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Retrofit Overlay With Fishing Net Reinforcement For Substandard Concrete Masonry In Coastal Areas

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ABSTRACT
Masonry made with low-strength cinder blocks is the residential construction system of choice in coastal and rural areas of Central America. Resistance to high-wind pressures is a recurrent concern for owners. This paper presents preliminary research on the feasibility of using cement-mortar overlays reinforced with recycled fishing nets to significantly enhance the out-of-plane capacity of substandard cinder-block masonry walls. The mechanical response of prototype fishing-net reinforced overlays was characterized based on uniaxial tensile tests. Proof-of-concept is provided based on evidence from out-of-plane load tests on masonry specimens, including a counterpart specimen reinforced with welded-wire steel mesh.

KEYWORDS
Cementitious matrix; fishing nets; recycled contruction materials; structural retrofit; wind loads.

INTRODUCTION
Nearly 40 percent of the Earth's population lives along coastlines. These areas are especially vulnerable to natural hazards due to extreme weather and the effects of climate change. For example, recent hurricanes such as Matthew in 2016 showed the destructive effects of high winds in coastal areas in the Caribbean and the US, especially in relatively low-income areas where substandard construction is common. Substandard masonry made with cinder blocks is a predominant construction material for dwellings in the coastal areas of Central America (e.g., Figure 1a) and the Caribbean.

a) Typical substandard concrete masonry dwelling in Progreso (Yucatán, Mexico) (credit: F. Matta) | b) Exterior weathering and damage (credit: J. Biles) | c) Interior weathering and damage (credit: J. Biles)

Figure 1: Vulnerability of substandard masonry in coastal areas of Central America and Carribean.

Local substandard concrete masonry is typically made of hollow-core concrete blocks having a compressive strength around 3-5 MPa, often with minimal or no internal reinforcement. In fact, a

2017 survey of 628 households in seven coastal communities in Yucatan, Mexico, highlighted the homeowners's recurrent concern about safety under windstorm events, along with a preference with familiar cement-based materials (Bresko et al., 2017). In addition, the mortar joints are often dotted with openings, posing the need for more effective physical barriers against water penetration to improve comfort and well-being in humid environments (Figure 1b-c). Reinforced cement-matrix overlays (e.g., ACI 2020) are a reasonable means to address these needs. In fact, cement mortar is a familiar material to local builders and can adhere well onto cinder block substrates. However, to devise solutions that truly pair sustainability and resiliency (e.g., Kijewski-Correa & Taflanidis, 2012), reinforcements more locally-appropriate than those made with relatively expensive carbon, glass and basalt fabrics should be considered.

This paper presents exploratory research on a cementitious-matrix overlay material made with standard Type N cement mortar and nylon fishing nets. This reinforcement material is common in low-income coastal areas and is attractive due to its relatively low cost (about one third that of welded-wire steel mesh), high strength, and deformability, which may be sufficient to maintain the structural integrity of substandard masonry subjected to high-wind loads. In addition, nylon fishing nets are recyclable though they are typically replaced every few months, and offer durability when exposed to the alkaline environment of cementitious matrices (Khajuria et al., 1991; Balaguru & Slattum, 1995). Abandoned and discarded fishing nets also cause ocean pollution and pose a significant environmental hazard to marine life (Do & Armstrong, 2023). The incorporation of nylon fibers in cementitious overlays has been demonstrated for the purpose of rehabilitating concrete (e.g., Srimahachota et al., 2020) and masonry (e.g., Ranjan et al., 2023) structures. The use of fishing nets in overlays bonded onto concrete masonry is a promising and untested strategy.

EXPERIMENTAL PROGRAM

Empirical evidence from uniaxial load tests on prototype overlays is used to comparatively assess the performance of fishing-net and counterpart welded-wire steel mesh reinforcement. In fact, contrary to popular belief, these reinforcement systems are capable of resisting similar tensile forces per unit width. Then, proof-of-concept is provided based on preliminary out-of-plane load tests on substandard masonry specimens.

Materials

Reinforced cementitious overlays

The overlay reinforcement consists of one layer of fishing net made of knitted nylon strands having a nominal diameter of 1.75 mm (Figure 2a), herein referred to using the commercial designation '#21'. The net has a mesh side length (i.e., on-center spacing) of 15 mm in both orthogonal directions, resulting in a nominal strand cross-sectional area of 160 mm^2/m.

a) Overlay reinforced with #21 nylon fishing net and bonded onto concrete masonry substrate

b) Welded-wire steel mesh #19 used for comparative assessment

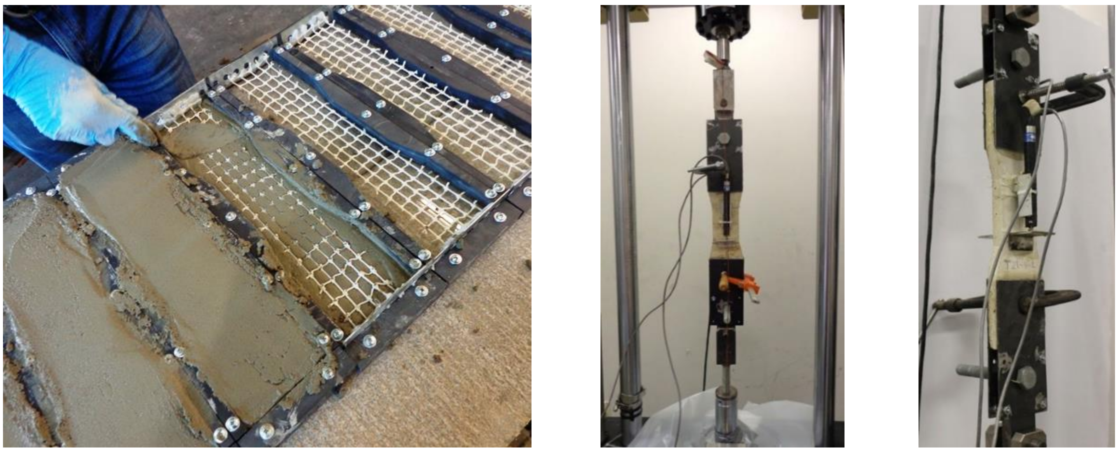
Figure 2: Overlay materials.

A welded-wire steel mesh was used as benchmark reinforcement given its suitability for masonry retrofit (e.g., Kadam et al., 2015). The mesh consists of welded galvanized stainless steel wires having a nominal diameter of 0.89 mm ('gauge #19', Figure 2b). The on-center spacing is 12.5 mm in both orthogonal directions, resulting in a nominal wire cross-sectional area of 50 mm^2/m.

A ready-mix Type N cement mortar was used as the cementitious matrix. Through a laboratory trial-and-error process (Mousa, 2017), the water-to-binder ratio was set to 0.55 to ensure sufficient workability, encapsulation of reinforcement, and adhesion onto typical concrete masonry substrates (Figure 2a). The mortar compressive strength of 18.4±1.15 MPa and flexural strength of 3.4±0.30 MPa were characterized according with ASTM C109 (ASTM, 2016) using six specimens, and ASTM C348 (ASTM, 2014) using five specimens, respectively.

Cinder-block masonry
Substandard concrete masonry was rendered using custom-made low-strength cinder blocks with 406 mm × 203 mm × 203 mm nominal dimensions, and low-strength cement mortar. The masonry compressive strength of 5.46±0.36 MPa was determined through uniaxial compression tests on three 406 mm × 406 mm × 203 mm two-block prisms according with ASTM C1314 (ASTM, 2016).

Prototyping and mechanical characterization of overlays
Fishing net-reinforced cementitious overlays were prototyped in the form of dogbone specimens for the purpose of uniaxial tensile characterization. Three specimens included one layer of #21 fishing net reinforcement and three specimens included one layer of gauge #19 steel mesh reinforcement. The overlays were cast in dogbone-shaped acrylic molds with total length of 406 mm, and length and width of the test region of 102 mm and 76 mm, respectively (Figure 3a). One layer of reinforcement (either #21 fishing net or gauge #19 steel mesh) was sandwiched between two layers of mortar. Each strand of the fishing-net reinforcement was slightly pre-tensioned prior to casting the top mortar layer (Figure 3a). The specimens were demolded after 24 hours and cured in wet burlap for 28 days.



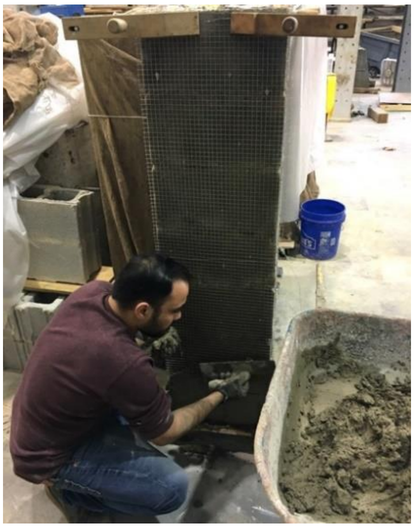
a) Casting of fishing net-reinforced cementitious overlay specimens   b) Uniaxial tensile test setup   c) Close-up of dogbone specimen

Figure 3: Prototyping and mechanical characterization of fishing net-reinforced cementitious overlays.

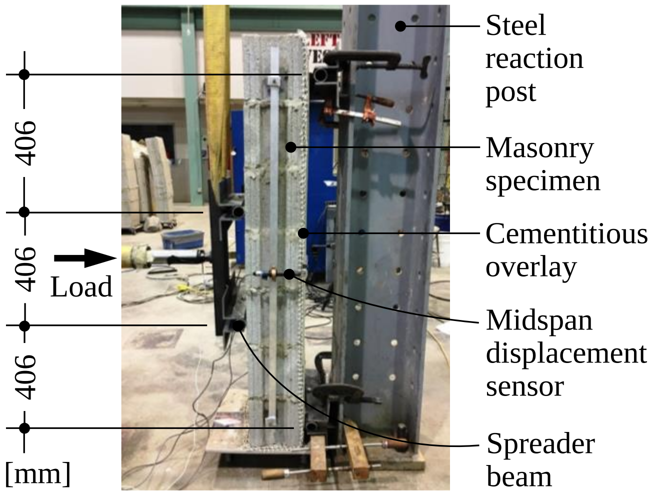
The overlay specimens were tested under uniaxial tensile loads using a servo-hydraulic test frame (Figure 3b-c). A clevis-grip setup (Arboleda et al., 2016; ACI, 2020) was used as a suitable means to investigate the interaction between reinforcement and cementitious matrix (Focacci et al., 2022), in addition to comparatively assessing load capacity and post-crack elongation for the two different reinforcements. The load was applied at a displacement rate of 0.2 mm/s, and was measured with a 10-kN load cell. The total elongation was measured over a gauge length of 95 mm using two displacement transducers, which were mounted symmetrically onto the front and back face of the specimen (Figure 3b-c). The data were acquired at a frequency of 100 Hz using two synchronized data acquisition systems.

Proof-of-concept testing of substandard masonry specimens

Proof-of-concept is demonstrated through out-of-plane load tests on three masonry prism specimens (Figure 4), each made using seven blocks and 10-mm thick bed joints. One unretrofitted specimen served as the control one. The other two specimens were retrofitted using cementitious overlays reinforced with one layer of #21 nylon fishing net and one layer of gauge #19 welded-wire steel mesh (Figure 4a), respectively. The overlay thickness was ~19 mm. The specimens were wrapped in wet burlap and moist cured for seven days, and then air cured indoors for additional 21 days.



a) Specimen construction



b) Schematic of test setup

Figure 4: Out-of-plane testing of substandard cinder-block masonry specimens.

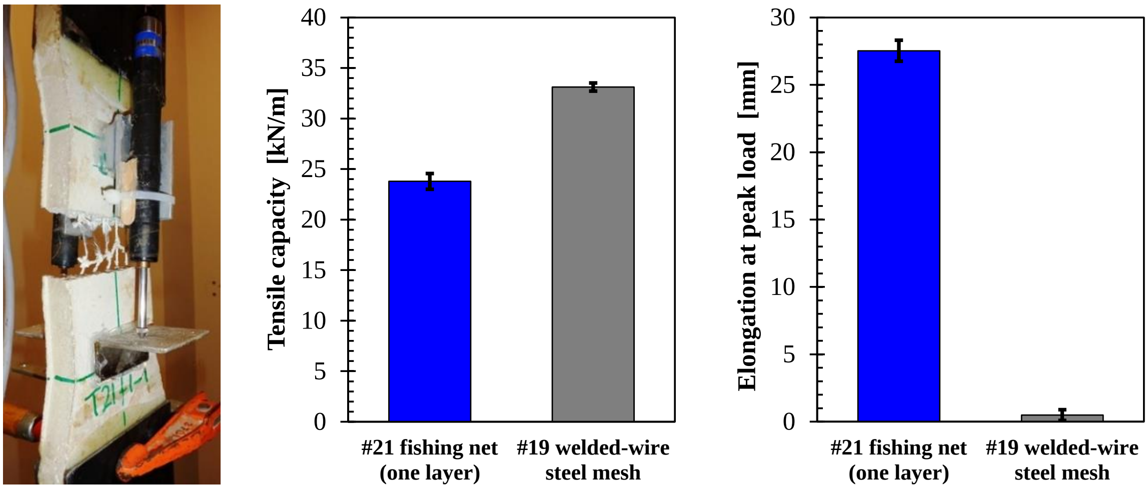
Each specimen was load tested using a four-point bending setup (Figure 4b). The load was imparted through a manually-operated hydraulic jack and was measured using a 22 kN load cell placed between the jack loading plate and the surface of the spreader beam. The out-of-plane midspan horizontal displacement was measured with two displacement transducers. Each sensor was mounted on an aluminum bar that was pin-connected to one side of the specimen (Figure 4b). The reference surface for measurement was provided by a steel plate that was bonded onto the back face of the specimen. All sensors and the load cell were connected to a data acquisition system. Data were recorded at a frequency of 100 Hz.

RESULTS AND DISCUSSION

Fishing net-reinforced cementitious overlays

The fishing net-reinforced specimens failed due to rupture of the nylon strands (Figure 5a). Unlike typical fabric-reinforced cementitious matrix (FRCM) composites (ACI 2020) where distributed transverse crack patterns develop, the specimens exhibited a single crack along a knot line due to the relatively low stiffness of the knitted fabric. This behavior was recently reported also by Truong et al. (2021) based on results of uniaxial tensile and bending tests on mortar specimens reinforced with polyethylene fishing nets. Failure occurred at an average load of 23.8 kN/m (Figure 5b). Multiple strands unraveled and ruptured simultaneously, indicating that the mortar matrix is effective in distributing axial forces among the strands, and that the knots did not act as a weak link in the reinforcement. In addition, the 0.78 kN/m standard deviation of the failure load indicates consistency in behavior up to rupture of the strands.

The tensile capacity of the fishing net-reinforced overlay is comparable to that of the steel mesh-reinforced overlays, which failed due to rupture of one or more steel wires at an average load of 33.1 kN/m (standard deviation = 0.40 kN/m). For the representative materials and configurations reported herein, these results indicate that the fishing net reinforcement can provide comparable load-carrying capacity to steel mesh reinforcement with comparable consistency.



a) Typical failure mode of fishing-net reinforced overlay

b) Tensile load at failure of fishing net- and steel mesh-reinforced cementitious overlays

c) Elongation at failure load of fishing net- and steel mesh-reinforced cementitious overlays

Figure 5: Results of uniaxial tensile tests on cementitious overlays (error bars indicate standard deviation).

However, unlike steel mesh-reinforced overlays, fishing net-reinforced overlays also offer high deformability as highlighted by the 27.5±3.84 mm average elongation at maximum load (Figure 5c). This capability is desirable in instances where energy dissipation is sought such as to resist seismic forces and impact of flying debris. In particular, the latter is a major safety concern under windstorms.

Out-of-plane behavior of retrofitted masonry

The salient results of the proof-of-concept load tests are summarized in Table 1. Figure 6 presents the applied load as a function of the midspan horizontal displacement data for the three test specimens.

The masonry specimen retrofitted with a #21 fishing net-reinforced overlay (W-N#21-1-1) failed at a transverse load of 29.1 kN/m due to the rupture of the nylon strands. This load capacity is over 4.5 times that of the unretrofitted specimen (W-C-1). The large out-of-plane deformation (Figure 7a) is due primarily to the progressive unraveling of multiple nylon strands across two cracked sections (one along a bed joint and one through a block) in the vicinity of the loading sections (Figure 7b). The fabric knots remained largely intact. This failure mode mirrors the one of the overlay specimens subjected to uniaxial tensile forces, and confirms the effectiveness of the mortar matrix in embedding the reinforcement and distributing the tensile forces among the nylon strands.

The masonry specimen retrofitted with a gauge #19 steel mesh-reinforced overlay (W-S#19-1-1) failed due to yielding followed by rupture of multiple steel wires at a transverse load of 29.8 kN/m. Consistently with the results of the uniaxial load tests (Figure 5), these proof-of-concept results are significant because they preliminarily verify the hypothesis that the masonry load capacity can be enhanced to a comparable extent using nylon fishing nets.

Table 1: Summary of proof-of-concept load tests

Specimen designation	Overlay reinforcement	Failure mode	Peak load [kN/m]	Midspan displacement at peak load [mm]
W-C-1	None	Overlay and masonry cracking	6.3	0.06
W-N#21-1-1	#21 fishing net	Fishing net (strands) rupture	29.1	78.2
W-S#19-1-1	Gauge #19 welded-wire steel mesh	Steel mesh (wires) rupture	29.8	1.22

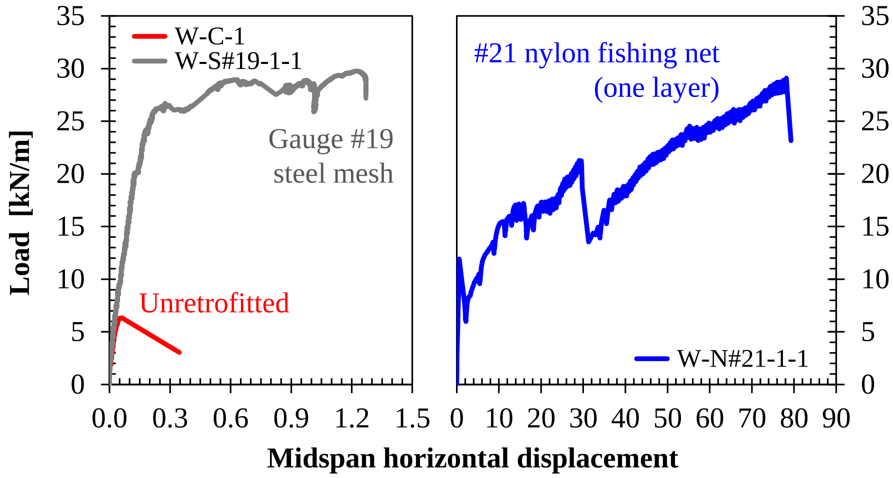


Figure 6: Load-midspan horizontal displacement response of cinder-block masonry specimens.

a) Out-of-plane deformation at failure

b) Close-up of ruptured fishing-net reinforcement

Figure 7: Failure mode of masonry specimen retrofitted with #21 fishing net-reinforced overlay.

The results presented in Table 1 and Figure 6 also highlight the fundamentally different deformability of the retrofitted specimens. In fact, the use of a fishing net-reinforced overlay resulted in an over 60-fold increase in midspan horizontal displacement compared to the steel mesh-reinforced counterpart. The full extent of the deformation might not be relied upon without undermining stability. However, it is clear that the proposed fishing net-reinforced overlay holds promise as a locally-appropriate and structurally effective means of retrofitting against high-wind loads, ranging from wind pressures to impact of flying debris.

CONCLUSIONS

The following conclusions are drawn based on the empirical evidence presented in this paper.

1. Recyclable fishing nets made of knotted nylon strands can be effectively embedded in cement mortar overlays, consistently providing a tensile load capacity that is comparable to that of steel mesh reinforcement.

2. The tensile behavior of prototype fishing net-reinforced mortar overlays is fundamentally different from that of typical FRCM systems. As a result, load-crack opening models are more suitable than approximated stress-strain models for the structural (kinematic) analysis of retrofitted masonry subjected to out-of-plane loads.
3. Proof-of-concept was demonstrated based on evidence from out-of-plane load tests on masonry specimens. The results confirm the potential of fishing net-reinforced mortar overlays to enhance load capacity to an extent similar to steel mesh-reinforced counterparts.
4. The progressive unraveling of the nylon strands characterizes retrofitting solutions that pair strength enhancement with a deformability that cannot be attained with steel mesh-reinforced overlays.
5. Evidence from repeat experiments is needed to verify the results of the uniaxial tensile tests on prototype overlays and the proof-of-concept structural tests presented herein.
6. The retrofit concept presented in this paper may also be applicable to substandard cinder-block dwelling structures in the US. These structures are often encountered in rural areas that are also vulnerable to windstorm hazards.

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CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY
Data on which this paper is based is available from the authors upon reasonable request.

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