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This paper proposes a method of reinforcing masonry referred to as wire stitching. The technique is applicable to cracked or damaged masonry walls to restore strength, or applied to high stressed areas to prevent cracking. As the name of the method implies, a crack is "stitched up" with binding wire to restore strength. A bending moment equation is derived, and several tests performed to determine the viability of the method.

Tests indicate that the equations adequately predict the bending capacity of masonry strengthened with wire stitching.

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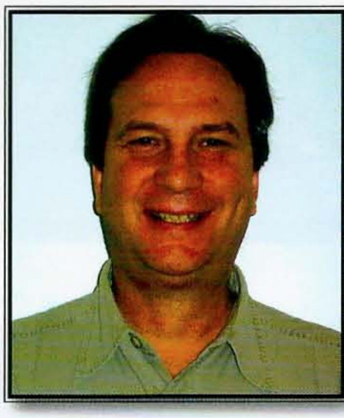
**Professor Gohnert received his BSc in civil engineering in 1985 and a Masters of Engineering Management in 1987 from Brigham Young University, USA. In 1995, he received a PhD in civil engineering from Wits University. He has worked for various companies in the United States and in South Africa as a structural engineer. In 1990, he joined the School of Civil and Environmental Engineering at Wits University where he is currently Head of School.*



Professor M Gohnert

Abstract: *Repair work to cracked masonry walls is a difficult task and usually entails demolition and rebuilding to restore strength. Furthermore, potential cracking around openings in masonry elements is difficult to control and requires some form of reinforcement. This paper proposes a method of reinforcing masonry, referred to as wire stitching. The technique is applicable to cracked or damaged masonry walls to restore strength or applied to high stressed areas to prevent cracking. As the name of the method implies, a crack is "stitched up" with binding wire to restore strength. A bending moment equation is derived and several tests performed to determine the viability of the method. Tests indicate that the equations adequately predict the bending capacity of masonry strengthened with wire stitching.*

Introduction

Reinforced masonry is a composite—the combination of reinforcing steel and masonry [1, 2]. The combination may also include concrete. A lintel over a door or window, with several courses of bricks or blocks above, is an example of reinforced masonry. Other types of reinforcement include wire (i.e. steel ladder) or bars set into mortar between masonry courses, which is common building practice in South Africa. When repairing a wall, a usual method of restoring strength consists of removing the old plaster, attaching mesh reinforcement to the face of the wall and re-plastering. This method of repair is common in Europe to restore historical structures, where large portions of the wall have weathered. Europeans have also used a method of placing "U" shaped reinforcement bars (straight bars with 900 nibs) across cracked regions. Holes are drilled into the masonry on either side of the crack. The nibs of the bar are placed in the holes and filled with epoxy. This system is similar to the proposed method, but differs radically in the type of reinforcement and the method of anchorage.

Since masonry is a brittle material, cracks are common as a result of movement in the foundation, temperature variation, wind and external loads. Cracks are unsightly, difficult to repair and the strength of the wall is diminished. To repair a masonry wall, the only options are to demolish and rebuild, chemical injections or apply reinforcement. Where cracks are singular or confined to a small area, a method referred to as wire stitching is a practical and economical solution to restore the strength of the wall. Since the steel is placed outside of the wall, the method is primarily applicable to plastered walls.

The type of masonry unit (solid or hollow) is an important factor when considering the application of the proposed method. In the series of tests conducted, the masonry units are solid—no tests were done on hollow units. The application to hollow masonry is inconclusive; therefore, the proposed system of reinforcing should not be applied to this type of unit.

The proposed technique is intended to increase (or restore) the moment capacity of masonry. Other forces, such as axial compressions and shears are separately considered and discussed in later articles.

The Stitching Technique

As the name implies, stitching masonry is similar to stitching a wound. Just as stitches are placed across a gaping wound, wire is wrapped perpendicular to a crack to restore the flexural capacity.

Similar to concrete, the compressive strength of masonry is much greater than the tensile strength (the tensile strength is about 1/10 of the compressive strength). For this reason, failures in masonry are usually due to tensile rather than compressive failures. Although cracks may form horizontally, vertically or diagonally, most cracks occur along a mortared joint and are orientated perpendicular to the direction of the tensile stress; therefore, wire is placed perpendicular to the crack, coincident with the direction of tensile force. In this article, however, the tensile forces considered are those caused by bending moments.

The wire stitching is placed by first drilling two holes through the masonry, 300 to 500mm from the crack. The distance between the holes should be sufficient to cover the tensile region. The size of the hole (approximately 12 to 16mm in diameter) should accommodate several wire wraps. An angle grinder is then used to cut two grooves equal to the depth of the mortar between the drilled holes and on each side of the wall. A channel is then chiselled out of the plaster. Ordinary binding wire (1 to 2mm in diameter) is used to stitch the masonry. The wire is fed through the holes and wrapped at least 3 times or more. The ends of the wire are twisted together and laid flat in the channel. Several wraps are necessary to ensure that the wire is sufficiently anchored (by friction) as well as to provide the necessary area of steel to restore the flexural capacity. A wall is usually stitched at a spacing of 200 to 300mm, depending on the tensile strength of the steel. Once the stitching is completed, the channel is filled in with plaster. An example of a stitched wall is illustrated in Figure 1.

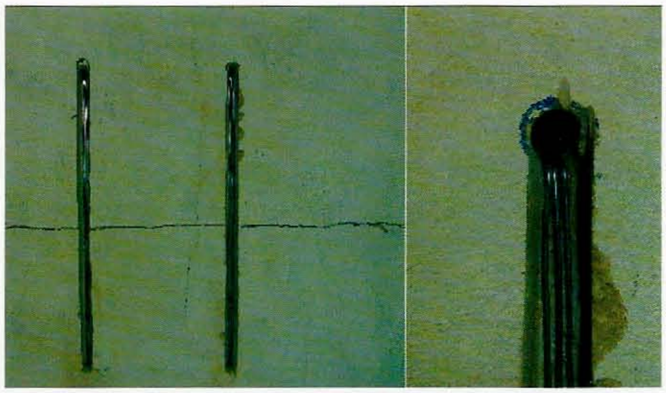


Figure 1: Stitched wall using binding wire

In reinforced concrete, the steel is anchored, or rather embedded, into the concrete. Embedment of the steel is the mechanical mechanism by which tensile stresses are developed in the reinforcement. Steel wire stitching differs in a sense that anchorage is achieved by the frictional restraint of the wrapped wire. It is for this reason that at least 3 wraps are necessary to attain anchorage. Although the plaster will provide some anchorage, it should not be counted on since plasters are relatively weak and the matrix is not designed for strength. The plaster, however, hides the repair work and protects the steel from corrosion.

Flexural Capacity of Stitched Masonry

The bending capacity of the masonry is predicted by a mathematical model using theory similar to reinforced concrete [3]—the tensile force is resisted by the wire stitching and the compressive force is resisted by the masonry, modelled as a parabolic stress block [2].

The internal moment arm (z) is the distance from the centre of steel to the centre of the compression area.

$$z = d - 0{,}45x \qquad (1)$$

where d is the effective depth and x is the depth to the neutral axis.

Rearranged,

$$x = \left(\frac{d - z}{0{,}45}\right) \qquad (2)$$

The resultant of the compressive force is given in Eqn (3), assuming a parabolic stress distribution.

$$x = 0{,}67\, f_k b\ 0{,}9\, x / y_{mm} \qquad (3)$$

where b is the width of the member, f_k is the masonry characteristic compressive strength and γ_{mm} is the partial safety factor for masonry.

The moment capacity is the compressive force times the internal moment arm. Combining Eqns (2) and (3),

$$M = Cz = \frac{1,34\, f_k b(d-z)}{\gamma_{mm}} z \qquad (4)$$

The moment capacity is also the resultant tensile force times the internal moment arm.

$$M = Tz = \frac{f_y A_s z}{\gamma_{ms}} \qquad (5)$$

where fy is the yield strength of the steel, As is the area of tension steel and is the partial safety factor of the steel.

By equating the moment capacities (Eqns (4) and (5)), the internal moment arm is determined.

$$z = \left(1 - \frac{0,746\, f_y A_s \gamma_{mm}}{f_k b d \gamma_{ms}}\right) d \qquad (6)$$

Similar to reinforced concrete theory, z should not be greater than 0,95d.

The bending moment strength of masonry is solved by first calculating the internal moment arm (Eqn (6)) and then the moment capacity, using Eqn (5).

Eqn (5) is identical to the flexural equation listed in SANS10164-2 [2]. However, the equation for the moment arm (Eqn (6)) differs by a factor within the brackets.

Testing Wire Reinforced Brickwork

A testing programme was embarked on to determine the capacity of wire reinforced masonry. Although the testing programme comprised of testing concrete brick beams, the experiments are intended to represent both masonry beams and walls.

The reinforcement used in the tests is an ordinary binding wire—A commercially produced wire used to bind reinforcement as well as other applications. Binding wire is ductile, which is necessary to construct a stitch and meet necessary ultimate limit state conditions. The diameter of binding wire is typically 1 to 2mm; for this reason, the testing programme included both diameters. The stress/strain curves of wire samples are given in Figures 2 and 3. Three wires of each type were tested to determine the yield strength of the steel. The results of these tests are given in Table 1. As seen from the test results, the 1mm wire has a very high yield stress compared to the 2mm wire.

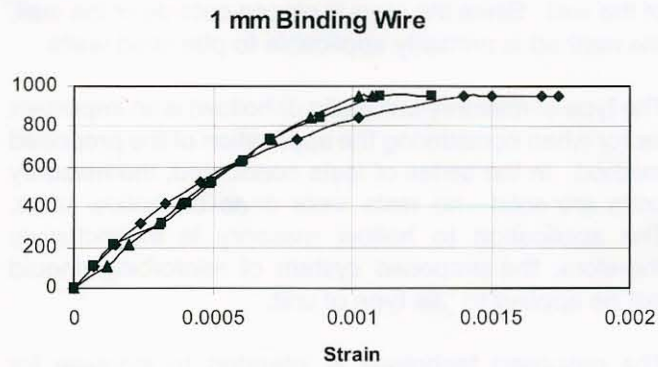


Figure 2: Stress/strain curve of 1mm binding wire

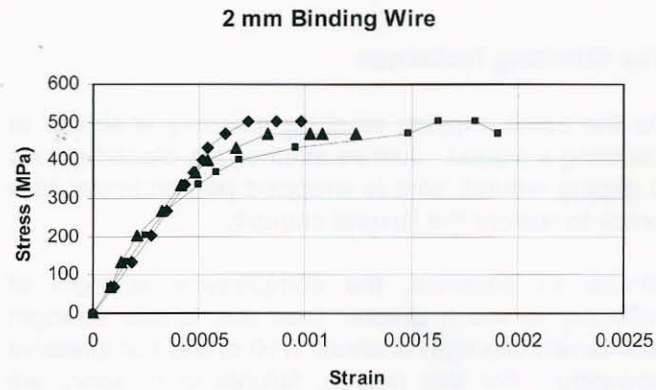


Figure 3: Stress/strain curve of 2mm binding wire

Table 1: *Test results of 1 and 2mm binding wire*

Wire diameter (mm)	Average yield stress (MPa)
1,1	947
1,95	480

Ordinary concrete stock bricks were used in the tests (210 x 100 x 70). The average compressive strength of the bricks is 12,1 MPa.

A class I mortar was used to construct the brick beams. The material ratio of the mortar is 1:3 (6 kg cement : 18 kg builder's sand). The design called for 3 litres of water; however, water was added slowly until a satisfactory consistency and workability was achieved. The mortar thickness between courses was approximately 10mm. The compressive strength of the mortar as well as the compressive strength of the concrete bricks are given in Table 2.

Table 2: *Mortar and concrete brick compressive strengths*

Mortar Specimen	Mortar Compressive Strength (MPa)	Brick Specimen	Brick Compressive Strength (MPa)
1	14,8	1	11,4
2	13,2	2	13,1
3	13,6	3	11,7
Average	13,9	Average	12,1

Under normal design conditions, the value of fk (characteristic compressive strength), used in bending moment equations, is extracted from Tables 3a and 3b of SANS 10164-1 [4]. However, when comparing theory with experiments, it is common to use the strengths of the actual materials used in the tests. For this reason, the value of fk will be based on the compressive strength of the concrete bricks rather than SANS 10164-1, to achieve a better agreement between tests and theory. Furthermore, the overall strength of masonry is based on the combined strength of the bricks (or blocks) and the mortar. The strength of the mortar was also determined and found to exceed the strength of the concrete bricks. However, the strength of the mortar is known to have minor influence on the overall strength of brick or blockwork [6]. For this reason, the value of fk is based on the compressive strength of the concrete bricks.

Two types of beam configurations were tested to simulate two different brick patterns. The two beam configurations are illustrated in Figures 4 and 5. Also shown are the dimensions of the test beams and the wire arrangement. Wire is wrapped 3 times at two locations and symmetrically placed on the exterior of the beams. The wire was then covered with a 20mm thick plaster. The plaster is also a 1:3 mix (cement : plastering sand) and water was added until the desired consistency was achieved, based on workability. Both beam types are 210mm deep.

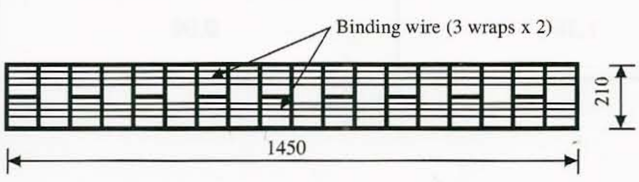


Figure 4: Brick and binding wire orientation of type I specimens (top view)

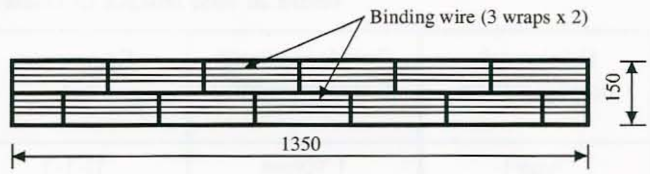


Figure 5: Brick and binding wire orientation of type II specimens (top view)

The wire is anchored by two mechanisms. Firstly, the wire is wrapped around the specimen 3 times. By wrapping the wire, anchorage is achieved by frictional resistance. The second mechanism is the chemical bond between the steel and the plaster. Although a relatively strong plaster was used in the tests (Class I), the bond strength is usually not sufficient to provide adequate anchorage and should not be relied upon; for this reason, wrapping the binding wire is essential to prevent slippage. The ends of the wire are twisted together and laid flat against the brickwork. The purpose of the plaster is to protect the wire from corrosion as well as for aesthetics reasons.

A total of 18 beams were tested to determine the capacity of different types of beams (horizontal and vertical arrangement of bricks) and wire diameters (1 and 2mm). Control beams were also tested to determine the capacity of the brickwork without reinforcement.

Figure 6: Load arrangement and mode of failure.

All tests were performed at 28 days and all specimens were cured in a high humidity room (an enclosed room designed to retain moisture) and soaked twice daily. The test beams were loaded by a series of 4 equally spaced point loads to represent a uniformly distributed load. The load arrangement is given in Figure 6. The beams were tested by an Amsler testing machine and the results are given in Table 3.

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Table 3: *Test results of brick beams reinforced with binding wire*

Brickwork configuration	Reinforcement (6 wraps/beam)	Specimen No.	Failure load (kN)	Estimated self weight of beam (kN/m)	Failure moment (kN.m)
Type I	1,10mm	TI-1-1	10,2	0,55	1,63
		TI-1-2	11,0	0,55	1,75
		TI-1-3	10,8	0,55	1,72
	1,95mm	TI-2-4	22,6	0,55	3,49
		TI-2-5	17,2	0,55	2,68
		TI-2-6	22,0	0,55	3,40
	No reinforcement	TI-C-7	5,6	0,55	0,94
		TI-C-8	5,1	0,55	0,86
		TI-C-9	4,6	0,55	0,79
Type II	1,1mm	TII-1-10	7,8	0,77	1,31
		TII-1-11	5,8	0,77	1,01
		TII-1-12	6,0	0,77	1,04
	1,95mm	TII-2-13	15,4	0,77	2,45
		TII-2-14	17,8	0,77	2,81
		TII-2-15	27,2	0,77	4,22
	No reinforcement	TII-C-16	2,0	0,77	0,44
		TII-C-17	2,0	0,77	0,44
		TII-C-18	2,0	0,77	0,44

Table 4: *Comparison of test results with the predicted capacity*

Specimen No.	Failure Moment of Specimens (kN.m)	Predicted Failure Moment Eqn (5) (kN.m)	Predicted Moment Capacity of Unreinforced Brickwork (SANS 10164) (kN.m) (γ_m=1)
TI-1-1 TI-1-2 TI-1-3	1,63 1,75 1,72	0,93	0,46
TI-2-4 TI-2-5 TI-2-6	3,49 2,68 3,40	1,76	0,46
TII-1-10 TII-1-11 TII-1-12	1,31 1,01 1,04	0,93	0,99
TII-2-13 TII-2-14 TII-2-15	2,45 2,81 4,22	1,76	0,99

Comparison of Test Results and Predicted Values

Equations (5) and (6) were used to estimate the bending failure of the test specimens. The comparison is given in Table (4).

By inspection, all of the predicted capacities (Eqn (5)) are less than the failure moment. This is advisable to ensure a conservative estimate.

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It is also noteworthy to see that the predicted moment capacities are closer to type II test specimens than type I. The strength of the brickwork to bending stresses is directly related to the orientation of the bricks [4,5,6]. The proposed equations do not account for the orthotropic nature of brickwork and the added strength which could be achieved by the orientation of the bricks. By neglecting the effects of brick orientation, the capacity equations are simplified and applicable to a crack orientated in any direction. A single crack may travel along two orientations and therefore the theory must be applicable to any orientation of brickwork. However, neglecting brick orientation has led to a difference between the predicted and the theoretical values.

The difference between the predicted and the theoretical is also attributed to the rising branch of wire stress/strain curve. The theory assumes a horizontal plastic plateau, but in reality the curve rises and therefore a larger tensile force is developed in the wire which significantly increases the bending capacity of the member.

The average failure moments of control beams type I and II are 0,86 and 0,44 kN.m respectively (beams without reinforcement). The quantity of wire (3 wraps of 1 or 2mm wire around each course) was adequate to restore the bending strength of the un-reinforced brickwork.

Reinforcing High Stress Regions

The stitching method may also be used to reinforce areas of high stress concentrations.

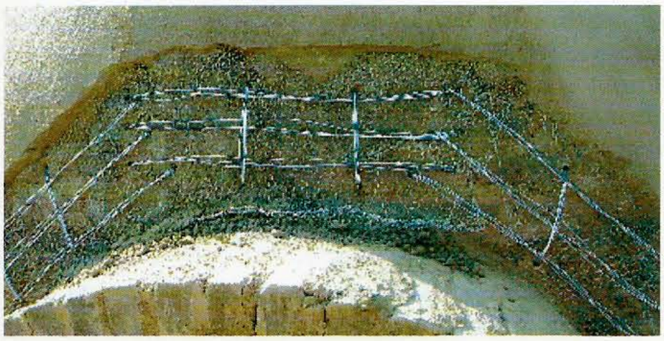

Figure 7: Stitching reinforcement to prevent cracking

These areas may be determined by analysis (e.g., finite elements) or by experience. For example, diagonal cracks often appear at the corners of doors and windows; these areas may be strengthened by applying binding wire stitching. Vertical cracks also appear at the apex of arches built into walls. An example of wire stitching over an arch is shown in Figure 7.

Conclusions

A comparison of the tests with predicted moment capacities indicate that wire stitching is a viable method to strengthen masonry. The tests, however show that the capacity is less where the failure plane is parallel to bed joints. As one would predict, the capacity is influenced by the orientation of the masonry units in relation to the applied stress. This observation is not detrimental since the predicted capacity is less than the actual failure moment. It was also observed that the wire reinforced bricks failed at a value that is 2 to 8 times greater than the capacity of non-reinforced brickwork; therefore, the restoration of strength is achievable by wrapped wire reinforcement.

Wire stitching may be applied to restore the strength of cracked masonry walls or to provide reinforcement to areas where the cracking potential is high. Diagonal cracks often occur around openings such as in the corners of doors and windows. Stitching these areas provide the necessary steel to prevent cracking.

The primary focus of this work is to restore or strengthen the bending capacity of masonry. Since the wire is wrapped with and even distribution of steel on either side of the member, the tensile strength is potentially increased or restored. Furthermore, the shear strength may increase by prestressing the wire binding (by twisting the ends of the wire together).

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