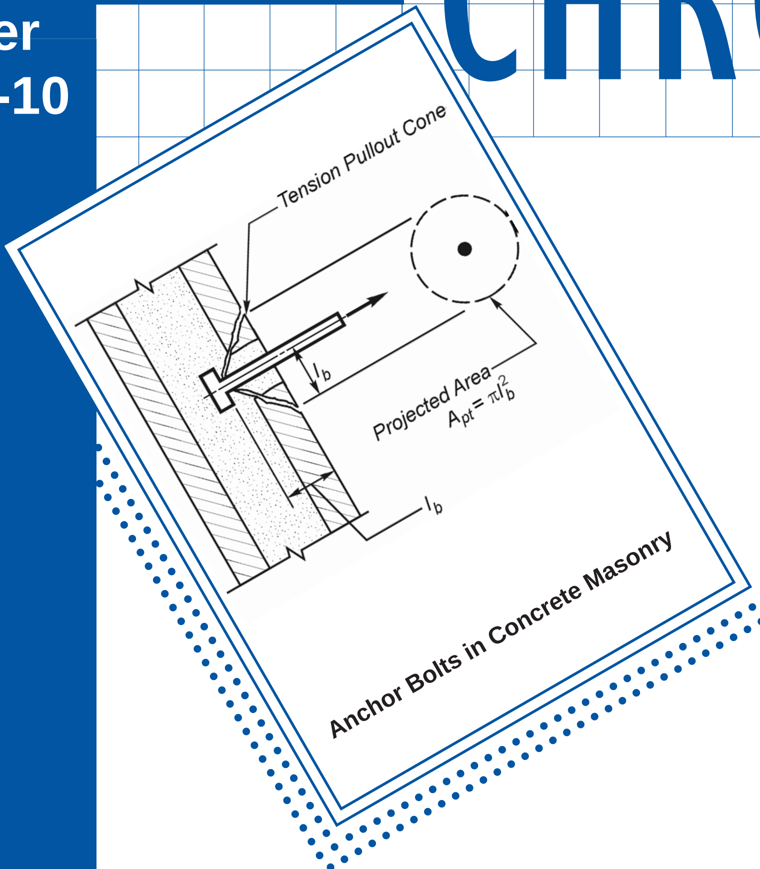
Engineering Notes For Design With Concrete Block Masonry

MASONRY CHRONICLES

Winter 2009-10



Design of Anchor Bolts in Concrete Masonry

Introduction

This edition of "Masonry Chronicles" will discuss the design of anchor bolts in concrete masonry and highlight the differences in the requirements of the 2006 International Building code[1] (IBC) and the 2009 IBC[2]. For masonry design, the 2006 IBC references the 2005 edition of Building Code Requirements for *Masonry Structures*[3] (ACI530-05/ASCE 5-05/ TMS 402-05) or simply ACI 530-05. The 2009 IBC references the 2008 edition of *Building Code Requirements for Masonry Structures*[4] (TMS 402-08/ACI530-08/ASCE 5-08/) or simply TMS 402-08.

The requirements for anchor bolts in the new code have changed significantly in the latest edition of the code. The primary changes include the following:

- Correction of an idiosyncrasy of the 2005 edition that resulted in large differences in the allowable loads on anchor bolts when using allowable stress design in comparison to values obtained using strength design.

- Reorganization of the anchor bolt requirements so provisions that are applicable to both allowable stress design and strength design are located in Chapter 1. This includes the requirements for bolt placement, effective embedment lengths, and the calculation of projected areas for tension and shear.

- Addition of anchor bolt failure modes that were not included in the previous code. Tables 1 and 2 show a comparison of the failure modes considered in the 2006 IBC and 2009 IBC for tension and shear, respectively.

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Table 1 – Tensile Failure Modes for Anchor Bolts on Masonry

	2006 IBC/ACI 530-05		2009 IBC/TMS 402-08	
	Allowable Stress Design	Strength Design	Allowable Stress Design	Strength Design
Masonry Tensile Breakout	Yes	Yes	Yes	Yes
Steel Tensile Yield	Yes	Yes	Yes	Yes
Anchor Pullout (Bent-Bar Bolts Only)	-	Yes	Yes	Yes

Table 2 – Shear Failure Modes for Anchor Bolts on Masonry

	2006 IBC/TMS		2009 IBC/TMS 402-08	
	Allowable Stress Design	Strength Design	Allowable Stress Design	Strength Design
Masonry Shear Breakout	-	Yes	Yes	Yes
Masonry Shear Crushing	Yes	-	Yes	Yes
Anchor Shear Pryout	-	-	Yes	Yes
Steel Shear Yielding	Yes	Yes	Yes	Yes

Anchor Bolt Placement Requirements

Anchor bolts cast in masonry are usually headed or bent-bar anchor bolts as shown in Figure 1. Headed bolts typically have a hexagonal or square head. Bent-bar bolts are usually either "J" or "L" bolts. Since these are the most commonly used bolts, the code provisions apply to these types of bolts. Other bolts, such as post-installed anchors may be determined by testing in accordance with ASTM E448.[5]

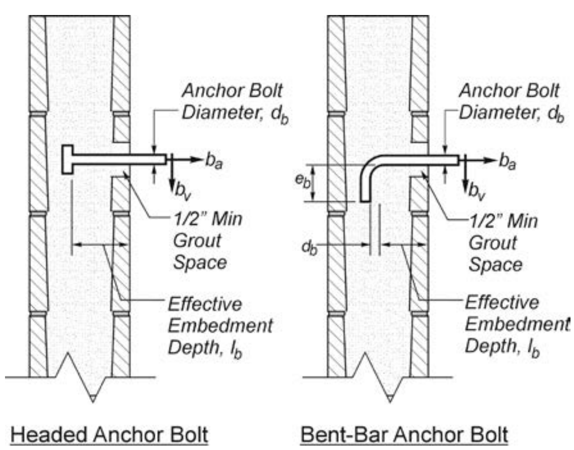

Figure 1 Anchor Bolts in Concrete Masonry

Anchor bolts must be embedded in grout. The code permits 1/4-inch diameter bolts to be placed in mortar beds that are at least 1/2-inch thick. However, this is not commonly done. There was some confusion in the previous code, with some interpretations requiring that all masonry with anchor bolts must be grouted solid. This has been clarified in the new code. Bolts may be placed in partially grouted walls, as long as the effect of open cells or head joints is considered.

The MSJC code requirements specify that the minimum effective embedment depth of anchor bolts, l_b, be 4 bolt diameters or 2 inches, whichever is greater. Figure 1 illustrates the effective embedment depth for the various types of anchor bolts. The effective embedment depth for headed bolts is equal to the length of embedment perpendicular from the surface of the masonry to the bearing surface of the anchor head. For bent bar anchor bolts, the effective embedment depth is measured as the distance perpendicular from the surface of the masonry to the bearing surface of the bent end minus one bolt diameter.

As shown in Figure 1, there must be a grout space of at least 1/2-inch of grout between bolts and the masonry unit. Note that the code permits the grout between the bolt and the masonry unit to be reduced to 1/4-inch if fine grout is used.

The clear distance between parallel anchor bolts must not be less than the diameter of the bolt or 1 inch.

Strength Design of Anchor Bolts

Tensile Strength of Anchor Bolts

In TMS 402-08, the tension failure modes considered and the equations for calculating the strength corresponding to each failure mode are identical to those in the 2005 code. However, the nomenclature has been slightly modified to be more consistent with other parts of the code.

As illustrated in Table 1, three failure modes are considered when determining the tensile strength of anchor bolts. Since anchor pullout is only considered in bent-bar bolts, only two failure modes are considered for headed bolts.

The nominal axial strength of an anchor bolt, B_{an}, is the smallest of the values obtained from the following equations for the various failure modes:

Masonry tensile breakout ($\phi = 0.5$):

$$B_{anb} = 4A_{pt}\sqrt{f'_m} \qquad (1)$$

Steel tensile yield ($\phi = 0.9$):

$$B_{ans} = A_b f_y \qquad (2)$$

Anchor pullout (bent-bar bolts only, $\phi = 0.65$):

$$B_{anp} = 1.5f'_m e_b d_b + \left[300\pi\left(l_b + e_b + d_b\right)d_b\right] \qquad (3)$$

where d_b and A_b are the bolt diameter and cross-sectional area, f'_m is the compressive strength of the masonry, f_y is the yield stress of the anchor bolt and e_b is the projected leg extension of a bent-bar anchor, as shown in Figure 1.

The term A_{pt} represents the projected tension area of a right circular cone on the masonry surface. As shown in Figure 2, the projected tension area is given by:

$$A_{pt} = \pi l_b^{\,2} \qquad (4)$$

where l_b is the effective embedment length of the bolt. The projected area should be reduced by any portion that lies outside the masonry or overlaps an open cell or open head joint. In addition, when the projected areas of adjacent bolts overlap, the value of A_{pt} should be adjusted so that no area is included more than once. Figure 3 shows some examples adjustments to the of the projected tension area.

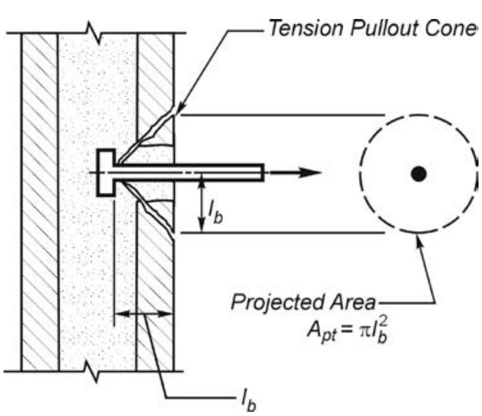

Figure 2 Tension Failure by Masonry Breakout

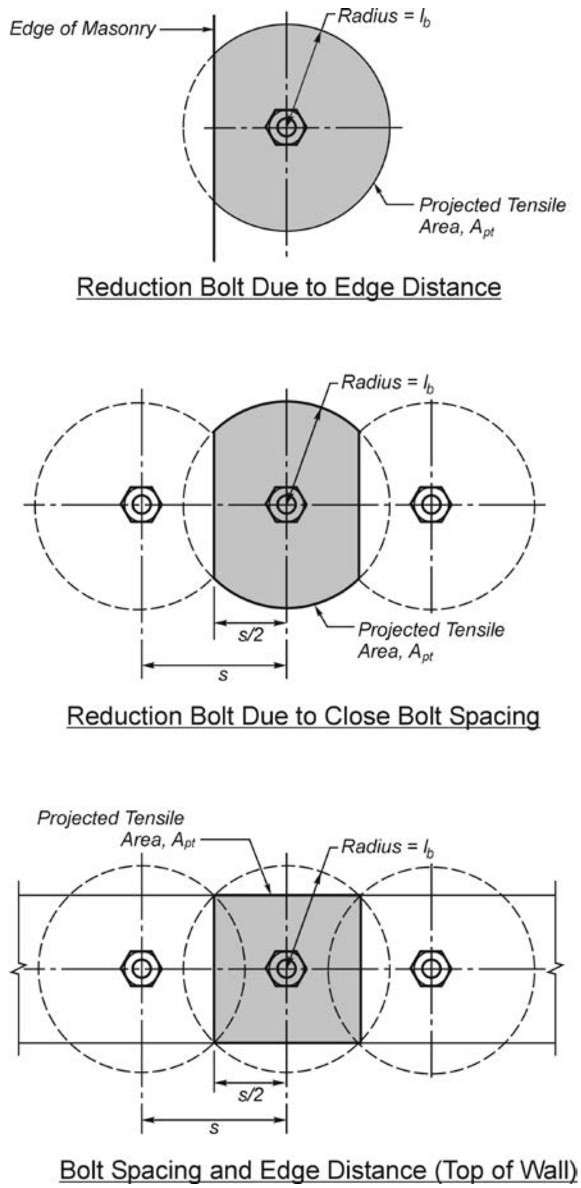

Figure 3 Examples of Adjustments to Projected Tension Area

<u>Shear Strength of Anchor Bolts</u>

The provisions for determining the shear strength of anchor bolts using strength design have been modified in the new code. As shown in Table 2, masonry shear crushing and anchor shear pryout have been added to the masonry shear breakout and steel shear yielding failure modes that were considered in the previous code. The nominal shear strength of an anchor bolt, B_{av}, is the smallest of the values obtained from the following equations:

Masonry shear breakout ($\phi = 0.5$):

$$B_{vnb} = 4A_{pv}\sqrt{f'_m} \qquad (5)$$

Masonry shear crushing (ϕ = 0.5):

$$B_{vnc} = 1050\sqrt[4]{f'_m A_b} \quad (6)$$

Anchor shear pryout (ϕ = 0.5):

$$B_{vpry} = 2.0B_{anb} = 8A_{pt}\sqrt{f'_m} \quad (7)$$

Steel shear yielding (ϕ = 0.9):

$$B_{vns} = 0.6A_b f_y \quad (8)$$

The projected shear area of half of a right circular cone, A_{pv}, is used to calculate the strength in the shear breakout failure mode.

$$A_{pv} = \frac{\pi l_{be}^2}{2} \quad (9)$$

where l_{be} is the distance to the edge of the masonry measured in the direction of the applied shear load. As with the tension pullout cone, A_{pv} must be reduced to account for overlapping areas of closely spaced bolts or for portions of the area that lie outside the masonry.

Combined Axial Tension and Shear

Tests on anchor bolts indicate that a linear interaction relationship provides a conservative estimate of the allowable loads on bolts subjected to both shear and tension. Thus, allowable loads are determined with the following equation:

$$\frac{b_{af}}{\phi B_{an}} + \frac{b_{vf}}{\phi B_{vn}} \le 1 \quad (10)$$

where b_{af} and b_{vf} are the factored tension and shear loads, respectively.

Allowable Stress Design of Anchor Bolts

Allowable Tensile Load of Anchor Bolts

TMS 402-08 considers the same tension failure modes for allowable stress design as strength design, with the equations modified to working values. This is different from the previous code, which did not consider anchor pullout for bent-bar bolts and used equations that typically resulted in significantly lower values when compared to strength design.

The allowable axial tensile load of an anchor bolt, B_a, is the smallest of the values obtained from the following equations for the various failure modes:

Masonry tensile breakout:

$$B_{ab} = 1.25A_{pt}\sqrt{f'_m} \quad (11)$$

Steel tensile yield:

$$B_{as} = A_b f_y \quad (12)$$

Anchor pullout (bent bar belts out):

$$B_{ap} = 0.6f'_m e_b d_b + \left[120\pi\left(l_b + e_b + d_b\right)d_b\right] \quad (13)$$

The terms in the above equations, including the projected tension area, are the same as those for strength design, including the projected tension area. This is different from the previous code, which required that the projected tension area be calculated using the edge distance l_{be}, when the edge distance was less than the effective embedment depth.

Allowable Shear Load of Anchor Bolts

As with the allowable tensile loads, the equations for calculating the allowable shear loads on an anchor bolt, B_v, are modifications of the strength design equations:

Masonry shear breakout:

$$B_{vb} = 1.25A_{pv}\sqrt{f'_m} \quad (14)$$

Masonry shear crushing:

$$B_{vc} = 350\sqrt[4]{f'_m A_b} \quad (15)$$

Anchor shear pryout:

$$B_{vpry} = 2.0B_{ab} = 2.5A_{pv}\sqrt{f'_m} \quad (16)$$

Steel shear yielding:

$$B_{vs} = 0.36A_b f_y \quad (17)$$

Combined Axial Tension and Shear

Similar to strength design, a linear interaction diagram is also used for allowable stress design when there is a combination of tension and shear loads on an anchor bolt:

$$\frac{b_a}{B_a} + \frac{b_v}{B_v} \le 1 \quad (18)$$

where b_a and b_v are the unfactored tension and shear loads, respectively.

Example

Determine if the 3/4-inch diameter anchor bolts shown in Figure 4 can resist the combined tension and shear loads on the wall connected to a flexible diaphragm. Two bolts with a yield stress of 36 ksi, an effective embedment length of 6 inches are spaced 7 inches apart every 4 feet, as shown in Figure 4. The projected extension of the bent bar is 4 inches. The masonry compressive strength is 1500 psi and the weight of the wall is 78 psf. The short period spectral acceleration, S_{DS} =1.2g.

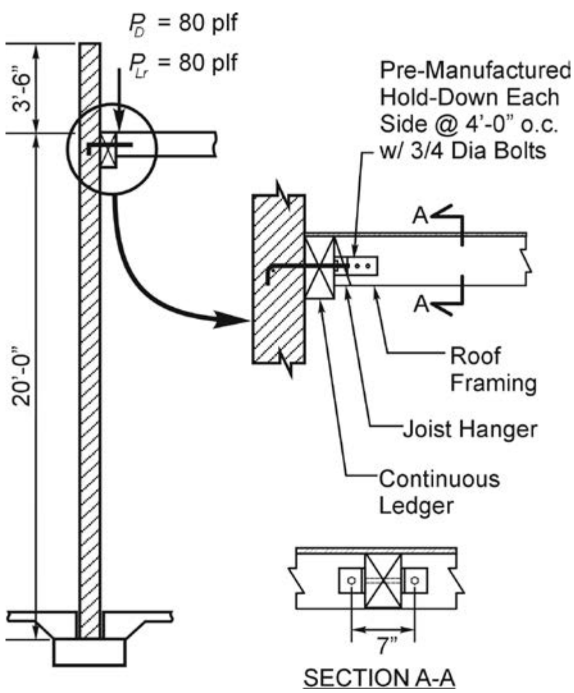

Figure 4 Anchor Bolt Design Example

<u>Strength Design Solution</u>

Consider the load combination 1.2*D*+1.0*E*, which governs by inspection. From ASCE 7-05, the out-of-plane anchorage force for a wall connected to a flexible diaphragm is given by:

$$F_p = 0.8S_{DS}IW_p$$

where I is the importance factor and W_p is the wall weight tributary to the connection. Assuming that I =1.0:

$$F_p = 0.8S_{DS}IW_p = 0.8(1.2)(1.0)W_p = 0.96W_p$$

The tributary wall weight is equal to:

$$W_p = 78\left(\frac{20}{2} + 3.5\right) = 1053 \text{ lbs/ft}$$

Therefore, the tension on the connection is given by:

$$F_p = 0.96(1053) = 1011 \text{ lbs/ft}$$

The shear on the connection is equal to:

$$\left(1.2 + 0.2S_{DS}\right)P_D = (1.2 + 0.24)80 = 115 \text{ lbs/ft}$$

The nominal tensile strength of each bolt is calculated using the smaller of Equations (1), (2) and (3). Without correction, the projected tension area for each bolt would be:

$$A_{pt} = \pi l_b^2 = \pi(6)^2 = 113 \text{ in}^2$$

However, since the spacing between the two bolts, s, is less than two times the effective embedment depth, l_b, there is overlap of the projected tension area of adjacent bolts. From Figure 3, the adjusted tension area is given by:

$$A_{pt}' = \pi l_b^2 - \frac{1}{2} l_b^2 \left(\theta - \sin\theta\right)$$

where θ is in radians and is given by:

$$\theta = 2\cos^{-1}\left(\frac{s}{2l_b}\right)$$

For the example:

$$\theta = 2\cos^{-1}\left(\frac{s}{2l_b}\right) = 2\cos^{-1}\left(\frac{7}{2\times 6}\right) = 1.9 \text{ radians}$$

And the modified projected tension area is equal to:

$$A_{pt}' = \pi l_b^2 - \frac{1}{2} l_b^2 \left(\theta - \sin\theta\right)$$

$$= 113 - \frac{1}{2}(6)^2 \left(1.9 - \sin 1.9\right) = 96 \text{ in}^2$$

The tension capacity of each bolt due to masonry breakout is thus given by Equation (1):

$$\phi B_{anb} = \phi 4 A_{pt}' \sqrt{f'_m}$$

$$= 0.5(4)(96)\sqrt{1500} = 7436 \text{ lbs}$$

From Equation (2), the bolt tension capacity due to yielding of each anchor bolt is equal to:

$$\phi B_{ans} = \phi A_b f_y$$

$$= 0.9(0.44)36000 = 14{,}256 \text{ lbs}$$

and the bolt tension capacity due to anchor pullout is given by Equation (3):

$$\phi B_{anp} = \phi\left\{1.5f'_m e_b d_b + 300\pi\left(l_b + e_b + d_b\right)d_b\right\}$$

$$= 0.65\begin{Bmatrix}1.5(1500)(4)(0.75) \\ +300\pi\left(6+4+0.75\right)0.75\end{Bmatrix}$$

= 9327 lbs

For the capacity of the bolts in shear, the masonry shear breakout failure mode can be ignored since the distance to the edge of the masonry in the direction of the load is large. For masonry shear crushing:

$$\phi B_{vnc} = \phi 1050\sqrt[4]{f'_m A_b}$$

$$= (0.5)1050\sqrt[4]{(1500)(0.44)} = 2661 \text{ lbs}$$

Anchor shear pryout:

$$B_{vpry} = \phi 8A_{pt}\sqrt{f'_m}$$
$$= 0.5(8)(96)\sqrt{1500} = 14872 \text{ lbs}$$

Steel shear yielding:

$$\phi B_{vns} = \phi 0.6A_b f_y$$
$$= 0.9(0.6)(0.44)(36000) = 8554 \text{ lbs}$$

Since each group of two bolts is spaced at 48 inches on center, the interaction equation is given by:

$$\frac{b_{af}}{\phi B_{an}} + \frac{b_{vf}}{\phi B_{vn}}$$

$$= \frac{1011(4)}{2(7436)} + \frac{115(4)}{2(2661)} = 0.36 \le 1.0 \qquad \text{...OK}$$

Allowable Stress Design Solution

Using the alternate basic load combination in the IBC, the governing load combination is *D*+*E*/1.4. The tensile load on the connection is:

$$b_a = \frac{1011(4)}{1.4} = 2889 \text{ lbs/ft}$$

The shear on the connection is equal to:

$$b_v = 80(4) = 320 \text{ lbs/ft}$$

The allowable tension on each bolt is given by the smallest of:

$$B_{ab} = 1.25A_{pt}\sqrt{f'_m}$$

$$= 1.25(96)\sqrt{1500} = 4648 \text{ lbs}$$

$$B_{as} = 0.6A_b f_y$$

$$= 0.6(0.44)36000 = 9504 \text{ lbs}$$

$$B_{ap} = 0.6f'_m e_b d_b + 120\pi\left(l_b + e_b + d_b\right)d_b$$

$$= 0.6(1500)(4)(0.75)$$
$$+120\pi\left(6+4+0.75\right)0.75$$

$$= 5739 \text{ lbs}$$

Ignoring the masonry shear breakout failure mode, the allowable shear on each bolt is the smallest of:

$$B_{vc} = 350\sqrt[4]{f'_m A_b}$$

$$= 350\sqrt[4]{(1500)(0.44)} = 1774 \text{ lbs}$$

$$B_{vpry} = 2.5A_{pt}\sqrt{f'_m}$$

$$= 2.5(96)\sqrt{1500} = 9295 \text{ lbs}$$

$$B_{vs} = 0.36A_b f_y$$

$$= 0.36(0.44)(36000) = 5702 \text{ lbs}$$

Using the smallest of the values in tension and shear, the interaction equation is given by:

$$\frac{b_a}{B_a} + \frac{b_v}{B_v}$$

$$= \frac{2889}{2(4648)} + \frac{320}{2(1774)} = 0.40 \le 1.0 \qquad \text{...OK}$$

Conclusions

The new code provisions for designing anchor bolts have been updated to include more failure modes and to ensure consistency in designs using different methods (strength design and allowable stress design). Prior editions of the code resulted in allowable stress designs for anchor bolts that were often extremely conservative when compared to those obtained using strength design. The new codes, on the other hand, result in similar designs.

References

1. ICC, 2006 International Building Code, International Code Council, Inc., Country Club Hills, Illinois, 2005.

2. ICC, 2009 International Building Code, International Code Council, Inc., Country Club Hills, Illinois, 2008.

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About the Author

Dr. Chukwuma Ekwueme is an Associate Principal with Weidlinger Associates, Inc. He received his BEng from the University of Nigeria and MS, DEng, (Degree of Engineer) and PhD Degrees from the University of California, Los Angeles. He is a registered Civil and Structural Engineer in the State of California.

Dr. Ekwueme is a member of the Masonry Standards Joint Committee (MSJC) and on the Board of Directors of the Masonry Society (TMS). He is also active in several other organizations such as the American Society of Civil Engineers (ASCE), Structural Engineers Association of California (SEAOC) and the American Concrete Institute (ACI).

Dr. Ekwueme has written several publications and co-authored CMACN’s “Seismic Design of Masonry Using the 1997 UBC,” and the “2006 edition of Design of Reinforced Masonry Structures”. He has also received awards for his work as a structural engineer.

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