A SIMPIFIED FINITE ELEMENT MODEL OF STRESSES INDUCED IN MORTAR JOINTS BY THE EXPANSION OF EMBEDDED TIES DUE TO CORROSION

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ABSTRACT

A simplified finite element model was developed in SAP2000 to explore the stress generated in the mortar surrounding a corrugated strip tie by the volume increase in the tie as it corrodes. The typical tensile and shear strength of masonry is taken to be 0.3 and 0.65 MPa [1] for design purposes, and it was deemed likely that the mortar would crack if this value was exceeded. Shell elements were used to model the brick, mortar and tie of a four brick tall prism based on the brick prism specimens used in experimental work. The first finite element model had a 22 gauge $1^{3}/_{16}$" x 6" corrugated strip tie embedded in the middle bed joint while the second finite element model had a 4.76 mm diameter wire tie embedded in the middle bed joint The finite element models demonstrated that expansion forces due to corrosion products can cause micro-cracking of the mortar surrounding the embedded tie when the volume reaches a critical amount. The amount of volume expansion due to corrosion on the very thin corrugated strip ties estimated in the field on 40 year old tie samples was approximately 110 to 120% at the advanced stages of steel corrosion. The finite element models demonstrated this level of expansion could induce stresses that may cause cracking of the mortar surrounding the tie.

KEYWORDS: corrosion, brick ties, finite element model

INTRODUCTION

A finite element model was developed in SAP2000 to explore the stress generated in the mortar surrounding a corrugated strip tie, by the volume increase in the tie as it corrodes. The amount of volume expansion due to corrosion of the steel substrate on the very thin corrugated strip ties estimated in the field and in experimental work was approximately 110 to 120% at the advanced stages of steel corrosion. An experimental program was developed to measure the corrosion rate of ties embedded in brick veneer. Several prism specimens containing various configurations of tie specimens were constructed. Each prism was four bricks high and had two structural ties of the same configuration placed in two of the bed joints. The prism specimens were placed in a room, held at 100% RH and 22°C, called the "Fog Room" and allowed to corrode for two years.

For design purposes, the typical tensile strength of brick masonry is between 0.3 and 0.65 MPa [1]. For this project, a tensile strength of the mortar of 0.5MPa was assumed and it was deemed likely that the mortar would crack if this value was exceeded.

Figure 1: Brick Prisms Containing Corroding Ties

CORRUGATED STRIP TIE FINITE ELEMENT MODEL

The first finite element model used shell elements to model the brick, mortar and tie of a four brick tall prism with two 22 gauge $1^{3}/_{16}$” x 6” (0.8 x 22 x 152 mm) corrugated strip ties embedded in the middle of the bed joint in an approximation to the brick prisms used in the experimental program (Figure 1). The moduli of elasticity of the mortar and brick were taken to be E_{mortar} = 11,900 MPa and E_{brick} = 20,000 MPa respectively [1], and a poisons ratio of 0.2. The properties of the steel were built-in to SAP 2000, being E = 200 GPa and a Poisson’s ratio of 0.3. Two finite element models were created: the first simulated the short direction (brick width) as illustrated in Figure 2, and the second modelled the long direction (brick width) as illustrated in Figure 3. A more elaborate 3D model that captured both directions in a single model was considered, but abandoned as it is easier to obtain shell stresses from the SAP2000 post processing for 2D shell elements than 3D solid elements. Furthermore, past FEM experience indicated that no significant increase in accuracy would likely result from using 3D solid elements. Given the simplification of the models, no elaborate interaction was undertaken for the interface between the mortar and the brick, nor the interaction between the mortar and the steel tie. However, the initial mesh automatically generated by SAP2000 was too course and generated less accurate results around the tie. Therefore the mesh was refined around the ties to give a more accurate result by overriding the automatic meshing and specifying a division of each shell in to a 4 x 4 grid (16 smaller shells). Figures 2a) and 2b) illustrate the finite element models.

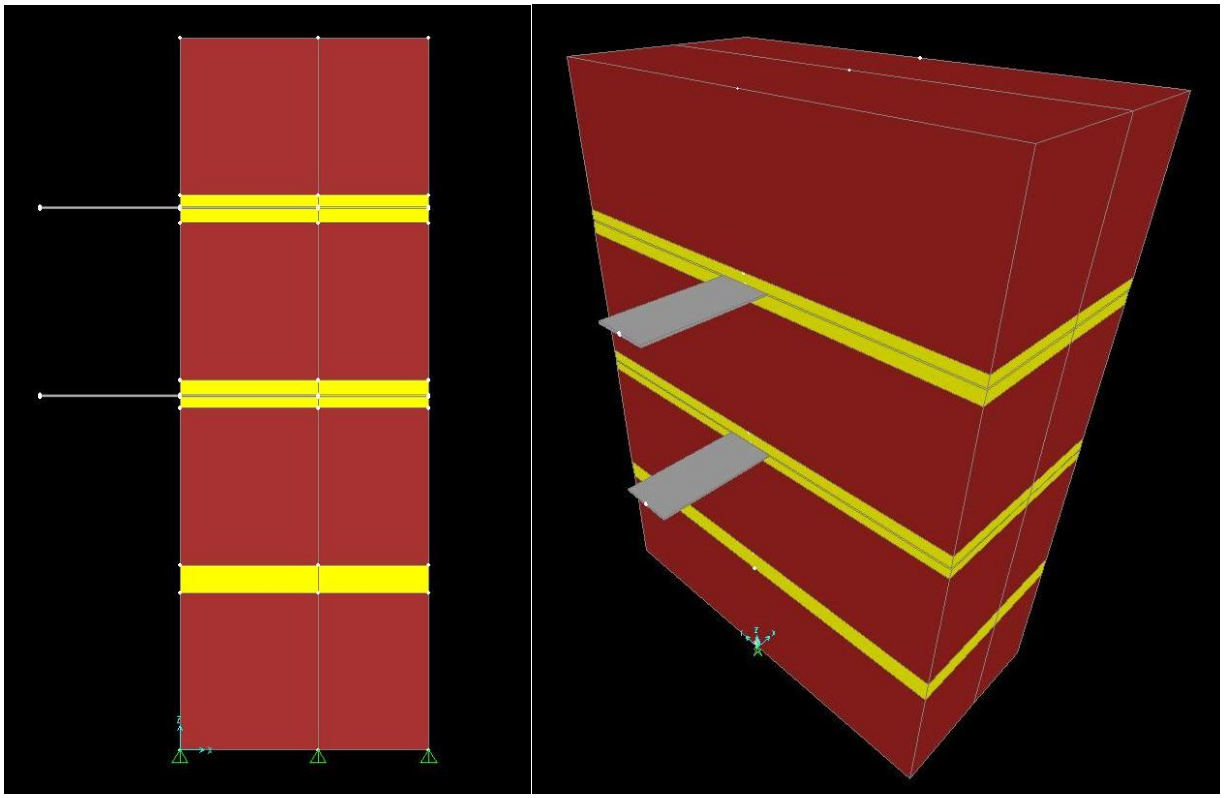

Figure 1: a) Strip Tie Finite Element Model of Short Direction b) Extruded View

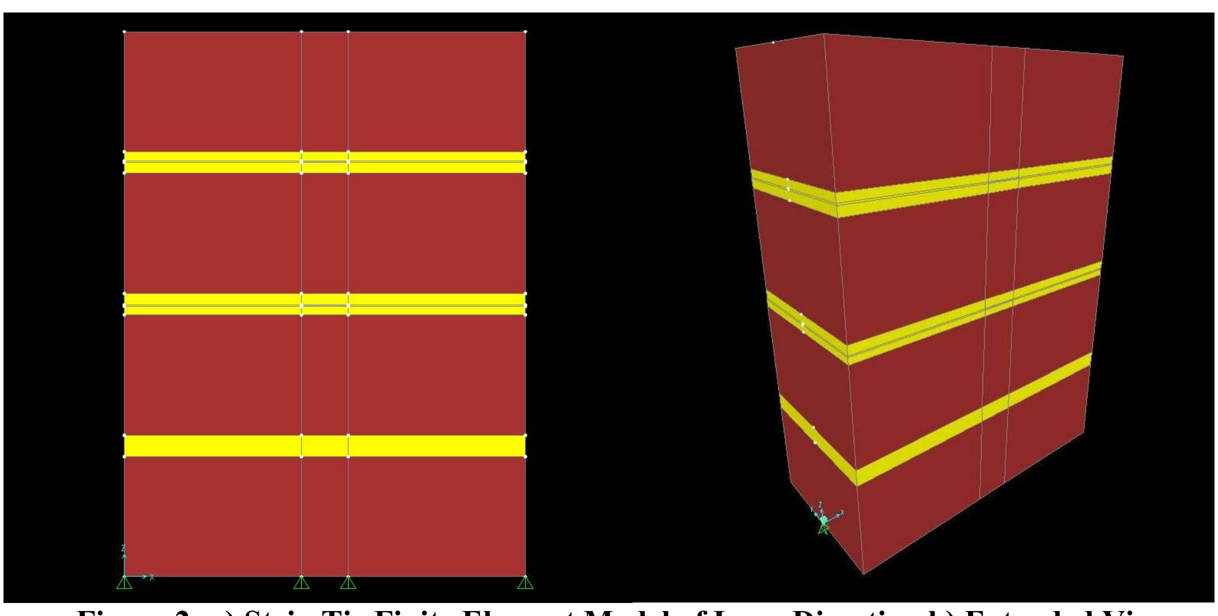

Figure 2: a) Strip Tie Finite Element Model of Long Direction b) Extruded View

As can be seen in Figure 2a), pinned restraints were applied to the bottom nodes of the brick veneer sample restricting movement in the three axes but not rotations. Given that the strip ties have a very thin cross-sectional thickness of 0.8 mm (22 gauge) the corrosion products form on the larger flat surfaces of the top and bottom of the ties and not the sides. Therefore, the initial strip tie finite element model accounted for a 10% increase in volume of the strip tie by prescribing a strain of 0.1 in the steel tie in the vertical direction only. The model produced much larger stresses in the mortar than was anticipated. To check the validity of the model, a very simple approximation was used to determine the critical amount of strain required to exceed the tensile capacity of the mortar in the masonry assembly using the stress strain relationship in Equation 1.

$$\varepsilon_{crit} = \frac{(f_t)_{mortar}}{E_{mortar}} \tag{1}$$

where $(f_t)_{mortar}$ is the tensile stress capacity of the mortar in the bed joint (assumed to be 0.5 MPa based on the tensile strength of the brick masonry assemblage) [1], ε_{crit} is the critical strain in the mortar corresponding to the first micro-cracking and E_{mortar} is the modulus of elasticity of the mortar (11,900MPa). Substitution into Equation (1) yielded:

$$\varepsilon_{crit} = 0.000042 = 0.0042\%$$

This result indicated that if the volume created by corrosion products of the steel tie displaced the mortar by 0.0042% micro-cracking would result. The SAP2000 finite element model was then revisited prescribing a strain of 0.000042 in the vertical direction only. The tensile stress in Megapascals (N/mm^2) the prism in the short direction is illustrated in Figure 3, while tensile stress in the prism in the long direction is illustrated in Figure 4.

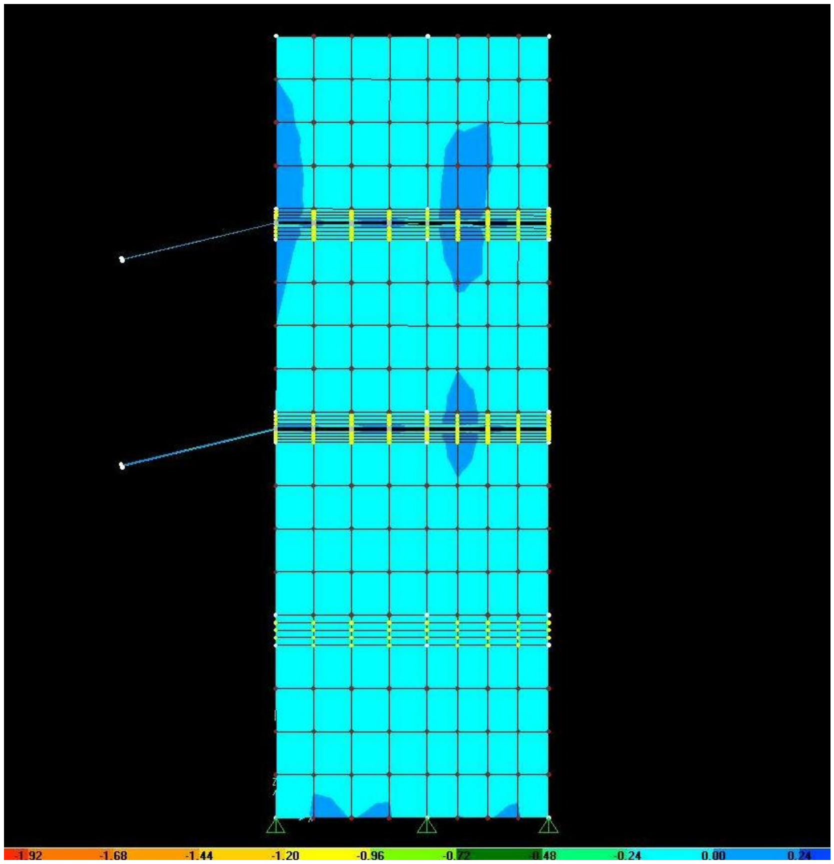

Figure 3: Tensile Stress from Strip Tie corrosion (ε = 0.0042%) in the short direction.

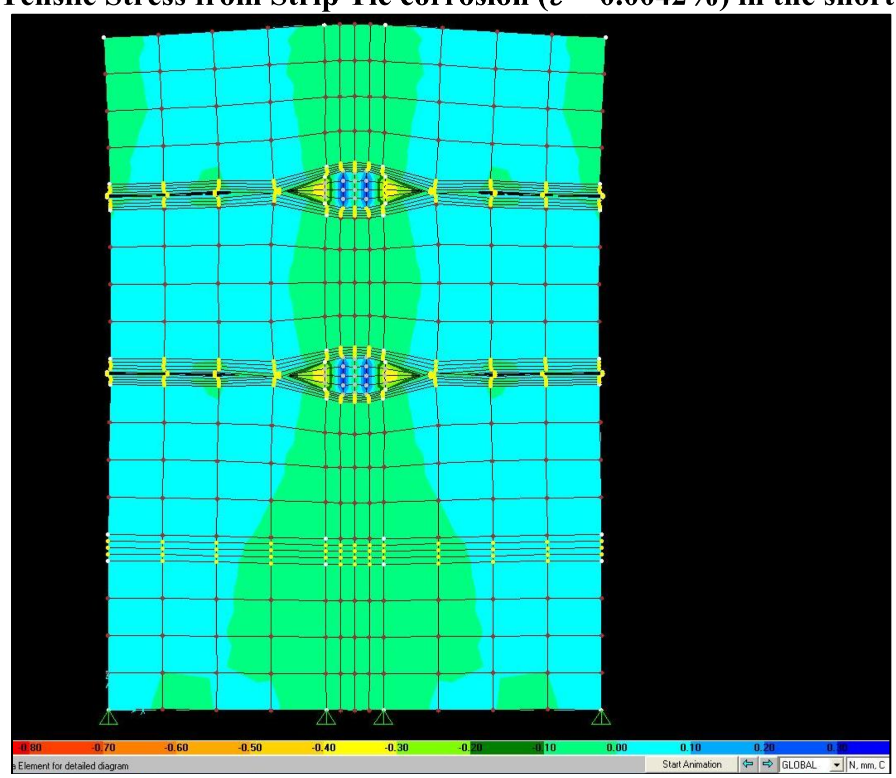

Figure 4: Tensile Stress from Strip Tie corrosion (ε = 0.0042%) in the long direction.

In these figures it can be seen that the stress in the mortar joints nearest to the steel tie exceeds 0.5 MPa as predicted by the simple hand check used in Equation 1. It can also be seen that the stress field is decreasing substantially as the distance from the tie is increased.

FERO WIRE TIE FINITE ELEMENT MODEL

FERO wire V-ties were also modeled for the effects of their corrosion. Figure 6 illustrates the typical FERO wire tie dimensions. As with the corrugated strip ties, two models representing the short (brick depth) and long (brick width) directions were created (Figure 7a and Figure 7b respectively). For simplicity, the circular cross section was approximated using a 4.76 mm rectangular projection. Once again a 0.0042% increase in volume of the tie was modelled by prescribed a strain of 0.000042. However, with the circular cross-section of the wire tie, the strain attributed to the steel, corresponding to the volume increase, was prescribed in both the horizontal and vertical directions.

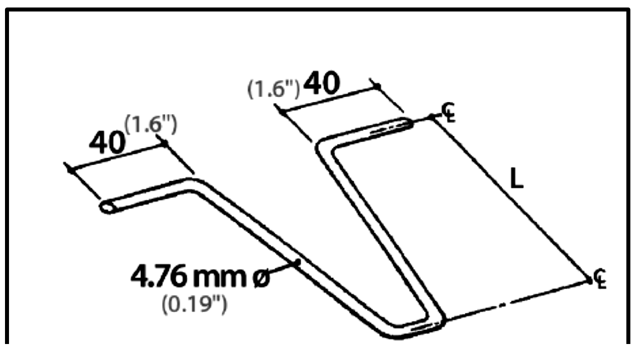

Figure 6: Typical FERO Wire Tie Configuration and Dimensions

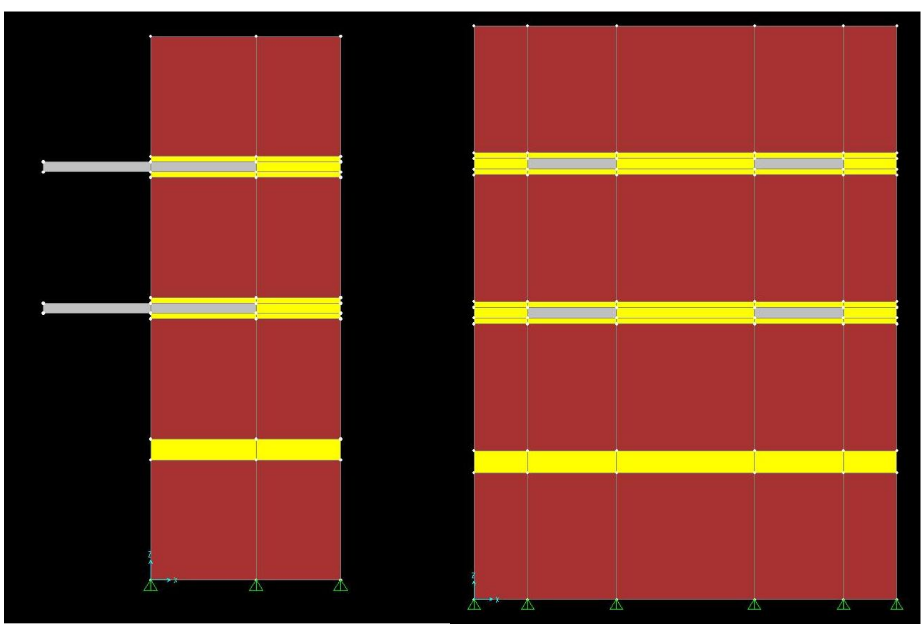

Figure 7: FERO Wire V-Tie Finite Element Model a) Short Direction b) Long Direction

In a similar exercise to the strip tie finite element model, the tensile stress distribution around the ties was explored. Figure 8 illustrates the tensile stress in Megapascals of the prism in the short direction, while Figure 9 illustrates the tensile stress distribution of the prism in the long direction. As with the Strip Tie model, stresses exceeding 0.5MPa were generated in the mortar directly surrounding the tie and with the magnitude of the stress decreasing with increasing distance from the tie.

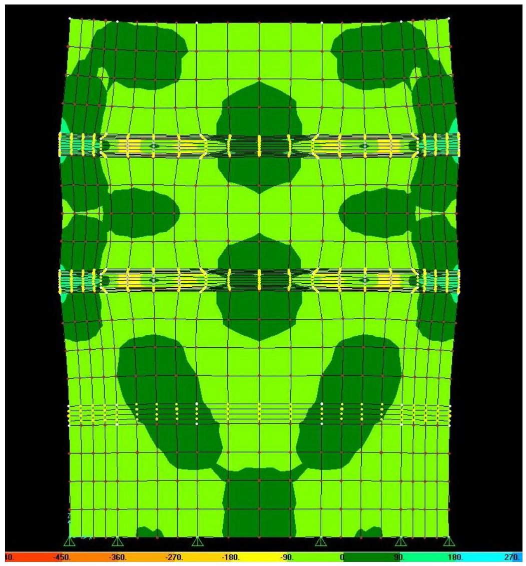

Figure 9: Tensile Stress from FERO V-Tie Corrosion (ε = 0.0042%) in the long direction.

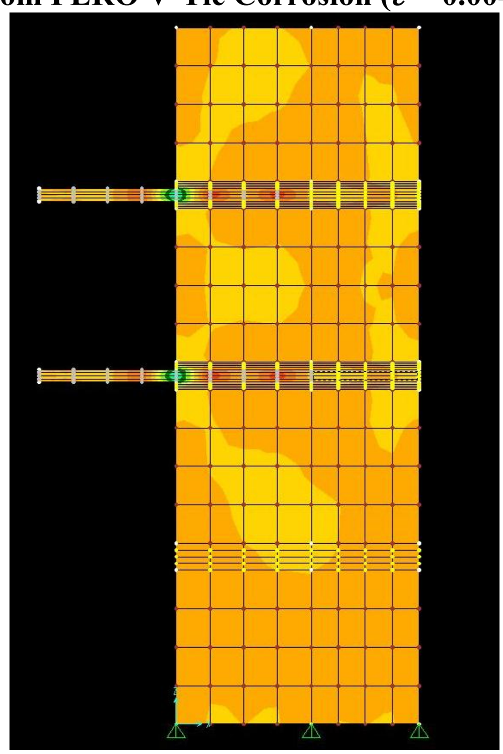

Figure 9: Tensile Stress from FERO V-Tie Corrosion (ε = 0.0042%) in the short direction.

DISCUSSION

The finite element models and the hand calculation demonstrated that the advanced stages of corrosion of the steel substrate on both the corrugated strip ties and the FERO wire V-ties will be substantial enough to cause micro-cracking of the mortar. The results are supported by similar findings with the corrosion of steel rebar in reinforced concrete [2] where it as determined that ε_{crit} = 0.0123% will cause cracks to form around the rebar when the assumed tensile strength of the concrete is 1.55MPa [3]. Table 1 provides a summary of the finite element results and hand calculations:

Table 1: Tensile Stress in the Mortar in Direct Contact with the Tie from Steel Corrosion

Tie Type	Finite Element Model: Prescribed Strain in the tie, ε	Finite Element Model: Minimum Tensile Stress in mortar (MPa)	Hand Calculation: Tensile Stress (MPa)
Strip Tie	0.000042	0.62	0.5 MPa
FERO Wire Tie	0.000042	0.53	0.5MPa

It is interesting to note that even in the advanced stages of corrosion, cracking around corrugated strip ties is not severe enough to present at the surface of the brick veneer in field observations. One possible reason for this is that the stress dissipates significantly with distance and that crack propagation releases stress. Table 2 and Table 3 provide a summary of the finite element results at various locations within the mortar joint.

Table 2: Tensile Stress from Steel Corrosion products on the Strip Tie within the Mortar

Prism Orientation	Prescribed Strain in the tie, ε	Tensile Stress in mortar approx. 5 mm vert. from tie	Tensile Stress in mortar approx. 10 mm horiz. from tie	Tensile Stress in mortar at veneer face
Short direction	0.00042	0.006 MPa	0.62 MPa	0.09 MPa
Long direction	0.00042	0.007 MPa	0.63 MPa	0.008 MPa

Table 3: Tensile Stress from Steel Corrosion products on a FERO V-Tie within the Mortar

Prism Orientation	Prescribed Strain in the tie, ε	Tensile Stress in mortar approx 5 mm vert. from tie	Tensile Stress in mortar approx. 10 mm horiz. from tie	Tensile Stress in mortar at veneer face
Short direction	0.00042	0.007 MPa	0.05 MPa	0.19 MPa
Long direction	0.00042	0.53 MPa	0.11 MPa	0.15 MPa

With respect to the brick prisms used in the experimental program, the white corrosion products associated with zinc corrosion were observed on the hot-dipped zinc galvanized FERO –V-ties and the beginning of orange steel corrosion products were present on the mill galvanized corrugated strip ties. In both cases, micro-cracking at the surface of the veneer was not observed. In the case of the FERO V-ties this is likely attributed to the fact that zinc corrosion products are not as voluminous as steel corrosion products, and the zinc coating prolongs the length of time before steel corrosion initiates. Zinc typically corrodes at 1/10th to 1/50th the rate of carbon steel under equivalent exposures [4] and has 2 to 3 times less expansion than steel when it corrodes [5]. It is important to note that the CSA-A370-04 requires a minimum corrosion protection for most areas in Canada of hot-dip zinc galvanizing of pre-bent corrugates strip ties and wire ties after fabrication to a minimum of 460 g/m^2 coating thickness [6]. For the more severe coastal areas CSA-A370-04 requires the ties be fabricated of stainless steel.

CONCLUSION

According to both the simplified finite element models and hand calculations, advanced stages of the corrosion of the steel substrate of corrugated and wire ties will likely cause micro-cracking of the mortar though this cracking even in the severe stages may not present at the surface of the veneer. These results were supported by similar findings with the corrosion of steel rebar in reinforced concrete. Hot-dip zinc galvanizing of pre-bent corrugated strip ties and wire ties after fabrication to a minimum of 460 g/m^2 coating thickness is an excellent method to reduce the volume of corrosion products and the life of the steel ties embedded in mortar and is the minimum corrosion protection required by the CSA-A370-04 [6] for masonry veneer ties on buildings greater than 11 m in height for most areas in Canada.

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