In situ tests were carried out following ASTM C1197, Standard Test Method for In Situ Measurement of Masonry Deformability Properties Using the Flatjack Method. Different data sets are considered for masonry constructed in different eras, geographic locations, and for masonry constructed with hard cement-based mortar versus masonry built with soft lime-based mortar.

KEYWORDS: flat-jack testing, historic masonry structures, strength, modulus of elasticity, existing masonry, compression

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Reliability-Based Analysis Model of Slender Masonry Walls

Paper 216

Odín Guzmán Sánchez[1], Carlos Cruz-Noguez[2], and Yong Li[3]

ABSTRACT

Design of loadbearing, out-of-plane (OOP), tall masonry walls must comply with stringent code limits related with their buckling stability and susceptibility to second-order effects. Recent studies have shown that certain elements in current masonry guidelines may be too restrictive, such as the effective stiffness at failure and the reliability levels associated to design equations. Analytical and experimental data indicate that code provisions underestimate the effective flexural stiffness $(EI)_{eff}$ of masonry walls, which translates into amplified second-order effects and reduced strength against buckling. On the other hand, very limited research on the reliability of non-slender and slender masonry walls has been performed since the 1980s – neglecting the fact that after the adoption of limited states design for masonry, walls undergo larger deflections and more cracking compared to those designed using working stress methods. This paper presents a reliability analysis for slender and non-slender masonry walls which takes into account recent developments on the probability distribution of loads and material resistance, as well as other parameters such as workmanship that have been proven to be highly important. The results of this work are expected to lead to a more accurate assessment of reliability levels in the design of masonry slender and non-slender walls, allowing for more economic walls designs while maintaining satisfactory structural strength.

KEYWORDS: reliability, out-of-plane, slender walls, walls

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Reliability-Based Assessment of Safety Factors for Masonry Walls in Vertical Bending

Paper 039

Mark G. Stewart[1] and Mark J. Masia[2]

ABSTRACT

Reliability-based calibration of partial safety factors ensures that structures are constructed to acceptable and consistent levels of safety. In Australia, this has led to the capacity reduction factor in the Australian Masonry Structures Code AS3700 being increased from 0.45 to 0.75 for unreinforced masonry walls in compression – i.e., a 67% increase in design capacity. The structural reliability of unreinforced masonry walls in one-way vertical bending under out-of-plane loading is the topic of this paper. High unit-to-unit spatial variability is observed, particularly for flexural tensile bond strength, due to variations in the quality of the workmanship, the weather during construction, and the materials from location to location. Hence, a stochastic computational model is developed which combines the Finite Element Method and Monte Carlo simulation to study how the unit-to-unit spatial variability of material properties affects failure progression and wall strength. Other work has quantified the probabilistic characterization of model error and flexural bond strength. A structural reliability analysis is developed for single skin infill masonry panels subject to a lateral (wind) load and where there is no vertical pre-compression. Two predictive models are used: (i) AS3700 design models, and (ii) FEA model. The structural reliability analyses consider the random variability of model errors, flexural bond strength, brick thickness, brick self-weight, and wind load. The effect of selection of predictive model on structural reliability is also assessed. Annual reliabilities are compared to target reliabilities recommended by ISO2394-2015, and capacity reduction factors are proposed and compared to the Australian Masonry Code AS3700-2018. It was found that there is evidence to support increasing the capacity reduction factor for flexure from 0.60 to 0.65 – i.e., an 8% increase in design capacity.

KEYWORDS: reliability, safety, code calibration, probability, masonry walls, vertical bending

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The Resistance of Masonry Veneer Walls Against Driving Rain Considering Windows and Door-Openings

Paper 264

Birger Gigla[1]

ABSTRACT

The resistance of masonry veneer walls against driving rain basically depends on the quality of the joints and the capillarity of the bricks. The risk of leakage is increasing with higher local precipitation and wind, growing building height and decreasing protection through roof or terrace overhang and local topography. Another significant factor is the fitting and sealing of windows and door-openings. Aspects of water tightness, energy-saving thermal insulation and sound insulation have to be considered and optimized. In practice, successful sealing requires adequate design, trained craftsmen and good workmanship.

To investigate the influence of the detailing of window and door openings, new laboratory tests have been performed at seven 1:1 scale specimen. The tests are focusing on the sealing at the footage between masonry veneer and window or door opening. They are including conventional designs and a new developed 'ready to use' insulation element with attached sealing system. The results presented are comparing the performance of the different technical designs in detail, considering the complete wall construction.

KEYWORDS: masonry veneer, wind-driven rain (WDR), windows, design, detailing, laboratory testing

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Response of Masonry Walls at Corners Under Shake Table Generated Motions

Paper 127

Rajat Avasthi[1] and Durgesh C. Rai[2]

ABSTRACT

Masonry construction practices are one of the oldest methods to construct the structures around the globe. Majority of the masonry research work is focused on in-plane or out-of-plane failure of masonry walls, and despite frequent reports of corner failures from past earthquakes, not much research is focused on corner failure in masonry walls. In these types of failures, simultaneous overturning of a portion of orthogonal walls occurs under lateral loading. This is possible only if lateral loads act along the corners, implying that each corner wall is subjected to bidirectional lateral loading. In the present study, to observe corner failure pattern, dry-stacked masonry was modeled in Abaqus, Finite Element (FE) environment using explicit solver. Experimental verification of the results obtained from the FE analysis was performed by subjecting the half-scaled masonry models to diagonal impulse lateral loading on the shake table at the Structural Engineering Laboratory, IIT Kanpur. Locations for maximum in-plane and out-of-plane displacement in masonry walls were identified and compared with the FE results. Limiting failure acceleration was also calculated for the studied model from the finite element results.

KEYWORDS: corner, walls, seismic, masonry walls

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Salt Attack of Masonry: Adhesive Forces in Damage

Paper 174

Leon S. Burgess-Dean[1]

ABSTRACT

Salt attack of clay and concrete masonry has been an old problem for the industry that has had a number of remedies that have proven to have limited success. Salt attack is a wide-reaching issue that encompasses both physical and chemical attack of masonry. Both physical and chemical attack of masonry has been researched in the past but due to the complexity of the masonry material and the large number of salts that may cause damage, there is much confusion over how and why damage occurs and how best to overcome it in masonry design. For many years the concept of a crystallization pressure and force has been proposed as the prevailing reason for attack by a crystallizing salt particle. This concept has many analogies with ice crystallization within masonry so has been likened by the literature as the preferred explanation. The reality of field and laboratory-based fracture studies indicate a much more complex damage mechanism is likely. The crystallization pressure theory is valid only if there is no significant physical or chemical adsorption of aqueous solute species on the masonry pore walls. In this paper, consideration is given to the likely adsorption forces present during a salt crystallization event within both clay and concrete masonry. It is shown the forces derived between evaporation and flow across masonry surfaces towards a growing salt crystal is responsible for deterioration of masonry surfaces through a lateral stress formed perpendicular to the masonry pore wall. This is supported by a mathematical and phenomenological discussion of the fracture of clay masonry.

KEYWORDS: salt, crystallization, damage, fracture, environment, solution

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Seismic Assessment of Historical Masonry Buildings and the Influence of Structural Retrofitting: A Case Study

Paper 056

Soheil Dadras[1], Mark J. Masia[2], and Yuri Z. Totoev[3]

ABSTRACT

The paper assesses the behavior of a culturally significant unreinforced masonry building in the city of Newcastle, Australia. The building was constructed in 1855 without considering the seismic design due to a lack of available codes and standards for seismic design at that time. The geometry of the building is simulated by finite element method in DIANA 10.2 software considering the nonlinear behavior of the masonry material. The performance and seismic vulnerability of the unreinforced masonry structure is determined through linear and nonlinear analyses. The form of the building has been changed over time which converts the type of the structure to a retrofitted masonry building. The effect of retrofitting on the structural factors such as ductility and performance factors as well as the related failure modes are investigated comparing the results of plain versus retrofitted masonry models. The influence of diaphragm flexibility on the behavior was also considered. It was concluded that assuming rigid diaphragm on the floors and the roof of the URM building resulted in more favorable structural behavior than was achieved for the retrofitted structure with the flexible diaphragms. Retrofitting, however, had a considerable impact on the crack widths by improving over-all the performance of the structure and positively influencing the modes of failure.

KEYWORDS: unreinforced masonry (URM), nonlinear behavior, retrofitted masonry, structural-factors, diaphragm flexibility

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Seismic Behavior of Infill Walls Made of Horizontally-Hollow Masonry Units

Paper 084

Daniel R. Quiun[1] and Luis Saenz[2]

ABSTRACT

In many countries, reinforced concrete (RC) frame buildings feature masonry infill walls. In Peru, partition walls are commonly made with horizontally-hollow clay bricks (called "pandereta" in Spanish). The width of the bricks and therefore, the wall thickness has been reduced from 130 to 80 mm, in order to maximize floor area inside the buildings. The "pandereta" bricks in this research had 105 mm thickness.

The objective of this research was to study the seismic behavior of these partition walls, using: 1) an in-plane infill wall for an RC frame, subjected to cyclic lateral loads; and 2) an infill wall with two bracing columns, subjected to out-of-plane forces by a shaking table test. Response of displacements and accelerations were measured during the tests.

Small masonry prisms and walls were also constructed with the horizontally-hollow units and subjected to axial compression load and diagonal compression load, respectively. These tests in the small specimens showed marked differences in behavior with respect to similar masonry specimens made with solid bricks. Both, axial compression test on prisms and diagonal compression test on small walls resulted in fragile failures. Such units should not be used for structural walls.

The in-fill wall subjected to the cyclic lateral load test exceeded the resistance predicted by the Peruvian Masonry Code expressions for partition walls, which means that more research is needed to calibrate the Code equations. Also, the partition wall subjected to out-of-plane forces in the shaking table resisted the Masonry Code design seismic loads. It was concluded that the horizontally-hollow bricks used in this research are able to be used for infills and non-structural walls, despite their small thickness.

KEYWORDS: horizontally hollow masonry units, masonry partitions, seismic behavior, masonry infill, cyclic in-plane shear, out-of-plane

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Seismic Fragility Assessment of Masonry Structural Units and Masonry Aggregates

Paper 172

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ABSTRACT

Aggregate masonry buildings are very common characterized by a set of non-homogeneous structural units; hence, the seismic analysis cannot ignore the unavoidable interactions between adjacent buildings. This work considered a row aggregation of identical structural units but, as first step, a seismic vulnerability assessment methodology with reference to a single isolated structural unit is used. In order to account for some variabilities and uncertainties involved in the problem, the Response Surface statistical method is used, where the expected value of a response parameter (the collapse PGA) is approximated through a polynomial function of a set of chosen variables. The Response Surface model is calibrated through numerical data obtained by non-linear static analyses and used to determine the fragility curves, by applying full Monte Carlo simulations.

Identical structural units chosen by the Response Surface generated simulations are aggregated, in order to compare the collapse PGA referred to the isolated structural unit and the one referred to the entire aggregate structure. The results showed significant differences in the value of the collapse PGA considering different directions of the seismic action, due to the geometry of the aggregate structure and the torsion effects deriving from the aggregation of structural units in row. Moreover, comparing the seismic behavior of the isolated structural unit and its seismic behavior when it is in the row aggregate structure, the results showed a decrease of the collapse PGA, if a larger number of structural units is considered.

KEYWORDS: masonry units, aggregates, fragility, vulnerability, uncertanties, fragility curves

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Seismic Performance Assessment of a Historic Masonry Structure Retrofitted with Various Distributions of FRP Laminates

Paper 035

Simon Petrovčič[1] and Vojko Kilar[2]

ABSTRACT

In recent decades externally bonded Fiber Reinforced Polymer (FRP) systems have become a common choice among architecturally less invasive seismic retro-fitting techniques. They present an efficient and light-weight alternative to traditional retrofitting measures that improve the behavior of masonry elements under seismic loading. By using this retrofitting measure the structure's dynamic properties are not altered since the added mass and stiffness are negligible. In this study a numerical case study comparison is presented in which a historic neo-renaissance unreinforced masonry (URM) structure is retrofitted with various Carbon FRP (CFRP) and Glass FRP (GFRP) laminates considering different reinforcement ratios in and distributions. The purpose of the study is to more thoroughly analyze the effect the applied FRP systems on the global seismic response of the structure for varying levels of seismic intensity. The FRP layouts for specific masonry panels in the study have been designed by following the CNR-DT 200 guidelines. An equivalent frame inelastic 3D numerical model with lumped plasticity has been used. Such a model can track the global seismic response and reproduce the earthquake induced damage and failure modes. Calculations were carried out using the commercially available computer program SAP2000 by con-ducting nonlinear static (pushover) analyses. This makes it possible to estimate the ultimate lateral force capacity and the displacement capacity of the building with sufficient accuracy. The seismic demand of each analyzed variant has been determined by the N2 method for multiple levels of seismic intensity. Code-based performance requirements have been considered and compared with the calculated seismic demand. Preliminary results show us that the seismic capacity of the building is considerably improved by the application of FRP and that a properly designed FRP system can fulfil the performance requirements set out in modern building codes.

KEYWORDS: retrofitting, historic masonry structures, fiber reinforced polymer (FRP), pushover analysis, incremental N2 method, SAP2000

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Seismic Performance Factors for Dry-Stacked Reinforced Masonry Shear Walls

Paper 024

Johnn Judd[1], Fernando S. Fonseca[2], and Joseph Eixenberger[3]

ABSTRACT

Preliminary seismic performance factors for low-rise buildings using dry-stack reinforced masonry shear walls are discussed in this paper. The focus in this study was to establish a relationship between the response modification factor, ¡i¿R¡/i¿, and the collapse safety of the buildings, as expressed by the adjusted collapse margin ratio. Seismic performance was predicted using nonlinear collapse simulations of prototypical buildings using dry-stack shear walls. The approach used in this study followed the Federal Emergency Management Agency (FEMA) P-695 (2009) Quantification of Building Seismic Performance Factors methodology. The results indicate that dry stack reinforced masonry shear walls do not pass the criteria specified in the FEMA methodology, but the walls perform better than ordinary shear walls. The relationship between R and the collapse safety of the buildings was established using a power law equation fitted to the analysis data. This relationship can be used to quantify the effect of quality ratings on the selection of ¡i¿R¡/i¿ and used to evaluate aleatory and epistemic uncertainties.

KEYWORDS: seismic, dry stack masonry, response modification factor

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Seismic Performance of Confined Masonry Buildings Designed with the Mexico City Building Code

Paper 012

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ABSTRACT

The current referenced code standard Technical Requirements for the Design and Construction of Masonry Buildings (NTC-M, by its initials in Spanish) of the Mexico City Building Code (MCBC), which is one of the most recognized prescriptive design formats in the world, was released in December 2017. This document increases to 1% (from a previous value of 0.5%) the maximum inter-story drift index for confined masonry shear walls with horizontal reinforcement.

A discussion on the maximum inter-story drift index considered by the actual version of the NTC-M is offered. Experimental data is presented, and the limitations of the use of this inter-story drift index are discussed in terms of the design of multi-story buildings that tend to develop shear damage in a soft story when deformed laterally. To understand the impact of the actual technical requirements, three confined masonry buildings with 6, 8 and 10 stories are designed according to them. Static non-linear analyses are carried out to establish the structural properties and lateral response of the buildings. Based on the results, the pertinence of some of the new design requirements of the NTC-M are discussed.

KEYWORDS: confined masonry, Mexico City code, maximum drift, seismic design, aspect ratio

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Seismic Resistance Mechanisms in Partially Grouted Shear Walls with New Design Details

Paper 120

Arturo E. Schultz[1] and Catherine A. Johnson[2]

ABSTRACT

As part of a research project to investigate the seismic performance of partially grouted concrete masonry shear wall structures, two full-scale sub-assemblage specimens were built and tested. The specimens had a C-shaped plan configuration with a single shear wall and two cross-wall elements. The shear wall featured a large opening. The masonry walls were anchored to concrete foundations, and topped, hollow-core roof slabs. The shear walls in the two specimens had the same amounts of vertical and horizontal reinforcement ratios, but the distributions of reinforcement differed. In one specimen the shear wall used standard single grouted vertical elements and bond beams, while the shear wall in the other specimen had double reinforced vertical cells (side-by-side grouted cavities) and a combination of bond beams and distributed joint reinforcement. The specimens were loaded quasi-statically using a cyclic drift history until lateral load capacity had deteriorated to 50% of maximum lateral load capacity. The tests demonstrated that while the piers on either side of the shear wall openings were the critical elements, the spandrels, especially those below the openings, also had important in-fluences on wall response. This paper compares the behavior of the two specimens under cyclic, lateral drift histories, with a view towards the load resistance mechanisms.

KEYWORDS: partially grouted masonry, seismic, testing, perforated walls

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Seismic Retrofitting of Existing Unreinforced Masonry Structures Using Post-Tensioning Technique: A Case Study and Lessons Learned

Paper 063

Ahmad A. Hamid[1] and Michael Schuller[2]

ABSTRACT

Existing unreinforced masonry (URM) buildings have limited strength and deformation capacity, rendering them highly vulnerable to damage during seismic events. Therefore, seismic retrofitting of these buildings is significant and vital. Post-tensioning is an effective retrofitting technique that improves the strength and deformation capacity of URM buildings. A case study of seismic retrofitting on URM stone building is presented in this paper. As-built condition, material distress, and material properties were evaluated and reported. Different retrofit options were considered, and the most cost-effective approach in this case was the application of vertical post tension loads to increase masonry resistance to rocking and in-plane shear forces. The combination of massive stone masonry loads, large lateral inertial forces, and building geometry ruled out other seismic retrofit approaches from both cost and practicality stand-points. The solution utilizing internal post-tensioning maintained external appearance and did not reduce interior spaces. It was concluded that, although expensive, the retro-fit was carried out in a cost-effective manner when compared with other more invasive retrofit approaches.

KEYWORDS: retrofitting, seismic, unreinforced masonry (URM), post-tensioned masonry, injection, in-situ testing

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Shadows Cast by Outward Things: Incorporating Texture into Brick Veneer

Paper 239

Cortney Fried[1]

ABSTRACT

Many architects are currently incorporating more prominent texture into their brick facades, using various combinations of projections and recesses in addition to reintroducing traditional articulated detailing. However, details that once were relatively straightforward to construct in mass masonry walls do not translate directly to contemporary anchored veneer construction without engaging other design team members.

In this paper, the author discusses various types of features being incorporated, both historic and modern, such as corbels, cornices, dentils, sawtooth units, and individual unit projections. The author also explains the limits of the prescriptive methods presented in the Building Code Requirements for Masonry Structures (TMS 402) and references the alternative design method to permit the construction of these details within an anchored brick veneer assembly. An approach to assist engineers in evaluating these types of details is proposed. In addition, general detailing concepts to adapt these types of details to veneer construction are recommended.

KEYWORDS: texture, corbel, projection, articulation, shadows

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A Shake-Table Test Investigating the Drift Capacity of Reinforced Masonry Wall Systems

Paper 263

Jianyu Cheng[1], Andreas Koutras[2], and P. Benson Shing[3]

ABSTRACT

An accurate quantification of the displacement capacity of a reinforced masonry shear-wall system is of critical importance to seismic design because it has a direct implication on the seismic force modification factor, which is the R factor in ASCE 7. In spite of the shear capacity design requirement in TMS 402, special reinforced masonry walls within a building system could still develop shear-dominated behavior, which is perceived to be far more brittle than flexural behavior. These walls have a low shear-span ratio either because of the wall geometry (i.e., a low height-to-length ratio) or the coupling forces introduced by the horizontal diaphragms, which are often ignored in design. Although shear-dominated walls appeared to be very brittle in quasi-static tests conducted on single planar wall segments, reinforced masonry structures survived major ground shaking well in past earthquakes. This could be partly attributed to the beneficial influence of wall flanges as well as the over-strength of the system. Flanged walls are common in masonry buildings, but their behavior is not well understood because of the lack of laboratory test data. Furthermore, other walls or columns that are present in the structural system to carry gravity loads could enhance the lateral resistance of the shear walls and the displacement capacity of the system by providing axial restraints as well as alternative load paths for gravity loads. A research project is being carried out with shake-table tests to investigate the displacement capacity of shear-dominated reinforced masonry wall systems. This paper presents results of the first shake-table test conducted in this project on a full-scale single-story coupled T-wall system. The structure was tested to a drift ratio exceeding 15% without collapse.

KEYWORDS: reinforced masonry, walls, displacement, seismic, shear, earthquake

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Shake-Table Testing of a Small-Scale Five-Story Confined Masonry Building

Paper 103

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ABSTRACT

The dynamic behavior of a small-scale confined masonry five-story building tested in a shaking table is discussed. The specimen represents a typical low-cost housing building constructed in Mexico. The model was subjected to a series or seismic motions characteristic of Mexican subduction events recorded in the epicentral region. The experimental program, test set-up and instrumentation, and test results are described herein. From recorded and observed results, resisting mechanisms were identified; the structural capacity was assessed in terms of strength, stiffness, deformation and energy dissipation. Response was evaluated and compared to expected performance under the recently published Mexico City Building Code standards for masonry construction and for seismic design.

KEYWORDS: testing, confined masonry, seismic performance, low-cost housing, masonry code

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Shake-Table Tests on a URM Building with Chimneys

Paper 220

Francesco Graziotti[1], Stylianos Kallioras[2], and António A. Correia[3]

ABSTRACT

The paper presents the results of a shake-table test performed on a full-scale unreinforced clay-masonry building with chimneys. The tests were part of a wider experimental campaign aimed at assessing the seismic vulnerability of buildings in an area prone to induced seismicity. The prototype building embodied construction details characteristic of old detached single-story houses of the Groningen province in The Netherlands, without any specific seismic detailing. The house featured a typical Dutch gambrel roof that allowed for living space above the attic floor, with high gables that were vulnerable to out-of-plane excitation. The floor was made of timber joists and planks, resulting in a flexible diaphragm. Two clay-brick chimneys were included to investigate the performance of falling non-structural masonry elements in earthquakes. A unidirectional, incremental dynamic test was carried out up to collapse conditions of the building, using input ground motions compatible with induced seismicity scenarios for the Groningen gas field. Structural and non-structural damage were surveyed in detail at the end of every earthquake simulation. Low-intensity random vibration tests were additionally performed to assess the effect of the cumulative damage on the dynamic properties of the structure. The paper summarizes the main characteristics of the specimen and part of the shake-table test results, focusing on the seismic response of the two chimneys.

KEYWORDS: clay-brick chimneys, collapse, shake-table testing, induced seismicity, unreinforced masonry (URM)

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Shear Resistance of Thermal Insulating Clay Unit Masonry

Paper 034

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ABSTRACT

Thermal insulating single leaf clay unit masonry is a common type of construction in southern Germany, a region with very low to moderate seismic exposure. The in-plane shear resistance is the most relevant parameter to describe seismic performance of that type of masonry. A shear test set-up for full-size masonry walls was developed within the European-Commission-sponsored research project ESECMaSE.

A series of shear tests with that method were carried out in laboratories in Kassel (Germany) and Ljubljana (Slovenia) to identify the shear capacity of that type of masonry. The tests comprised different wall geometries, different load levels and different types of units, as well as different support lengths of the slab on top of the shear walls

The results are presented and discussed.

KEYWORDS: clay masonry, shear tests, shear resistance, combined loading, design code, seismic loading

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Shear Strength of Autoclaved Aerated Concrete Confined Masonry Walls Subjected to Lateral Loads

Paper 057

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ABSTRACT

The experimental results of a study on the shear behavior of autoclaved aerated concrete (AAC) confined masonry walls are presented. Five full-scale walls were tested in the laboratory under constant axial compressive stress and incremental reverse cyclic loads until failure. The variable studied was the wall aspect ratio. Class AAC-4 masonry-type units were considered. The performance of walls was characterized in general by diagonal and flexure-shear cracks on the AAC wall panels. Failure of walls was associated with propagation of diagonal cracks into the top and bottom ends of the vertical confining elements. Final cracking pattern of walls was characterized by the traditional "X" pattern. Lateral load-drift ratio curves of walls are presented. The shear strength of walls increased as the aspect ratio decreased. Drift ratios increased as the aspect ratio increased. An equation for shear strength as a function of wall aspect ratio is proposed. Shear strength of walls is predicted adequately with the proposed equation.

KEYWORDS: autoclaved aerated concrete (ACC), confined masonry, shear strength, aspect ratio

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Shear to Elastic Modulus Ratio in Unreinforced Masonry

Paper 183

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ABSTRACT

In the seismic design of unreinforced masonry walls, the elastic modulus E and shear modulus G are essential parameters for the calculation of the in-plane wall stiffness. Current codes provide empirical estimates of the elastic modulus and furthermore a ratio of shear to elastic modulus G/E. This ratio, however, is not based on scientific evidence and consensus concerning the value and influencing parameters is lacking. This article develops a closed-form formulation for the G/E ratio of masonry walls with running bond pattern. The formulation is derived by using an analytical homogenization technique already employed in the literature and modified here to consider the finite thickness of the wall. The resulting formulation is based on the geometry of the units, the thickness of the joints and the elastic moduli of units and joints. The resulting analytical expression for the G/E ratio is used to assess the influence of various parameters and validated by comparing it to finite element simulations.

KEYWORDS: unreinforced masonry (URM), shear modulus, modulus of elasticity, homogenization

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A Simple Test to Evaluate Direct Tension Pullout Strength of Reinforcing Bars Embedded Within Grout and Preliminary Results

Paper 275

Bryce Fiore[1], Kyle Walter[2], and Jennifer E. Tanner[3]

ABSTRACT

Sufficient embedment, or development, length is required to develop yielding stresses in a reinforcing bar and achieve full plasticity in masonry. There is little reason to believe that a coarse-grout pull-out failure would be different than that of concrete. The primary objective of this study is to present a simple direct-tension test to evaluate the capacity of reinforcing bars grouted in concrete masonry units subjected to direct-tension pull-out forces. Several embedment lengths were used in order to obtain a range of results from under- to fully-developed bars. As expected, the capacity increases with the embedment length. A secondary objective is to present requirements from current North American codes. Re-quired lengths are smallest for the Canadian Masonry Society (CMS) provisions, followed by the American Concrete Institute (ACI) and longest for The Masonry Society (TMS) provisions.

KEYWORDS: grouted masonry, bond strength, experimental testing

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Simplified Method for Predicting Flexural Behavior of Reinforced Masonry Walls Strengthened with FRP

Paper 262

Zuhair Al-Jaberi[1] and John J. Myers[2]

ABSTRACT

The purpose of this study is to predict the full flexural behavior of Reinforced Masonry Walls (RMW) strengthened with Fiber Reinforced Polymers (FRP). The out-of-plane behavior prediction is carried out based on moment-curvature relation and then verified by the experimental results. The experimental parameters that considered in this study include steel reinforcement ratio (23, 24, and 15), fiber reinforcement ratio from (ρ_f=0.075% to ρ_f=0.56%) and different types of fibers (glass and carbon). The proposed method succeeded for predicting full behavior of strengthened wall as close as possible to the experimental behavior, especially for the uncracked and partially cracked stage. For the fully cracked stage, it is very hard to predict the effective moment of inertia with high accuracy. The approximation of predicting the effective moment of inertia missed the value of ultimate deflection. As a result, the proposed approach predicts the strengthened wall behavior with reasonably good accuracy.

KEYWORDS: strengthening, masonry walls, fiber reinforced polymer (FRP), moment-curvature method

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A Simplified Modeling and Analysis Approach for RCM Shear Wall Buildings Under Lateral Loading

Paper 147

Hassan Bedeir[1], Marwan Shedid[2], Hussein Okail[3], and Osama Hamdy[4]

ABSTRACT

This paper presents part of an ongoing research to investigate the behavior of mid-rise buildings composed of Reinforced Concrete Masonry (RCM) shear walls as their main Lateral Load Resisting System (LLRS) under lateral loads. Current design codes assign unique reduction factors for lateral loads calculated based on an elastic analysis of the structure to account for the ductility provided by the LLRS. For RCM shear walls, stiffness modifiers are assigned in analysis to account for their cracking. Based on literature and structural mechanics, the building ductility is different than that of its constituent elements since the building is usually composed of walls differing in ductility based on their dimensions, reinforcement ratios, and applied axial stresses. Additionally, most structures are subjected to twisting under lateral loads. This torsional behavior applies different displacement demand on each element of the LLRS. Some walls might displace within their elastic limit while others may yield or even go past their peak strength. This implies that the stiffness of the constituent walls is not constant over the loading history; hence, the use of a unique stiffness modifier for all walls is not realistic. In this paper, numerical models are developed for RCM shear wall buildings with different wall configurations using OpenSEES software package, subjected to quasi-static cyclic lateral load with varying levels of eccentricity and loaded up to 50% loss of strength. The effect of lateral load eccentricity and wall arrangement in plan on the structure ductility is extracted; and the loss of stiffness for constituent walls is traced over the loading history. Finally, a simple analytical tool using Microsoft EXCEL software is developed to predict the behavior of an RCM building under lateral load without the need for tedious nonlinear analysis. The results of the developed tool were verified using the OpenSEES models results.

KEYWORDS: modeling, reinforced concrete masonry shear walls, lateral loading, ductility, system level, OpenSees

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Simplified Numerical Model of URM Wall-to-Timber Floor Connections

Paper 252

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ABSTRACT

Although the vulnerability of unreinforced masonry walls to out-of-plane damage and collapse has been observed many times in past earthquakes, there is little analytical research addressing the explicit seismic evaluation of the connection between walls and timber diaphragms and its effects in the global response of URM buildings.

In this paper, a simple nonlinear numerical model of a floor-to-wall connection including steel plates and nailed anchors is proposed and validated. The model accounts for friction, impact and potential nonlinear behavior of anchors or nails under static or dynamic seismic lateral loading.

A friction slider element accounts for the inherent friction between wood joist and masonry walls. In addition, a gap element combined with a spring-dashpot system simulates the potential impact between the end of the joist and the masonry walls under seismic events. Also, a nonlinear spring element is used to simulate steel anchors, which were occasionally used in older masonry buildings and are a common retrofit solution recommended by the current rehabilitation codes. Comparison with key experimental results from the literature shows that the friction-impact-nailed model accurately predict the cyclic quasi static behavior of the floor-to-wall connection.

The model has been implemented in the commercial software SAP2000, so that can be easily replicated for practicing structural engineers.

KEYWORDS: modeling, floor-to-wall, connection, seismic, out-of-plane, wall-to-timber floor connections

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Statistical Analysis of Total Absorption Results in Hot and Cold Water for Ceramic Blocks

Paper 254

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ABSTRACT

This paper describes the results of water absorption index tests conducted according to the Brazilian standard for ceramic and structural ceramic blocks. The standard allows the test to be carried out by immersing the blocks in cold water and, to obtain accelerated results, in hot water. The tests were conducted on samples from eighteen manufacturers from eight Brazilian states: São Paulo, Minas Gerais, Rio de Janeiro, Rio Grande do Norte, Pará, Piauí, Maranhão, and Ceará. A statistical analysis was performed comparing the mean value for the two tests procedures. From the comparison of the means, the analysis does not indicate any statistical differences for the blocks evaluated with a margin of error of 2% and reliability of 95%. In other words, most of blocks have a saturation coefficient close to 1.0. The reasons for the statistical similarity presented by these blocks are discussed in detail.

KEYWORDS: ceramic, water absorption, structural masonry, block test

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Strength of Random Rubble Masonry Panels Under Compression and Flexure

Paper 071

B. V. Venkatarama Reddy[1] and S. N. Ullas [2]

ABSTRACT

Random rubble masonry (RRM) is used for the construction of foundations and superstructure in low rise buildings. Generally, RRM construction is an in-situ operation. Construction of RRM masonry involves use of irregular shaped stone boulders arranged randomly and packing the crevices with flowable earth mix mortar. The paper presents results of strength tests on RRM wallettes subjected to compression and out of plane bending. The compressive strength of the RRM wallettes was in the range of 3 – 8 MPa and the flexure strength in the range 0.57 – 0.72 MPa. The strength of RRM was sensitive to the mortar proportion. Rich mortar yields higher strengths. The failure patterns of RRM are different from of regular coursed masonry. The results are useful for the design of load bearing RRM walls.

KEYWORDS: rubble masonry, masonry strength, earth mortar

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Strengthened Thin Clay Masonry Infills: In-Plane and Out-of-Plane Experimental Tests

Paper 219

Massimiliano Minotto[1], Nicolò Verlato[2], Marco Donà[3], Elisa Saler[4], and Francesca da Porto[5]

ABSTRACT

Clay masonry infill walls have shown brittle behavior during recent earthquakes due to the combination of in-plane and out-of-plane actions. These negative aspects are even more pronounced in thin infill walls, often characterized by masonry units with high void ratio, horizontal holes and low compressive strength. Thin masonry infills are typical in existing R.C. frames and extensively used in current construction practice to build internal partitions.

This work presents the results of eight full-scale tests on RC infilled frames (one-bay, one-story) with three different types of strengthened thin clay masonry panel. The first strengthening type is characterized by the application of a bi-directional basalt mesh embedded in a special geo-polymeric plaster. The other two strengthening solutions consist of applying a fiber-reinforced lime-based plaster, and one of them is also provided with an additional bi-directional basalt mesh. The specimens have been test-ed firstly imposing increasing in-plane cyclic displacements at the frame top beam until reaching pre-determined drift levels, and secondly monotonically loading the infill in the out-of-plane. In particular, to investigate the relationship between the out-of-plane strength reduction and the in-plane damage, out-of-plane tests have been performed at three different in-plane drift levels: 0% (un-damaged), 0.5% and 1.2%.

The results are discussed and compared taking an unreinforced masonry infill, tested in a previous experimental campaign, as a reference. Experimental evidences prove the effectiveness of the strengthening solutions in reducing infill damage and, there-fore, in increasing both the out-of-plane strength and deformation capacity. Further-more, the bi-directional mesh positively influenced the failure modes, avoiding the brittle out-of-plane collapse, which conversely characterizes the behavior of thin un-reinforced masonry infills.

KEYWORDS: masonry infill, in-plane/out-of-plane interaction, strengthened masonry, fiber reinforced, mesh reinforcement, experimental testing

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Strengthening and Conservation of the Early Phrygian Gate Complex at Gordion, Turkey

Paper 280

David T. Biggs[1] and Semih Gonen[2]

ABSTRACT

The fortress city of Gordion in central Turkey (modern-day Yassıhöyük) was constructed by the Early Phrygians (ca. 950-800 BCE) and is now renowned as the seat of the most famous Phrygian king, Midas of the Golden Touch, and also for being the spot where history records Alexander the Great cutting the Gordian knot in 333 BCE.

Large-scale excavations that uncovered the fortress city and the Early Phrygian Gate Complex were begun by the University of Pennsylvania in the 1950s. Archeologists believe the gate walls were originally as much as 16 m tall, even though the exposed remains are now less than 10 m. They comprise the best-preserved Iron Age gate building in the entire eastern Mediterranean and ancient Near Eastern worlds and are thus of inestimable cultural-historical significance.

This paper is the companion to "Investigation and assessment of the early Phrygian gate complex at Gordion, Turkey". Together, the two papers address the assessment and conservation of the South Court walls whereas this paper specifically describes the strengthening details and implementation of the conservation project.

KEYWORDS: strengthening, conservation, stone masonry, heritage site, case study, historic preservation

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Strengthening of Reinforced Brick Slabs Using Section Enlargement Scheme

Paper 186

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ABSTRACT

Reinforced Brick (RB) Masonry slabs have been a popular choice of construction for roof and floor diaphragms in Northern India due to its simplicity of construction, cost-effectiveness, ease of availability of high-quality materials and good workmanship. Many buildings constructed using RB slabs are now past their service life and are in a state of distress. This study was conducted to devise a strengthening scheme that could be popularly adopted for strengthening such distressed RB slabs. The experimental investigations were performed on pre-loaded half-scaled reinforced brick slabs, which were strengthened using the popular Reinforced Concrete (RC) retrofitting technique called Section Enlargement Scheme. Two, two-way slabs had been casted and pre-loaded to 50% of their capacity. These slabs were strengthened using reinforced micro-concrete overlay of 24 mm thickness at both top and bottom surfaces. The two-way slabs were centrally loaded using a patch load. From the experimental study, it was observed that in two-way slabs the primary failure was by punching shear. Debonding failure was observed in those specimens in which full composite action did not take place. The strengthened slabs showed remarkable improvement in the strength, stiffness, load-displacement behavior, and crack pattern. Therefore, the proposed scheme can be efficiently adopted for strengthening of existing distressed RB slabs.

KEYWORDS: reinforced brick (RB) masonry slabs, strengthening, diaphragm

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Strengthening the Past, Building the Future: Lessons Learned from School Buildings in Indonesia and Sub-Standard Housing in Colombia and Philippines

Paper 265

James P. Mwangi[1] and M. Lisbeth B Collins[2]

ABSTRACT

The horseshoe-shaped Pacific "Ring of Fire" marks the world's most earthquake active region and extends across five of the seven continents. A large portion of the region is located in developing countries where some of the world's largest population lives including Indonesia, Mexico and Colombia. Building construction in some of the countries in this region is comprised mostly of unreinforced masonry or con-fined masonry using locally available materials. Building codes, where available, are rarely enforced and most low-rise buildings, often including schools, are not engineered. Construction methods are typically passed down through on-the-job apprenticeship. The use of low-quality materials, lack of enforced building codes, and inadequate construction practices result in poor earthquake and hurricane/typhoon resistant building structures that either totally collapse or are heavily damaged during earthquakes or strong storms leading to large numbers of casualties and heavy economic losses. Existing government design guidelines were reviewed for school buildings in Indonesia and for sub-standard housing buildings in Colombia and Philip-pines. This paper reports on the lessons learned from application of ASCE 41, and other international standards, to evaluate existing capacity and design retro-fit/strengthening systems of low-rise school buildings in Indonesia and sub-standard housing in Colombia and Philippines. In the three countries, retrofit/strengthening design and construction guideline recommendations were submitted to government agencies. Prototype low-rise buildings retrofitted/strengthened using local materials and improved construction practices in an effort to enhance capacity building, sustainability and resiliency using the newly established guideline recommendations are also reported.

KEYWORDS: unreinforced masonry (URM), confined masonry, out-of-plane, retrofitting methods, earthquake-resistant design

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Structural Reliability of Reinforced Concrete Block Masonry Wall Subjected to Seismic Force

Paper 040

Bin Chi[1], Xu Yang[2], Fenglai Wang[3], and Zhiming Zhang[4]

ABSTRACT

The reinforced grouted concrete block masonry structures are usually present in modern structure throughout in China and North American. As the increase of structural height, RCBM walls have increased many new configurations but the safety of it is uncertain designed by old edition of Chinese standards, especially during earthquake. This paper mainly develops a reliability model and method to analysis the structural reliability for reinforced masonry walls subjected to seismic force. This model was established incorporating the effect of model error, axial force and the compressive strength for grouted concrete block masonry. The results show that the model error had great influence on the reliability index. Additionally, the reliability index shows little relationship with compression strength of concrete block masonry. Moreover, the reliability index increases as the increased of axial load in all distribution of model error. It indicates that axial load had a positive influence on the reliability index of RCBM walls under horizontal seismic load.

KEYWORDS: masonry structure, concrete masonry, shear walls, seismic force, structural reliability

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Suggested Method for the Determination of the Weathering Index of Ancient Fired Clay Bricks

Paper 032

Laurent Debailleux[1]

ABSTRACT

Historical fired clay bricks are well known to present non-heterogeneous structures, mainly influenced by the raw material, the burning process and longtime exposure to climatic conditions. In the scope of building conservation, the lack of affordable technical means to simply evaluate the degree of decay of historical fired clay bricks may lead to extensive restoration campaigns.

This article presents results of non-destructive Schmidt hammer tests performed on ancient fired clay bricks sampled from historical masonry. The reliability of the rebound hammer tests is evaluated by assessing how the rebound readings vary for fired clay bricks when considering their specific exposures and locations within a wall. Based on these results, a weathering index is suggested to quantitatively evaluate the degree of decay of the brick surfaces.

Referenced surfaces were tested for bricks from a facade and interior wall. On each surface, repeated impact readings were recorded at ten different points to provide the mean rebound value of the surface for each successive impact. Statistical results indicate that five repeated impacts at ten different points might give a better estimation of the surface hardness of the material. It could also provide a more realistic estimation of the weathering degree and compressive strength of the material. In addition, this research indicates that this technique is sensitive enough to distinguish sample locations and measure weathering differences, even for different surfaces of a particular sample.

KEYWORDS: ancient fired brick, rebound hamer, weathering indices, conservation, cultural heritage, historic masonry

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Tall Masonry Walls with In-Line Cage Reinforcing

Paper 028

Clayton Pettit[1], Joseph Entz[2], Odín Guzmán Sánchez[3], Carlos Cruz-Noguez[4], and Bennett Banting[5]

ABSTRACT

Tall, slender masonry walls are a competitive and effective solution to resist out-of-plane and gravity loads in both low and high-rise structures. Taller and thinner walls led to fewer construction materials, smaller foundations, faster construction, lower seismic forces, and the ability to create more interior space. However, utilization of conventional tall walls in out-of-plane applications is limited due to practical limitations regarding axial load capacity, buckling stability, and reinforcement detailing. Designers who seek to enhance the strength and stiffness of a wall by using non-conventional reinforcement or non-conventional masonry units are hindered by empirical limits set in the Canadian standards for masonry design. A new type of moderately slender masonry wall, incorporating an in-line stiffening element as an alternative reinforcement scheme, is proposed in this study. Localized regions of strength and stiffness are created by providing a concealed "column" in the thickness of the wall. The response of this alternative rebar placement detail was investigated through experimental testing and numerical analysis on a series of 5-course prisms subjected to concentric and eccentric loads, and 2.4-meter-high wallettes subjected to both a gravity load and out-of-plane four-point bending. The response of the walls with the alternative rebar detailing is then compared to walls with the same amount of reinforcement using conventional detailing. The advantages and limitations of using the alternative rebar detailing are discussed.

KEYWORDS: flexural walls, out-of-plane, boundary element, experimental testing

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Testing Compressive Strength and Young's Modulus of Semi-Interlocking Masonry

Paper 111

Mehdi Hemmat[1], Orod Zarrin[2], Yuri Z. Totoev[3], Mark J. Masia[4], and Goran Simundic[5]

ABSTRACT

The Semi Interlocking Masonry (SIM) system has been developed in the Centre for Infrastructure Performance and Reliability at The University of Newcastle, Australia. This system is designed for the construction of earthquake-resistant in-fill panels in framed structures. SIM panels dissipate earthquake energy through the sliding friction on bed joints within a panel as the frame is distorted in-plane with the infill panel.

The compressive strength and Young's modulus of SIM are important design properties, particularly where SIM is used as a confined masonry system. Different design and testing standards proposed various methods to test the compressive strength and Young's modulus of traditional mortared masonry. However, there is no standard testing method/protocol for a mortar-less masonry like SIM.

This paper presents a new protocol for testing the compressive strength and Young's modulus of SIM. Eight and three specimens of mortar-less SIM prisms contain 3-bricks and 7-bricks, respectively, were tested. Linseed oil-based putty was used on bed-joints as joint filler. It is used in SIM to improve buildability, thermal insulation, and water resistance. The required curing time for the putty was investigated first in the preliminary testing program before the compressive tests. The test results indicate that the sufficient curing time for linseed oil-based putty is about 5 days, the average compressive strength of prisms is 5.46 MPa, and Young's modulus of prisms is approximately 3233 MPa.

KEYWORDS: mortar-less masonry, semi-interlocking masonry (SIM), compressive strength, modulus of elasticity, curing time, linseed oil-based putty

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Textile Reinforcement in the Bed Joints of Basement Walls: Increase of Out-of-Plane Flexural Capacity

Paper 211

Wolfram Jäger[1] and Maik Erler[2]

ABSTRACT

The verification of basement walls under earth pressure is often difficult because of the lack of vertical loads or of the small amount of it. This situation is often encountered for external basement walls under large terrace doors or window openings, where the theoretically necessary vertical loading is missing. This makes it impossible to resist the acting bending forces from earth pressure using a vertical arch model like it is contained in the EN 1996-1-1. In such cases, the lateral loading has to be resisted in a horizontal direction. Since however the horizontal flexural strength capacity of unreinforced masonry is low, it will be possible to increase it by using a textile-reinforced bed joint with longitudinal fibers of alkali-resistant glass or carbon fiber. With appropriately adapted textile reinforcement in the bed joints, the masonry can fulfil the requirements for out-of-plane flexural capacity against earth pressure even under small vertical loads. Textile reinforcement has the advantage that it has no corrosion risk and does not need an appropriate covering due to corrosion resistance. Textile reinforcement can also be inserted into thin bed joints of 3 mm thickness. The results show for textile reinforced masonry an increase of up to ten times of the flexural strength capacity in horizontal direction and a doubled out-of-plane flexural capacity compared to unreinforced masonry. The bed joint is not weakened and still shows the full shear capacity. The initial shear strength in the interface between mortar and unit plays an important role what was not seen until today. With an improvement of this a further increase of the bending capacity of bed joint reinforced masonry is possible. All the findings and the experiments will be presented in the paper.

KEYWORDS: textile-reinforcement, basement walls, low vertical load, bed joint reinforcement, reinforced masonry, textile-mortar

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Thermal and Acoustic Retrofitting of Concrete Masonry Units

Paper 094

Ahmed A. Gheni[1], Mohamed A. ElGawady[2], and John J. Myers[3]

ABSTRACT

The low thermal and sound insulation capacity of concrete masonry unit motivated the researchers to investigate the impact of using waste rubber powder as a re-placement of cement in plastering mortar. Using recycled rubber resulted in more sustainable construction and reduces the buildings' energy consumption. An experimental investigation was conducted to explore the impact of using various thicknesses of plastering and ratios of waste rubber powder in plastering cement mortar on the thermal conductivity and the sound insulation. The thermal conductivity at the masonry material level test was performed according to the ASTM C136311 to evaluate the thermal insulation for the plastered masonry unit. The sound absorption test was performed according to the requirements of ASTM E1050 using a tube, two microphones, and a digital frequency analysis system. The results indicated that adding the waste rubber powder as a replacement of cement in plastering mortar has a positive impact on reducing the thermal conductivity. Plastering mortar mixtures with up to 40% of the cement replaced by waste rubber powder did not show any difficulties to mix and apply with different thicknesses on the masonry units. The new rubberized material exhibited a clear increase in sound absorption and noise reduction compared to standard conventional masonry units.

KEYWORDS: concrete masonry unit (CMU), thermal insulation, rubber powder, eco-friendly, absorption, sustainable materials

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Thermo-Mechanical Behavior of Refractory Masonry Linings: An Overview on Numerical Simulation

Paper 137

Pratik Gajjar[1], João Pereira[2], and Paulo B. Lourenço[3]

ABSTRACT

Refractories are unique materials used in linings of vessels to contain and process fluids at high temperatures. They can withstand complex combination of thermo-mechanical stresses and chemical wear generated by fluids and chemical agents during process. The main challenges for the usage of refractories are linked to the cost, availability of raw material and environmental regulations. This paper presents an overview of recent developments of numerical models using a multi-scale approach in order to identify the impacts of various parameters on the overall behavior of the masonry linings in industrial structure. The results presented in this paper provide, for specific boundary conditions and thermal loading, the evolution in time of the dis-placements, strains and temperature profiles on laboratory models. The overview of numerical models their results further help to validate models at industrial scale, reducing the burden of laboratory testing and ultimately, can be used for optimizing refractory linings, thus extending an economic and environmental benefits to the refractory industries.

KEYWORDS: refractory, thermo-mechanical behavior, numerical modeling

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A Two-Story Italian Masonry Dwelling: Structural Reliability

Paper 241

John M Nichols[1] and Adrienn K. Tomor[2]

ABSTRACT

One of the hardest structures on which a structural reliability assessment must be performed, usually for determining seismic capacity, is a two-story dwelling or building in northern Italy. The structure is often very old, of indeterminate construction and potentially subjected to severe earthquakes with a long return period. These earthquakes often have return periods in excess of 2500 years as occurred in Abruzzo, Italy in 1915. One of the critical stages for a structural reliability analysis is the failure tree analysis and the associated diagram, the purpose of this paper is to develop the failure tree diagram and the associated failure modes for a two-story masonry dwelling as studied by Benedetti in 1996 using shaking table tests. The failure tree diagram can be associated with the non-linear stiffness matrix and then calibrated against the time and Fast Fourier transform analysis (FFT) for the Micro-Electro-Mechanical Systems (MEMS) based acceleration data. The results point to the use of statistical changes in the frequency data being determined using Bayes Theorem to overcome the Central Limit Theorem issue with frequentist analysis of FFT data sets. The Italian house provides the ideal model for an extremely difficult structural problem.

KEYWORDS: reliability, masonry dwelling, timber floors

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Typical Failure Modes of Hollow Load-Bearing Block Walls

Paper 269

Antonio Borri[1], Marco Corradi[2], Romina Sisti[3], and Giulio Castori[4]

ABSTRACT

Many recently-constructed unreinforced masonry (URM) buildings in Italy performed poorly in the recent earthquakes. Cracks opened in the shear walls and slippage between wall panels occurred. These buildings were made of tile hollow load-bearing blocks, also known as Porotherm block masonry. As part of a program of research to study and experiment reinforcement methods for upgrading such recent building, this paper reports first results of an experimental investigation carried out in the laboratory. Based on on-site survey of damaged buildings after 2016 Central Italy earthquake, full-scale wall panels (160x90x25 cm in nominal dimensions) were constructed and testing was conducted to investigate their structural behavior. Typical defects were added during construction in order to assess their contribution on the structural behavior of wall panels subjected to in-plane lateral loading. It was found that Hollow Load-Bearing Block Walls often require preventive reinforcement. The effects of construction defects reduced the resisting capacity of the in-plane loaded wall, and also changed the failure mode from shear cracking to horizontal sliding.

KEYWORDS: unreinforced masonry (URM), earthquake-resistant design, retrofitting methods

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Unexpected High Performance of Modern Adobe Precision Flat Block Masonry

Paper 208

Raik Hartmann[1] and Wolfram Jäger[2]

ABSTRACT

Earthen buildings had a long tradition in Europe but largely lost their importance during industrialization in the 19th century. Since the 1980s the activities – construction with clay – are steadily increasing again. Standard guidelines (the German "Lehmbau-Regeln") introduced in the 1990s, however, appear to be rather too cautious when examined in the light of today's research findings on the capabilities of load bearing earthen walls: these can be trusted much more, provided essential design principles are observed.

Based on the evidence of historical earthen buildings as well as on structural engineering calculations and building physics, our research is supporting the assumption that masonry with modern, large format adobe blocks have a much higher performance potential than previously assumed. This applies particularly to its sustainability. The biggest apprehension until today relates to the water sensitivity of this building material in regard to structural stability. This can be countered however with reliable, prophylactic safeguarding principles of construction.

The modern load bearing masonry is made from extruded adobe – precision flat blocks with the following dimensions: 30,5cm length, 24cm width and 24,9cm height. These are produced in existing industrial block factories by excluding the firing process, which is the biggest energy factor in block production process. Our tests of this type of modern adobe masonry have shown very good strength behavior with little scatter of the results and a high modulus of elasticity – compared to other load bearing clay constructions with unfired clay materials. This performance is higher than conventional load bearing clay constructions, despite its 24cm thickness. In combination with the usual on-site processing methods, contemporary planning details and safeguarding principles tested for the adobe masonry, it is possible to build stable modern adobe precision flat block masonry sustainably and effectively.

KEYWORDS: adobe, earthen masonry, safeguarding

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The Unification and Update of the Brazilian Masonry Codes

Paper 115

Humberto R. Roman[1], Guilherme A. Parsekian[2], and Wallison A. Medeiros[3]

ABSTRACT

Currently in Brazil different design and execution codes are valid for concrete block masonry and clay block masonry. Since 2016 a technical committee is working on the draft of a unified code. The new code shall unify not only the procedures used to design with these materials but also will include execution and quality control. The new Brazilian Structural Masonry Standard will be divided into 5 parts: 1) design; 2) execution and quality control; 3) test methods; 4) design in fire situation; 5) seismic design. The proposals for Parts 1 to 3 have been finished and are discussed in this paper. Parts 4 and 5 are scheduled to be discussed between 2018 and 2022. In spite the committee has been based to several international codes, several aspects are unprecedented and take into account the boldness degree of Brazilian structural masonry, particularly related to building construction. The new version of part 1 maintains the consideration of the wall gross area reference for most of the design procedures and includes topics such as: specification for structural bricks, design of slender walls, use of lateral bracing for wall slenderness, special specification for one-story houses, a new method to design shear walls subjected to both vertical and in-plane or out-of-plane loads,, more accurate specification for concentrated load design, definition of the hollow block shape to consider full bond between grout and block, demand for third part structural design review, lateral stability specifications and limits, new specifications for beam design, new annex with specifications for lateral load design and wall infill design, recommendations for materials specifications (block, mortar, block strength combinations and resulting strengths of the prism assemblage). Part 2 brings completely new specification for quality control. Part 3 basically unifies the testing procedures and includes recommendation for removal of masonry specimens from existing construction.

KEYWORDS: building code, Brazilian masonry, design, execution, quality control

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The Use of Hydrated Lime and Its Impact on the Pore Structure of Masonry Mortars

Paper 009

Andrew S. Smith[1]

ABSTRACT

This paper focuses on the investigation and assessment of the benefits of hydrated lime additions to cement-based mortars in respect of the development of the observed and measured pore structure. The investigation has been undertaken on mortars recovered from laboratory-built clay masonry panels, where hydrated lime has been used as a mortar additive to provide both workability, in the fresh state, and hardened mortar properties.

In a limited number of examples comparison is made between mortar from panels containing hydrated lime additions, and mortar from masonry panels constructed of an equivalent strength, but where air-entrained cement-sand mortar has been used.

The results indicate that there is a fundamental difference in the pore structures observed, relating to the proportion of macro (>10m) and micro (>10m) pore structures in the mortar paste. The mortars containing hydrated lime appear to have a lower macro porosity but a greater micro pore structure, most likely attributed to the more significant development of the capillary pore structure.

The mortars containing hydrated lime, compared to those of a similar design strength that contain and air-entrainment admixture, appear to be both stronger (in compression) and of a higher bulk dry density, both of which can be attributed to the difference in the observed pore structure between the mortar types investigated.

KEYWORDS: hydrated lime, mortar, pore structure

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The Use of Portland Limestone Cements in Masonry Applications.

Paper 108

Todd Laker[1], Barry Descheneaux[2], and Wayne Wilson[3]

ABSTRACT

Sustainability has become an increasingly important element in the design and construction of commercial, residential, and infrastructure projects. Concrete products including masonry products are the most widely used construction materials on the planet and have a significant environmental impact. Although portland cement is a relatively minor constituent by volume, its presence can significantly contribute to the CO_2 associated with masonry products. Therefore, the key to reducing the carbon footprint of masonry products is to reduce the amount of traditional portland cement used. One way to accomplish this is by using alternative cement binders including Portland Limestone cements meeting ASTM C595 and ASTM C1157 hydraulic cement specifications. This paper will discuss the environmental impacts of cement for masonry products and use case studies to show that masonry projects utilizing Portland Limestone cements and supplementary cementitious systems are readily constructible and can easily achieve specified strength and durability requirements at a significantly lower environmental impact.

KEYWORDS: cement, sustainability, construction

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The Use of SRG to Improve the Displacement Ductility of Confined Masonry Walls

Paper 048

Jhair Yacila[1], Jhoselyn Salsavilca[2], Nicola Tarque[3], Paolo Casadei[4], and Guido Camata[5]

ABSTRACT

The construction of confined masonry dwellings has become an attractive alternative for people who build their houses on their own. This means no engineering or technical intervention, therefore, there is an intrinsic high seismic vulnerability related to the dwelling's quality. If this fact is added to the disorderly growth of the Peruvian population, an undesirable increase of informal constructions becomes important. Just in Lima, it is registered that at least 70% of the total dwellings are informal and are located in hills. Additionally, seismologic information has revealed that the asperity between Nazca and South American plates are so concentrated, which means that they already have enough energy to cause a big earthquake in the southern and central coast of Peru. Thus, there is no doubt that a big disaster will occur if these buildings are not properly reinforced as soon as possible. Following this line, this study contributes with the reduction of the seismic vulnerability of these kinds of buildings and opens a research line for controlling damage to an acceptable limit state. For this purpose, an experimental campaign of a new strengthening technique based on steel rein-forced grout (SRG) has been conducted. In this campaign, three confined masonry walls that were previously tested until a collapse state, were repaired and strengthened with SRG to be retested under in-plane lateral cyclic loads. The results showed the benefits of strengthening with SRG for improving the lateral displacement ductility. It is pretended that SRG could be widely used to reduce seismic risk on confined masonry dwellings of developing countries, due to its easy and fast installation and its ability to improve the ductility of walls and controlling damage in different limit states.

KEYWORDS: steel-reinforced grout (SRG), confined masonry, informal dwellings, cyclic in-plane shear

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Vectorized and Parallelized Finite Element Method for Modeling Masonry Infilled RC Frames

Paper 043

Reza Rahimi[1], Yi Liu[2], and Gordon A. Fenton[3]

ABSTRACT

This paper presents the development of a modular, open-source finite element model, called VPFEM library, for simulation of the in-plane behavior of masonry infilled RC frames. It was developed to use the parallel algorithm to be able to run on Graphical Processing Unit (GPU) architectures to reduce the commonly high computational time associated with modeling masonry infilled frames. In this study, the masonry infill was modeled as a continuum with nonlinear quadrilateral elements. A smear cracking model, referred to as Modified Compression Field Theory (MCFT), was employed to smear the constitutive laws of mortar and concrete units. The theory was based on a smeared crack modeling technique that averages the stress and strain throughout the element. The crack direction was defined based on the direction of the principal stress and the cracking development traced the direction of principal stress at each load iteration as material responded. This model was implemented to improve the accuracy of simulation from the conventional smear cracking model and particularly improve the post-peak behavior prediction. The load vs. displacement response obtained using the developed VPFEM model was compared with the experimental response of a masonry infilled RC frame under lateral loading. A comparison with a finite element model based on the conventional smear crackling model implemented on OpenSEES was also presented. The results show that while both finite element models provide the prediction of the initial behavior with relatively similar accuracy, the VPFEM performed better in predicting the post-peak behavior. However, the runtime comparison shows that the VPFEM model on GPU devices ran at a fraction of the time of the OpenSEES model on a CPU device.

KEYWORDS: graphical processing units (GPUs), masonry infill, vectorized and parallelized finite element method, stiffness matrix stiffness matrix

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What We Wish Your Students Knew About Masonry: The Industry's Perspective

Paper 144

Heather A. Sustersic[1] and Mary E. Haynes[2]

ABSTRACT

Not every University has a masonry design course. Of those that do incorporate masonry into the curriculum, courses are often tailored to architecture students or included as a technical elective. The result is that many entry-level engineers have limited knowledge of masonry as a structural material, even though masonry, in one form or another, is present on the vast majority of architectural building projects.

With limited time in a typical 4-year engineering curriculum available to focus on masonry design, how do instructors prioritize the information presented to ensure that their students are prepared for what they will see in industry? What are the big-picture masonry design constraints that all practicing engineers should know? What tools and resources are available to masonry instructors? This presentation will explore these questions and more to provide a springboard for masonry instructors looking to improve the quality of masonry education at their institution, and for entry-level engineers looking to 'hit the ground running' in professional practice.

KEYWORDS: instruction, masonry teaching, entry-level engineers, design, practice

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Written in Stone: In-Situ Study of Historic Edinburgh Sandstone Structures Relating Deterioration Type and Extent to Physical Properties and Mineralogy

Paper 129

Jordan Christine Dick[1]

ABSTRACT

The historic city of Edinburgh, Scotland is built predominantly of sandstone, providing a valuable long-term physical record of the relative durability of various sandstones. While many buildings have weathered steadfastly over the centuries, others have not fared so well. Through conservation practice, the sandstone is frequently assessed for the type, severity and extent of deterioration; however, the underlying root cause(s) of why the stone has deteriorated (e.g., the deterioration mechanisms) are not always considered.

Organizations like the British Geological Survey and Historic Environment Scotland have extensive knowledge about the properties of Scottish sandstones and advocate strongly that replacement stones should be "compatible" with the existing stone – both visually and technically.

While the practice of using "compatible" stone is becoming more widely accepted in the conservation field in Scotland, this begs the questions, "What is a compatible stone?" And from this, "Why do different stones deteriorate in different ways and at different rates?", and "Can deterioration types be linked to something intrinsic to the stone?"

This paper proposes to answer these questions by summarizing findings from an in-situ visual survey of approximately 100 buildings, with stones from twelve known quarries, in the Edinburgh area. The study also considers the effects of numerous other factors and discusses the presence of strongly cementitious materials (e.g., portland cement-based mortar, repairs, or renders), the effects of the level of maintenance and occupancy (e.g., vacant vs. occupied), and relative exposure to moisture (e.g., sheltered, exposed, protected by flashings).

The survey results show that four deterioration types are most common in the types of stones surveyed: scaling, pitting stone, peeling, and mineral pop-out. Each deterioration type is demonstrated to show some correlation between its frequency and at least one intrinsic physical or mineralogical property, and suggested specifications to minimize the common deterioration types are included.

KEYWORDS: sandstone, Edinburgh sandstones, sandstone deterioration mechanism, sandstone, sandstone mineralogy

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Zeolite Geopolymers: A New Class of Concretes and Composites for the Masonry Industry

Paper 176

Leon S. Burgess-Dean[1]

ABSTRACT

Zeolite geopolymers or zeopolymers have been formulated to remain stable indefinitely as aqueous suspensions. These suspensions are produced using organic and organometallic complexing agents combined with aqueous alkali silicate solutions. Stable suspensions were produced with molar equivalent reactive materials such as fly ash from black coal fired power stations, ball clay and calcium hydroxide. Solutions remained stable through a number of added agents that included acrylic suspensions, siloxane suspensions, silicone oil, terpene resin, alkali borates and alkali aluminates. Application of these solutions to wood, concrete, masonry, steel and aluminum provided a stable, thermally resistant zeolite-polymer hybrid geopolymer. The zeopolymer coatings exhibited excellent thermal properties while maintaining excellent durability to environmental attack through the addition of organic resins to the matrix. Hybrid geo-organic polymers were made by mixing aqueous suspensions of natural and synthetic organic polymers with the pre-conditioned silicate geopolymer mixture. This produced a large range of flexible and semi-rigid sealed zeolite-organic coatings. The range of possible composite products is vast due to the adhesive power the zeolite-organic hybrid polymer has towards ceramic, metals, and cellulosic materials. Standard zeopolymer masonry units were produced as an alternative to traditional extrusion, drying and firing of clay masonry and curing of concrete masonry units. This new class of hybrid polymer between inorganic and organic materials provides the next step in materials development for the built environment.

KEYWORDS: zeopolymer, hybrid structural system, geopolymer, masonry industry, coatings, composite

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Innovative Technology Presentations

There are no papers associated with the innovative technology presentations.

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The Fourth Edition of the Popular TMS Publication: Masonry Structures: Behavior and Design

Ahmad A. Hamid[1]

ABSTRACT

The most widely used masonry textbook, Masonry Structures: Behavior and Design, has been completed updated and was published by TMS in 2018. This long-awaited update to this popular textbook includes much of the discussion that made previous editions so useful in both the classroom and in the workplace, but it has also been revised to discuss new research findings and to reflect the design and construction provisions in the most recent 2016 TMS 402/602 Building Code Requirements and Specification for Masonry Structures. The textbook includes numerous design examples based on the strength method. Two complete building designs for a single-story building and a multistory building are presented in the last two chapters.

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Material and Labor Efficiency in Reinforced Concrete Masonry Buildings: Advantages of the Single Face-Shell Approach

Francisco Gomes[1]

ABSTRACT

A presentation on the principles and development process of an innovative single-wythe drained-cavity load-bearing reinforced concrete masonry wall assembly. The patented MineralBuilt wall system is designed to compete with and recapture market share from open stud frame construction, with unprecedented efficiencies realized both in the block plant and on the construction site.

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Material Attributes and Form: The Shape of Things to Come

Mark Weber[1]

ABSTRACT

There are two pillars of influence that impact how successfully a building material will work: Material Attributes and Form. In a traditional sense, we'll discuss how material attributes influence the form and design of building materials. The majority of building materials are designed in this manner, determining the size, shape and method of assembly of building materials we use today. We'll discuss how looking at the development of building materials through attributes of form, allows for a different perspective that opens an alternate pathway to innovation.

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Spherical Block's Innovative Masonry Systems

Peter Roberts[1]

ABSTRACT

This talk will address the topological interlocking manufactured concrete block systems developed by Spherical Block, LLC. Two different types of block design will be described, including triangular block used to make domes and spheres; and voussoirs used to build arches, flying buttresses, windows and more. The molds used by block makers to produce these blocks will be described, including methods for handling these blocks, including cubing and palleting for shipping. The advantages of these innovative masonry systems will be summarized; including taking advantage of the anisotropy of these blocks; the extensive design flexibility which they provide; the safety provided by these masonry systems for fire, extreme weather, seismic events, and resistance to terrorist threats; the low cost and ease of production, and both manual, semi-automated methods of assembly. The speaker will address all of these considerations in the real-world context of his ongoing experiences in the development of using these specialty manufactured concrete blocks to build masonry roof arches, domes, spheres, flying buttresses, boats ships, and much more. This talk will summarize the role of this profitable innovation in the masonry industry relative to the block maker, masons and the end-user.

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Using Arial Drones to Assist with Assessment

Peter Babaian[1]

ABSTRACT

Facade assessment is generally completed from the ground or via temporary access, such as an aerial lift, rope access, or swing stage. Ground based assessment is generally faster and less expensive, but limited due to angle of incidence and distance, especially for buildings more than three or four stories. Temporary access provides an up-close, direct level of assessment with no distance or angle of incidence issues. However, it may not be feasible for all buildings due to access (difficulty reaching a spire), time, or cost. Drone technology offers a potential way to solve the angle of incidence and distance issues without the cost and difficulty of setting up temporary access. As with any new technologies, limitations exist and as a result it should be pursued with some level of caution. This presentation will discuss recent experiences with drone technology on masonry buildings and how it helped with the assessment and limitations encountered.

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Deconstructing the Masonry Wall: A Methodology for Wall Design

Scott Conwell[1]

ABSTRACT

The exterior masonry wall is a complex assembly challenging architects in the problems of aesthetics, performance, and structure. This session analyzes and graphically deconstructs a variety of complex masonry wall types commonly used in new construction. The session takes a detailed look at the basic decision-making process for walls in the pre-design and early design stages. Attendees will learn a design approach that quickly and systematically takes them through a series of micro-decisions on a small number (eight or fewer) of subassemblies of the wall, resulting in a well-informed system design. This session will use examples of walls from real projects and walk the audience through the uniquely swift linear decision-making process. It will also discuss development of a wall taxonomy, the curation of a Wall Systems Library, and opportunities for BIM integration.

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Improving Thermal Efficiency Through Offset Shelf Angle Support

Adam Kimble[1]

ABSTRACT

Continuous insulation is an effective way of achieving high R-value walls; however, thermally inefficient materials, such as façade attachments, penetrate the building envelope causing thermal bridging significantly degrading the insulation's thermal performance. Heavy masonry veneer requires a robust structural attachment system to transfer cladding loads back to the primary structure. A primary location to address thermal bridging is the shelf angle to the building structure.

1. Identify thermal bridging in masonry construction
2. Comparison of conventional shelf angle installation to Fero FAST bracket examining the following topics;
   - Adjustability for construction tolerances;
   - Thermal performance;
   - Cost; and
   - Installation methods

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Masonry Veneer Anchors and Structural Relief Systems

Jeremy Douglas[1]

ABSTRACT

Increasing the energy efficiency of our wall configurations to meet more demanding code requirements is an escalating challenge we are all tasked with meeting. In this session, we will take a look at some new masonry veneer anchors and structural relief systems that are designed to limit the amount of thermal transfer occurring through the building envelope.

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Using Fabric-Reinforced Cementitious Matrix (FRCM) for Strengthening and Retrofit of Existing Structures

Aniket Borwankar[1]

ABSTRACT

Fabric-Reinforced Cementitious Matrix (FRCM) combines high-performance sprayable mortar with a carbon-fiber grid to create thin-walled, reinforced concrete shells without adding significant weight or mass to the structure. With this system, we can repair, protect and strengthen aging, damaged or overloaded concrete and masonry structures in one application and significantly reduce your installed cost.

Significant flexural, axial or shear strength gains can be realized with an easy-to-apply composite. FRCM provides a low-impact, low-weight alternative to traditional concrete strengthening and retrofit methods. Many times, it is the most economical strengthening solution available, given its reduced preparation installation time. This system will be suitable for the following applications.

1. Projects that also require a surface repair and levelling in addition to strengthening
2. Seismic retrofit of concrete, brick and masonry buildings
3. Projects with large, overhead, and vertical surface areas where higher production rates are possible with shotcrete material
4. Repair applications that cannot afford significant member enlargement
5. Composite strengthening applications that require an increased level of abrasion and fire resistance

In this seminar, we dive into important considerations including latest industry standards, material properties and key governing limits when designing with FRCM. We will also discuss repair and strengthening of Napa County Courthouse using FRCM. Napa County Courthouse is a historic building that had significant damage during the Napa earthquake. FRCM was chosen to repair and strengthening the existing brick walls on this project.

[1] *Composite Strengthening Systems Field Engineer; Simpson Strong-Tie; San Francisco, CA, USA; aborwankar@strongtie.com*

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Practical Installation Considerations for Post-installed Adhesive Anchors in Masonry

Mark Ziegler[1]

ABSTRACT

This session will cover general considerations for good installation practices for post-installed adhesive anchor systems into masonry wall construction. Attention during the presentation will be given to important practical factors such as the existing base material and conditions, adhesive anchor system selection, preparation, hole drilling and cleaning, installation equipment and accessories. The discussion will also include suggestions for effective special inspection and site proof loading of adhesive anchors in masonry.

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New TMS Publication: Assessment and Retrofit of Masonry Structures

Ahmad A. Hamid[1]

ABSTRACT

This exciting new publication has been encouraged and sought for years, and it fills a need for a practical and current guide on evaluating, testing, and, where needed, repairing existing masonry. The book provided background, reference material, and guidance to design professionals, building owners, and contractors on existing masonry. Construction characteristics of masonry structures, typical material properties, and analytical approaches are included for historic, transitional, and modern masonry construction typologies. The main focus of the book is structural stabilization, strengthening, and retrofit with maintenance and serviceability items (such as water penetration and cleaning) addressed as subtopics. This book also incorporates discussion on the evaluation and retrofit process, site investigation and analysis, retrofit, monitoring, and maintenance. Assessment and retrofit projects conducted by the authors are presented as case studies to highlight technical issues and illustrate the process of developing a rational methodology for different types of masonry assessment and retrofit projects.

[1] *Professor of Civil Engineering; Drexel University; Philadelphia, PA, USA; hamidaa@drexel.edu*

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Assessment of Unit/Grout Bond Strength With and Without Integral Water Repellent Admixtures: Need and Viability

Jason Thompson[1] and Craig Walloch[2]

ABSTRACT

Masonry is a composite system – consisting of units, mortar, grout, and reinforcement. For the system to perform as intended, the assembly of materials must be sufficiently bonded together to transfer loads and stresses between and throughout the entire composite assembly. Since masonry units were first laid in mortar, materials, technologies, and workmanship practices have focused on ensuring adequate bond between the units and mortar. As reinforcing steel began to be introduced, research documented and validated the bond that can develop between the mortar/grout and embedded reinforcement. In more recent years, as integral water repellent technologies were introduced into concrete masonry units, the question surfaced as to whether these admixtures had an adverse effect on the unit/grout bond strength.This session will review recent research investigating the effects on unit/grout bond strength with and without integral water repellent admixture in the units, regional requirements that require this property to be evaluated, the testing procedures used for measuring unit/grout bond strength, and offer recommendations on whether continued assessment of unit/grout bond strength is necessary.

[1] *Vice President, Engineering; National Concrete Masonry Association; Herndon, VA, USA; jthompson@ncma.org*
[2] *; ACM Chemistries; Norcross, GA, USA; cwalloch@acmchem.com*

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Innovative Research Studies Key Mortar Properties for Best Performance

Bill Kjorlien[1] and Wayne Wilson[2]

ABSTRACT

As part of a recently approved change in ASTM C12's C270 Specification for Mortar for Unit Masonry, a group representing a balanced group of the masonry industry investigated water penetration resistance of masonry wall panels. While many past researchers had studied the topic, results were not always conclusive, and modern-day materials have evolved, so it was decided that taking another look was warranted. Testing by E514 Standard Test Method for Water Penetration and Leakage through Masonry allowed for direct comparative testing of different mortars to establish which characteristics have the most influence on creating water-resistant masonry construction, while providing the superior bond strength that demanding codes require. This research adds to the body of knowledge about cementitious mortars and their interaction with masonry units. A brief summary of the new research (being presented in a paper by Dr. McGinley) will summarize the important points, then allow a question and answer period for attendees to better understand the significance of the findings and how they are addressed by the C270 standard.

[1] *Masonry Technical Service Director; Argos; Atlanta, GA, USA; bkjorlien@argos-us.com*
[2] *Production Manager; LafargeHolcim; Suwanee, GA, USA; wayne.wilson@lafargeholcim.com*

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Direct Design Software

Russ Peterson[1]

ABSTRACT

This presentation provides an introduction to Version 3.0 of the Direct Design Software (DDS). DDS is a unique structural design software package that combines the loading requirements of ASCE 7 and the material resistance provisions of TMS 402 to quickly and easily produce code-compliant concrete masonry designs in accordance with the structural requirements of the International Building and Residential Codes (IBC and IRC). DDS not only performs structural design checks for masonry per TMS 402, but concurrently resolves design loads -inclusive of seismic, wind, snow, dead, and live loads – based on simple user defined parameters.

[1] *Engineer, Software Developer; Ensoltech; Bozeman, MT, USA; russp@ensoltech.com*

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In-situ Evaluation of the Hygrothermal Properties of Mass Masonry Walls

Rex A. Cyphers[1]

ABSTRACT

The presentation will highlight how in-situ instrumentation and field evaluations are coupled with computer modeling to evaluate mass masonry buildings being considered for deep energy retrofits. The in-situ evaluation is used to determine the actual thermal performance and moisture migration properties of the walls in order to select the most appropriate type and amount of insulation. The presentation will also include how ASTM E3069, "Standard Guide for Evaluation and Rehabilitation of Mass Masonry Walls for Changes to Thermal and Moisture Properties of the Wall" is utilized as a part of the evaluation.

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Resiliency of Reinforced Structural Brick

Steven Judd[1]

ABSTRACT

A presentation on the resiliency of reinforced structural brick specific to its ability to resist extreme events such as projectile impact, blast, fire, and ballistic attack. Presentation will touch on current active testing for ballistic resistance and past testing for fire resistance and projectile impact resistance.

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