10th Canadian Masonry Symposium, Banff, Alberta, June 8 – 12, 2005

EMPIRICAL VS. THEORETICAL SERVICE LIFE FOR WALL TIES IN BRICK VENEER STEEL STUD WALL SYSTEMS

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ABSTRACT

The issue regarding the corrosion of steel ties connecting brick veneer to a steel stud (BVSS) backup is well known and well documented. However, none of the research to date has developed corrosion rate and service life models specific to wall ties in BVSS systems. In this paper, the corrosion rate and service life estimates, produced by two models developed by the International Standards Organization (ISO), were compared to the empirically determined corrosion rates and service lives of nine zinc galvanized tie specimens taken from five buildings located in four different Canadian cities. It was discovered that both models relied heavily upon the judgement of the designer to account for the environment of the ties in the wall cavity. The best estimate, using actual environmental data for inputs, was discovered to be the ISOCORRAG formula using the high-end of the range for inputs. Here, the high-end range of inputs is defined as those that generated the largest (most rapid) corrosion rate and smallest (shortest) expected service life. Using the high-end of the range, the expected service life of the ties determined by the ISOCORRAG model produced a better estimate than the ISO 9223-9226 for 67% of the specimens. This method produced a maximum difference of 102% and a minimum difference of 18.4%. Under the same assumptions, the ISO 9223-9226 produced estimates with a maximum difference of 107% and a minimum difference of 20%. Given that the maximum difference for predicting the expected service life was so large, a better understanding of the mechanics governing the corrosion of a tie embedded in mortar is necessary. A semi-empirical, stochastic model is a more suitable model for predicting the complex and random nature of the corrosion of steel components in BVSS wall systems.

KEYWORDS: Corrosion Rate, ISOCORRAG, Stochastic Corrosion, Service Life, Connector Durability

INTRODUCTION

The issue regarding corrosion of the steel ties connecting a brick veneer to its steel stud backing in brick veneer steel stud (BVSS) wall systems is well known and well documented. Past research has investigated occurrences, location and cause of corrosion as well as measures to mitigate the rate of corrosion and materials to use, such as stainless steel, when an environment is expected to be severe. However, none of the research to date has developed non-empirical corrosion rate and service life models that are able to estimate the corrosion rate or service life with reasonable accuracy or that are specific to wall ties in BVSS systems. Typically, corrosion of the portion of the tie embedded in the mortar joint and galvanic corrosion between the tie and the mild steel stud due to dissimilar metals in contact, are the dominant mechanisms acting on ties of BVSS wall systems. Focusing on the corrosion of the portion of the tie in the mortar, in this paper, the corrosion rate and resulting service life estimates produced by two models developed by the International Standards Organization (ISO) were compared to the empirically determined corrosion rates and service lives of nine zinc galvanized tie specimens taken from five buildings located in four different Canadian cities. The two models are the ISO 9223-9226 [1], and the ISOCORRAG [2]. Both existing models were developed based on data collected from the atmospheric corrosion of flat zinc coupons exposed to an unsheltered environment in several locations around the world. The ISO 9223-9226 was selected because it is similar to the method outlined in the CSA S478 – Guideline on Durability of Building Materials [3]. The CSA S478 is the only readily available model to Canadian wall designers. The ISOCORRAG was selected because it is an actual formula for the corrosion rate and was developed from a program using the same background methodology as the ISO 9223-9226 model [2].

EMPIRICAL CORROSION RATE DATA

Keller, Trestain and Maurenbrecher conducted research in 1993 that yielded the empirically determined corrosion rates for the nine specimens [4] used here for comparison with the ISO models. A more thorough description of each building can be found in their paper including detailed wall cross-sections. These buildings and locations were chosen because they represented a spectrum of climatic regions in Canada in terms of rain and temperature. The empirically determined corrosion rate (CR) for each tie was obtained by dividing the amount of zinc cover that had corroded at the time of inspection by the age of the building. In all nine cases, corrosion occurred predominantly on the portion of the tie embedded in the mortar and the entire zinc cover was corroded resulting in a CR equivalent to the initial cover divided by the age of the building. Table 1 contains the relevant information taken from their research.

Table 1 –Brick Veneer Steel Stud Tie Details and Empirical Corrosion Rate [4]

Location	Building Type	Spec. No.	Building Age (yrs)	Connector Type	Tie Thickness (mm)	Zinc Cover (g/m^2)	Chloride Content in Mortar (%)	Empirical CR ($g/m^2/yr$)	Service Life (yrs)
St John's	Apartment	1	7.5	Strip Tie	0.64	255	N/A	34.0	7.5
		2	7.5	Strip Tie	0.41	362	N/A	48.0	7.5
Montreal	Apartment	3	9	Strip Tie	0.30	200	1.10	22.0	9
		4	4	Strip Tie	0.91	220	0.05	55.0	4
Toronto	Apartment	5	7.5	Wire Tie	4.80	92	0.77	12.0	7.5
Toronto	Apartment	6	11.5	Wire Tie	4.80	92	0.03	8.0	11.5
Calgary	Apartment	7	8.5	Strip Tie	0.33	220	0.26	28.0	8.5
		8	8.5	Strip Tie	0.36	234	0.26	25.0	8.4
		9	8.5	Strip Tie	0.37	269	0.26	31.0	8.5

The performance of the ties in all nine cases was quite poor. From Table 1 it can be seen that the ties in the study corroded in less than 12 years. Most buildings have at least a 25-year service life indicating poor specification of the corrosion protection required for the ties in the wall systems.

ASSUMPTIONS

The ISO models were not expected to perfectly model the corrosion of the tie embedded in mortar given this type of corrosion is more akin to the corrosion of reinforcement in concrete than atmospheric corrosion of flat coupons. The mechanics governing the corrosion of reinforcement in concrete typically account for an initiation period where pollutants such as chloride must reach the steel according to Fick's Law of Diffusion and capillary action. This initiation period extends the service life of the steel. Obviously, this period is negligible or non-existent during atmospheric corrosion of fully exposed metals. Therefore, two assumptions were necessary in order to implement the models. First, it was assumed that the moisture and pollutants diffused into the mortar in a rapid fashion and equalized to that of the wall cavity environment in a negligible amount of time. This assumption implies that the mortar around ties has the same environmental parameters as the wall cavity. The second is that the mortar around the tie acts as the tie's atmosphere or micro-environment. This assumption was necessary given that the ISO 9223-9226 and ISOCORRAG both model atmospheric corrosion.

THE ISO 9223-9226 MODEL [1]

The ISO 9223-9226 model estimates the corrosion rate of a metal by establishing a corrosivity category and then converting the category to its corresponding corrosion rate according to set ranges for each category [1]. Before a corrosivity category can be established, the designer must determine three parameters for the environment under consideration, these being the time of wetness (ToW), sulfur dioxide (SO_2) and chloride (Cl) deposition rates.

The ToW includes all times when the relative humidity (R.H.) is greater than 80% and the temperature is greater than 0ºC [3]. The ToW was calculated for the macro-environment by taking the ratio of the number of months per year when the R.H. was greater than 80% to 12 months per year and multiplying this value by the ratio of the number of days per year the minimum temperature was above 0ºC to 365 days per year. Statistically, this value represents the percentage of days that were *both* warmer than 0º and greater than 80% R.H. Actual weather data from Environment Canada from the four cities was used in determining these ratios. The ToW for the brick veneer cavity environment was determined by applying an adjustment factor to the macro-environment ToW. This adjustment factor represented an increase in the ToW ranging from 5%-35% due to the impact of sheltering [5]. Sheltering actually increases the ToW because the cavity is being sheltered not only from wetting but also from drying, relative to the atmosphere. Furthermore, the masonry veneer and mortar joint are being sheltered from drying, by their water retention properties. These results are tabulated in Table 2. The adjustment factor found in Table 2 varied according to geographical location and was assumed to vary from 5% in the arid climate of Calgary and maximizing at 35% in the marine environment of St. Johns.

Table 2 –Time of Wetness (ToW) Calculation

City	No. Of months R.H. >80%	No. Of days Min Temp. > 0ºC	ToW (%/yr)	ToW Adjustment factor	ToW Cavity
St. John's	12	191.3	52.4	1.35	70.8
Montreal	11	201.8	50.7	1.15	58.3
Toronto	11	258.6	64.9	1.10	71.4
Calgary	3	169.3	11.6	1.05	12.2

The ISO 9223 uses the ranges found in Table 3 to categorize the severity of the moisture and pollution exposure. As with the ToW, the environmental conditions present in the mortar joints were assumed to be identical to those of the wall cavity.

Table 3 - ISO 9223 Classification of ToW, Sulfur Dioxide, & Chloride Pollution

ToW Category	ToW (%)	Sulfur Dioxide Category	Sulfur Dioxide Deposition rate (mg /m^2/d)	Chloride Category	Chloride Deposition rate (mg/m^2/d)
τ_1	<0.1	P_0	≤ 10	S_0	≤ 3
τ_2	0.1 to 3	P_1	11 to 35	S_1	4 to 60
τ_3	3 to 30	P_2	36 to 80	S_2	61 to 300
τ_4	30 to 60	P_3	81 to 200	S_3	300 to 1500
τ_5	> 60				

The ISO 9224 converts the environmental parameters to corrosivity categories. To determine the SO_2 and Cl deposition rates, and their corresponding category, the ISO 9225 Corrosion of Metals and Alloys – Measurement of Pollution is generally used. However, for this investigation, the ISO9225 was not used and will not be discussed here. Instead, rational estimates were used. For example, Toronto and Montreal being larger metropolitan centres were deemed to be more polluted than St. Johns or Calgary and have a greater SO_2 deposition rate. Pollution data from 1995 supported this rationale, where Montreal and Toronto both had an ambient SO_2 Concentration between 7.0 and 11.0 parts per billion as opposed to St. Johns' and Calgary where the concentration ranged between 3.0 and 5.0 parts per billion [6]. On the other hand, St. Johns is a coastal city on the Atlantic Ocean and was deemed to have a much greater Cl deposition rate than the in-land cities. The P-ratings and S-ratings for the four cites was determined from these assumptions. Having established the P-ratings and S-ratings of the macro-environments, the wall cavity micro-environments were obtained using the method suggested by S.V. Thompson [7] where the lower to mid-point of the range of the parameters in Table 3 are expected to exist in a sheltered environment, relative to the atmosphere. Table 4 contains the estimates of the ToW, SO_2 and Cl deposition rates, their corresponding classifications, and the resulting corrosivity category for the cavity environments in the four Canadian locations.

Table 4 –ISO 9223/9224 Wall Cavity Parameters and Corrosivity Categorization

Location	ToW	ToW τ - Rating	[SO2] (mg/m2/d)	P - Rating	[Cl] (mg/m2/d)	S - Rating	Corrosivity Category
St. John's	70.8	τ_5	35	P_1	300	S_3	C_5
Montreal	58.3	τ_4	55	P_2	60	S_1	C_4
Toronto	71.4	τ_5	55	P_2	60	S_1	C_{4-5}
Calgary	12.2	τ_3	45	P_2	60	S_1	C_3

Table 5 was constructed from the ISO 9226 [1] and was used to convert the corrosivity category to a corrosion rate for the zinc covering. Due to the complexity in modelling the cavity micro-environment, the corrosion rate was determined for three cases: the low-end, mid-point and high-end values of the CR range. This provided perspective on the sensitivity of the model to the environmental inputs and established upper and lower bounds on the corrosion rate of the tie embedded in mortar. Given the simplifying assumptions necessary to use the ISO models, upper and lower bounds provided a better idea of the models' limitations. Once the corrosion rate was established, the expected service life was determined by dividing the initial zinc covering of the specimen (Table 1) by the ISO 9223-9226 predicted corrosion rate in Table 5.

Table 5 –ISO 9226 Zinc Corrosion Rate by Corrosivity Classification

Category	Corrosion Rate (CR) After 1 year Exposure ($g/m^2/yr$)	Range Low End ($g/m^2/yr$)	Range Mid-point ($g/m^2/yr$)	Range High End ($g/m^2/yr$)
C_1	$CR \leq 0.7$	N/A	N/A	0.7
C_2	$0.7 < CR \leq 5$	0.7	2.85	5
C_3	$5 < CR \leq 15$	5	10	15
C_4	$15 < CR \leq 30$	15	22.5	30
C_5	$30 < CR < 60$	30	45	60

THE ISOCORRAG MODEL [2]

The ISOCORRAG equation was generated by a multiple linear regression applied to the corrosion data from fully exposed flat zinc coupons situated on 28 different sites located in North America, South America, Europe, Japan, and Russia [2]. As with the ISO 9223-9226, the three parameters that had the most profound impact on the corrosion rate of the fully exposed flat zinc coupons were the deposition rate of sulfur dioxide, the deposition rate of chloride and the time of wetness. The ISOCORRAG model is defined mathematically in Equation 1. In this model, the user estimates the deposit of sulfur dioxide [SO_2] in $mg/m^2/d$, the deposit of chloride pollutants [Cl] in $mg/m^2/d$ and time of wetness [ToW] as a percentage per year. If the zinc specimen under consideration is unsheltered, actual environmental data for the location can be used. However, if the specimen under consideration is sheltered the user must again estimate values for these parameters that the specimen is likely to experience.

$$CR = a_1 + B_1 \bullet [SO_2] + B_2 \bullet [ToW] + B_3 \bullet [Cl] \qquad \text{Equation 1}$$

The coefficients $a_1 = 0.2098$, $B_1 = 0.38$, $B_2 = 0.15$, and $B_3 = 0.31$ were obtained from literature [2]. As with the ISO 9223-9226, the sensitivity of the model to the environmental inputs was demonstrated by determining the corrosion rate for the low-end, mid-point and high-end of the range of inputs. In the case of the ISOCORRAG model, the inputs that were varied between, low-end, mid-point and high-end were the sulfur dioxide and chloride deposition rates. For each city, the two pollution parameters were assigned a range based on their P and S-ratings established in Table 4 and the corresponding range from Table 3. For example, St. Johns was given a P-rating of P_1 in Table 4, which corresponds to a SO_2 deposition rate between 11 and 35 $mg/m^2/d$. Again, this provided upper and lower bounds on the corrosion rate of the tie embedded in mortar under the simplifying assumptions that the environmental conditions of the mortar and wall cavity were identical, and that the corrosion mechanism was similar to that of atmospheric corrosion. The ToW values from Table 2 were used as the input for the [ToW] parameter for each location. The ToW was not varied between low-end, mid-point and high-end, as in the case of the SO_2 and Cl deposition rates. The parameters used as inputs into Equation 1 are found in Table 6.

Table 6 –Parameters Used for Inputs into the ISOCORRAG Equation

City	ToW (% / yr)	Range Low-End		Range Mid-point		Range High-End	
		[SO_2] (mg/m^2/d)	[Cl] (mg/m^2/d)	[SO_2] (mg/m^2/d)	[Cl] (mg/m^2/d)	[SO_2] (mg/m^2/d)	[Cl] (mg/m^2/d)
St. John's	70.8	11	300	23	900	35	1500
Montreal	60.8	36	4	58	32	80	60
Toronto	71.4	36	4	58	32	80	60
Calgary	12.2	36	4	58	32	80	60

RESULTS

The low-end, mid-point and high-end for the corrosion rates found in Table 5 were used to predict the corrosion rates of the nine wall tie specimens according to the ISO9223-9226 model. The expected service life was then determined by dividing the specimen's initial zinc coverage in Table 1 by the corrosion rate predicted using the ISO9223-9226 model. The results are presented in Table 7.

Table 7 – Difference between ISO9223-9226 and Empirical Results

Specimen No.	Predicted Corrosion Rate (g/m^2/yr)			Expected Service Life (yrs)			Low-End % Diff. Lifetime	Mid-point % Diff. Lifetime	High-End % Diff. Lifetime
	Low-End	Mid-point	High-End	Low-End	Mid-point	High-End			
1	30.0	45.0	60.0	8.5	5.7	4.3	13.3%	24.4%	43.3%
2	30.0	45.0	60.0	12.1	8.0	6.0	60.0%	6.7%	20.0%
3	15.0	22.5	30.0	13.3	8.9	6.7	48.1%	1.2%	25.9%
4	15.0	22.5	30.0	14.7	9.8	7.3	266.7%	144.4%	83.3%
5	22.5	33.8	45.0	4.1	2.7	2.0	46.7%	64.4%	73.3%
6	22.5	33.8	45.0	4.1	2.7	2.0	64.4%	76.3%	82.2%
7	5.0	10.0	15.0	44.0	22.0	14.7	400.0%	150.0%	66.7%
8	5.0	10.0	15.0	46.8	23.4	15.6	460.0%	180.0%	86.7%
9	5.0	10.0	15.0	53.8	26.9	17.9	520.0%	210.0%	106.7%

▨ Represents an Over-Estimate of Tie Service Life

Similarly, the corrosion rates of the nine wall tie specimens were predicted using the ISOCORRAG model. The low-end, mid-point and high-end of the chloride and sulfur deposition ranges found in Table 6 were used to calculate the corrosion rates for these three cases. Again, the expected service life was determined by dividing the specimen's initial zinc coverage in Table 1 by the corrosion rate predicted by the ISOCORRAG model for each case. The results are presented in Table 8.

Table 8 – Difference between ISOCORRAG and Empirical Results

Specimen No.	Predicted Corrosion Rate ($g/m^2/yr$)			Expected Service Life (yrs)			Low-End % Diff. Lifetime	Mid-point % Diff. Lifetime	High-End % Diff. Lifetime
	Low-End	**Mid-point**	**High-End**	**Low-End**	**Mid-point**	**High-End**			
1	46.3	115.8	185.4	5.5	2.2	1.4	26.6%	70.7%	81.7%
2	46.3	115.8	185.4	7.8	3.1	2.0	3.7%	58.6%	74.1%
3	14.8	21.0	27.2	13.5	9.5	7.3	50.4%	5.8%	18.4%
4	14.8	21.0	27.2	14.9	10.5	8.1	272.2%	161.9%	102.1%
5	16.4	22.6	28.8	5.6	4.1	3.2	26.7%	46.9%	58.3%
6	16.4	22.6	28.8	5.6	4.1	3.2	51.1%	64.6%	72.2%
7	7.5	13.7	19.9	29.4	16.1	11.0	234.1%	82.5%	25.5%
8	7.5	13.7	19.9	31.3	17.1	11.7	274.2%	104.4%	40.6%
9	7.5	13.7	19.9	36.0	19.6	13.5	314.3%	126.3%	55.6%

▨ Represents an Over-Estimate of Tie Service Life

DISCUSSION

From the results it can be seen that both the predicted corrosion rate and resulting expected service life varied greatly depending on the inputs (i.e. the assumptions made). Under reasonable assumptions, the theoretical models under-estimated the empirically determined corrosion rate, which resulted in an over-estimate of the service life of the tie. Over-estimating the service life is undesirable even when the difference is small because the ties will likely experience unanticipated reduced capacity, and may even experience structural failure if the corrosion is extensive.

When the low-end of the range was input, the ISOCORRAG model overestimated the service life of a wall tie for 6 of the 9 ties studied or 66.7% of the time. Under the same assumptions, the ISO 9223-9226 overestimated the service life of a wall tie for 7 of the 9 ties or 77.8% of the time. In the low-end case, the ISOCORRAG model produced the better estimate of the empirically determined corrosion rate for 6 of the 9 ties. The maximum difference between the empirically determined service life and the expected service life determined using the ISOCORRAG model was 314% and the minimum was 3.7%. Under the same assumptions, the maximum difference for ISO 9223-9226 was 520% and the minimum difference was 13.3%. Clearly ISOCORRAG produced a better estimate when using the low-end of the range, although the majority of results have very large differences (56 – 314%).

Using the mid-point of the range as inputs, the maximum difference for both the ISOCORRAG and the ISO 9223-9226 model was significantly reduced. Furthermore, both models now overestimated the service life of the wall tie for 5 of the 9 ties. The ISOCORRAG model produced the better estimate of the empirically determined service life for 5 of the 9 ties. Under the mid-point assumptions, the maximum difference between the empirical and ISOCORRAG expected service life was 162% and the minimum was 5.8%. Under the same assumptions, the maximum difference for ISO 9223-9226 was 210% and the minimum difference was 2.1%. Again, ISOCORRAG produced the better estimates of the empirically determined corrosion rate and resulting service life.

Finally, when the high-end of the range was input, both the ISOCORRAG model and the ISO 9223-9226 model overestimated the service life of the wall tie for only 4 of the 9 cases. The ISOCORRAG model produced the better estimate of the empirical corrosion rate for 6 of the 9 ties. The maximum difference between the empirically determined service life and ISOCORRAG expected service life was 102% and the minimum was 18.4%. Under the same assumptions, the maximum difference for ISO 9223-9226 was 107% and the minimum difference was 20%. ISOCORRAG produced better estimates but by a very small margin when the high-end of the range was used.

Both the ISO 9223-9226 and the ISOCORRAG models are based on corrosion data for fully exposed zinc coupons. As a result, two obvious sources of error are likely to occur when applying the models to zinc-galvanized ties in BVSS wall systems. The first source occurs when converting the environmental parameters of the macro-environment to environmental parameters that apply to the micro-environment of the ties embedded in mortar. Given the ISO 9923-9226 and ISOCORRAG models are based upon fully exposed specimens, they must rely heavily upon the ability of the wall designer to determine the ToW, chloride deposition and sulfur dioxide deposition rates of the macro-environment, then estimate an adjustment of the rates for the micro-environment of a brick veneer wall cavity and further adjust these parameters for the environment of the mortar surrounding the ties. The ISO 9223-9226 has an even stronger dependence on designer judgement than the ISOCORRAG by further requiring the designer to estimate the corrosion rate once a corrosivity category has been established from the estimated environmental parameters. A situation with such a strong dependence on the judgement and assumptions of the designer lends itself to a large probability of error, especially when the model is so sensitive to the inputs.

The second source of error results from the understanding that atmospheric corrosion is a different mechanism than the corrosion mechanism experienced by that portion of the tie embedded in the mortar. The mechanism the ties actually experience is more akin to the corrosion of steel reinforcement in concrete than to the atmospheric corrosion of a fully exposed flat zinc coupon. Atmospheric corrosion tends to cause uniform corrosion of the specimen, while corrosion of steel in concrete has the appearance of uniform corrosion but is actually the result of extensive pitting. Therefore, the ISO models better suit an unsheltered galvanized steel streetlight than a tie embedded in mortar.

CONCLUSION

Despite having the same background methodology and modelling the same atmospheric corrosion mechanism, ISOCORRAG provides better, more consistent, service life estimates than ISO 9223-9226. This is a direct result of having an analytical relationship that determines a unique corrosion rate rather than depending on designer judgement to determine it from a range. This point is well illustrated by examining Table 5 where it can be clearly seen that a CR range, rather than a unique value for the CR corresponds to each corrosivity category. Although the end-points of these ranges don't seem widely spread, the effect of using the low-end versus the high-end of the range doubles the expected service life.

It was discovered that with the nine cases investigated in this work, inputting the worst-case pollution parameters into the ISOCORRAG model, over-estimated the empirically determined service life only 44% of the time with an average difference of 58%. Furthermore, it appears that the ToW and chloride pollutants in the mortar have a greater impact on the corrosion rate of a tie than they have on a fully exposed coupon. Therefore, when using the ISOCORRAG model to estimate the service life of brick ties in BVSS wall systems, it is suggested that a ToW input between 85% and 100%, and a chloride deposition rate input of 300 mg/m^2/d for marine and 150 mg/m^2/d for non-marine environments be used regardless of the macro-environment parameters. When these parameters were input into the ISOCORRAG equation for the nine cases under investigation, the service life was over-estimated for only 1 of the 9 ties, the maximum difference was 76%, the minimum difference was 1.5%, and the average difference was only 34%. Although the difference was small when using these parameters, it may only be valid for the nine ties in this study.

Overall, the likelihood of making an error and the percentage difference between empirical and theoretical results when applying the ISOCORRAG or ISO 9223-9226 models to zinc-galvanized ties in BVSS wall systems is too large and a more effective model is needed. Currently, there are no corrosion models for zinc-galvanized ties in BVSS wall systems that capture actual corrosion mechanisms that the ties experience.

Due to the complexity of corrosion processes of steel and their highly random nature, semi-experimental, stochastic corrosion models appear to be more reliable in real applications [8]. Therefore, development of a theoretical model that accounts for uncertainties associated with its critical parameters using random variables distributed according to field and experimental data seems more useful than either a pure theoretical or pure empirical model for tie corrosion [8]. One possibility under investigation is the modification and randomization of Bamforth's model [9]. Bamforth's model is based on Fick's Law of Diffusion and is often used to estimate time until cracking and Maintenance Free Life (MFL) due to the corrosion of steel in concrete. After modifying the equation to account for the different porosity of mortar, the method could be applied to wire ties and if modified to account for rectangular cross-sections instead of the circular cross-section of steel reinforcement, it could also be applied to strip ties.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Canada Masonry Design Centre and NSERC for their financial support.

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