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TABLE SIZE EFFECT ON WIND RESISTANCE OF MOD-BIT ROOFING SYSTEMS

S.M. Zahrai*
Center of Excellence for Engineering and Management of Civil Infrastructures, School of Civil Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran

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ABSTRACT

Roofing systems have been vulnerable to strong wind uplift pressures. Roofing systems are basically evaluated for wind uplift pressures according to standardized test methods. Currently, there is no consensus on the ideal table size to be used in these testing protocols. Table size effect has been recently studies by the authors for the Thermoplastic roofing systems. The objective of this paper is to study the impact of table size on the Modified Bituminous (Mod-Bit) roofing system performance. To achieve this purpose, extensive analytical experiments have been conducted to investigate the performance of Mod-Bit roofing systems subjected to wind uplift pressures. Analytical results compared well with those obtained from experimental work, benchmarking the numerical modeling. This paper presents some of these comparisons and also suggests ideal table sizes and correction factors for various configurations having Mod-Bit membrane.

Keywords: Table size; wind resistance; roofing systems; modified bituminous; uplift pressure; numerical modeling; correction factors.

1. INTRODUCTION

Wind effects must be taken into account when designing roofing systems, since, like all other parts of structures, roofing components are vulnerable to strong wind uplift pressures and serious damage [1]. Wind resistance rating of roofing systems is based on standardized test methods. In these tests, roof specimens are generally placed in an apparatus whose size (length and width) is normally far less than the size of a real roof. Roofing manufacturers assemble the test specimen with its respective components such as insulation, vapor barrier, etc., on the test frame, Figure 1. Air pressure is applied until system failure occurs, e.g.,

*E-mail address of the corresponding author: mzahrai@ut.ac.ir (S.M. Zahrai)

membrane tearing, fastener pull out. The fastener force and membrane deflection obtained from these testing protocols are not necessarily the same as the field values, even though the system configuration (e.g., fastener spacing and membrane width) is the same as that of the field system and the specimen is subjected to the pressures similar to the design requirements. This is clearly due to the fact that the test rig edges offer some resistance to the applied pressure. This effect increases in narrower tables. If the testing table is sufficiently wide then the roofing system response remains constant or minimum changes can occur. However, the adequate width depends upon the roofing system configuration.

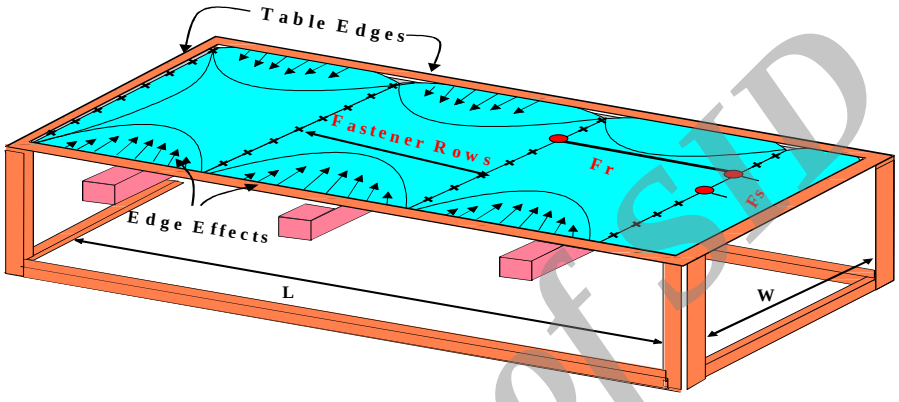


Figure 1. Effect of table size on the roofing system response

As grouped in Table 1, current test methods consider different table sizes for the performance evaluation of roofing systems. Figure 2 shows table sizes used by different testing protocols for roofing systems. For instance, the FM (Factory Mutual, 1988) [2] tests use table size of 2743 by 1524 mm (9’ by 5’) or 7315 by 3658 mm (24’ by 12’) depending on the roofing system. A chamber size of 3048 by 3048 mm (10’ by 10’) is used by the UL (Underwriters Laboratories, 1991) [3] standard. Research efforts in the recent decade by a North American roofing consortium, the Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS) established at the National Research Council of Canada, have led to the development of a facility making it possible to evaluate roofing systems dynamically [4]. A table size of 6100 by 2200 mm (20’ by 7.2’) is used by SIGDERS.

Table 1: Existing table sizes for evaluation of roofing system performance

No.	Testing Protocol	Table Size mm (ft)	Location	Reference
1	FM 4470 Standard	2700x1500 (9x5)	U.S.A.	FM research 1986
2	Revised FM 4470	7300x3800 (24x12)	U.S.A.	FM Research 1992
3	UL 580 Standard	3000x3000 (10x10)	U.S.A.	UL Inc. 1991
4	UEAtc Standard	6100x1500 (20x5)	Europe	Gerhardt et al 1986
5	BRERWULF	5000x5000 (16.4x16.4)	UK	Cook et al. 1988
6	NT Build 307 Standard	2400x2400 (8x8)	Norway	Paulsen 1989
7	SIGDERS	6100x2200 (20x7.2)	North America	Baskaran and Lei 1997

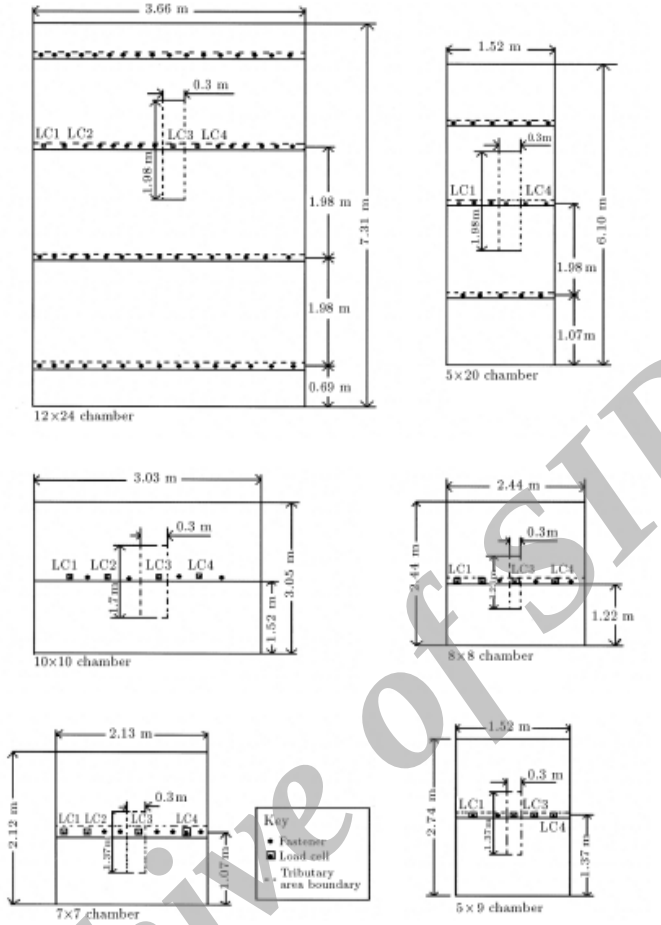


Figure 2. Table sizes used by different testing protocols for roofing systems

Careful examination reveals that the table size is important in evaluating roofing systems and it should be selected properly to obtain realistic wind uplift resistance. For example, the use of narrow tables would increase the edge effects on the results particularly for roofing systems having wider membranes, i.e., spacing between fastener rows. On the other hand, using wider tables would make the system response slower. The SIGDERS load cycle [5] developed based on extensive wind tunnel studies of full-scale roofing systems measuring 3048 mm by 3048 mm (10 ft by 10 ft) was considered in this research.

Table size effect has been studied recently for the Thermo Plastic systems subjected to wind uplift pressures [6,7]. Zahrai and Baskaran [8] developed an analytical model to investigate the wind resistance performance of some roofing systems specially the Thermo Plastic systems, followed by some preliminary results for Mod-Bit roofing systems [9]. After being verified through experimental studies, the analytical model was used to investigate the effect of table size on the roofing system performance. It was found that an increase in the table width beyond a certain level (depending on the system configuration) did not significantly change the system response. Systems with greater fastener spacing generally increased the required table width. Zahrai [10] presented the impact of table size on roofing system performance by conducting extensive analytical work to investigate the

performance of roofing systems subjected to wind pressure. Analytical results compared well with those obtained from experimental work, validating the numerical modeling. He found that an increase in table width beyond a certain level, about 3 m for cases considered here, did not significantly change the results, while the rate of fastener load change might be high for a smaller table width. This specific limit depends on the roofing system configuration. Furthermore, a larger membrane width (fastener row spacing) would increase the width of the ideal table.

Despite the significance of table dimensions and few related research outcome, there still exist no criteria and specific standard to suggest a required table size for some roofing systems. A number of parameters may influence the required table size, in particular fastener spacing, F_s, fastener row spacing, F_r, and membrane modulus of elasticity, E. In this paper, Mod-Bit is considered as the roofing membrane. For this purpose, it has been decided to develop a Finite Element (FE) based numerical model for the problem discussed above. This paper discusses the involved steps in the present numerical study as follows:

- Adopt a numerical model to simulate the experimental results;
- Benchmark the model using the experimental data;
- Investigate the effect of table size on the roofing system response; and
- Develop correction factors for tables smaller than the required one.

Numerical techniques can offer flexibility in exploring scenarios that would be too expensive, or in some cases impossible, to set up experimentally. In addition to the economical advantages, the analytical models are generally faster for solving problems where there is a need to investigate the impact of various influencing parameters.

2. ADOPTING A NUMERICAL MODEL

2.1 General

ABAQUS version 5.7 [11], a commercially available Finite Element program with non-linear analysis capability was used to carry out all the numerical analyses. The large strains and deformations that occur during the loading of the membrane were accounted through geometrical non-linearity (large deformations theory). Small load increments were considered to accommodate the flexibility of the single-ply membranes. The modeled roofing system has a Thermo Plastic membrane as the waterproof component. Only a summary of the experimental setup and system details are presented here but details are reported elsewhere [7].

2.2 System details

Figure 3 shows the Group#2 (Glass+Polyester) Mod-Bit roof assembly used in the experimental investigation. The roofing system has 991 mm (39”) wide membrane glass base sheets and polyester cap sheets and fastened to the structural deck at every 305 mm (12”) apart along the seam, as shown in Figure 3a. Two different testing protocols, FM and SIGDERS, were used to evaluate each roofing system. To monitor the system response, appropriate instrumentation was used to measure typical design parameters (i.e., pressure, force, and deflection) at certain locations. Force balances and ultrasonic sensors were respectively used to measure the tensile forces in the fasteners and uplift movements of the

membrane.

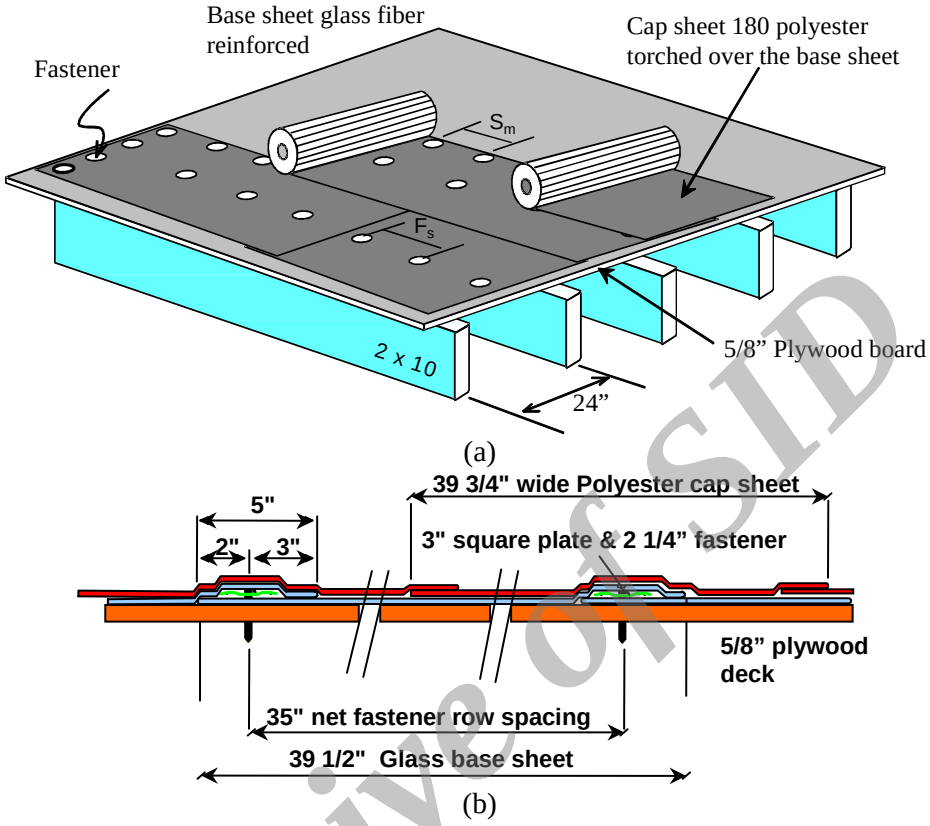


Figure 3. Group #2 Mod-Bit roofing system assembly: a) Schematic view of the roof during installation; b) System details.

Typical seam details are also shown in the Figure 3b. The seam has an overlap of 102 mm (4"), with the fastener placed 38 mm (1.5") from the edge of the bottom base sheet, and 63.5 mm (2.5") from the edge of the overlapping base sheet. The portion of the seam beyond the fastener row was welded with hot air such that a waterproof top surface was obtained. The width of the welded portion varied between 38 and 45 mm (1.5 and 1.75"). The polyester cap sheets were torched over the glass base sheets.

Similar procedure was followed for installation of Group#3 roofing system assembly with the exception of having polyester for both base and cap sheets. Figure 4 shows schematic view of the Group#3 roofing assembly.

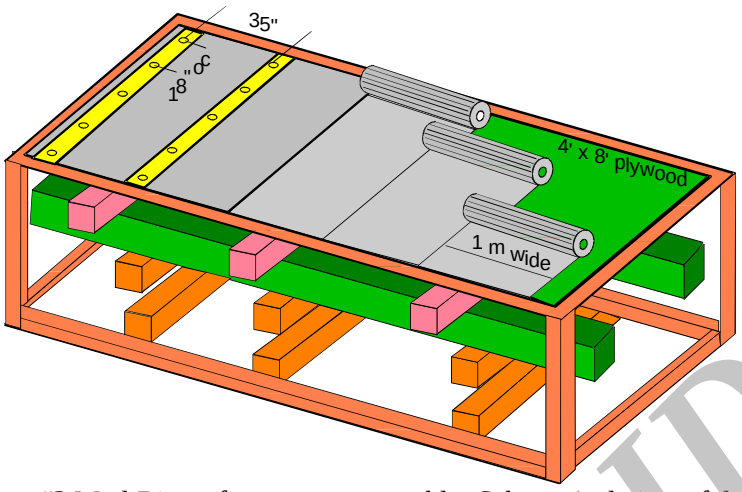


Figure 4. Group #3 Mod-Bit roofing system assembly: Schematical view of the roof during installation

2.3 FE model

Figure 5 shows the FE model for the roof systems. The membrane alone was considered in the numerical modeling due to its much greater flexibility compared to other components, insulation and steel deck. In other words, the deflections of the steel deck and insulation were assumed negligible in comparison to the membrane deflection.

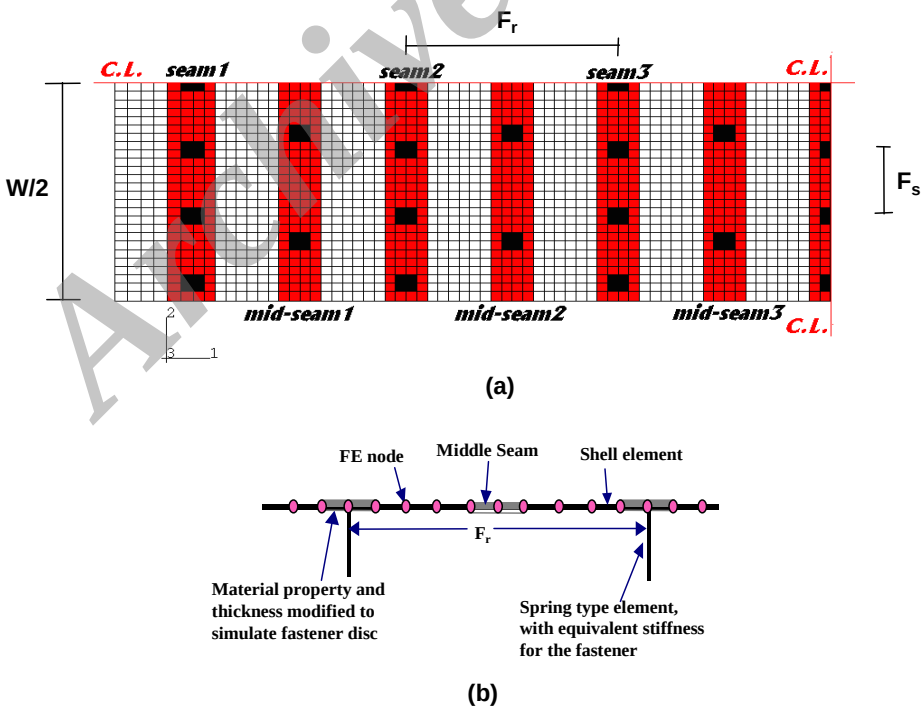


Figure 5. (a) Roofing system layout for the numerical modeling; (b) seam details considered in the model.

A rectangular grid of nodes and shell elements was used in each case to discretize the membrane. The shell elements consisted of 4-nodes and 1.04mm thick with an equivalent modulus of elasticity of 200 and 100MPa respectively for Glass and Polyester reinforced membranes. Figure 6 shows the stress-strain characteristic curves for these two Mod-Bit materials. The modulus of elasticity, the material property of the membrane, was obtained through mechanical tests. Membrane edges were assumed as spring supports and fastener locations were modified to account for the plastic fastener discs. Different material properties were simulated for fastener discs in the seam areas using shell elements. These discs were 3 mm thick with a diameter of 50 mm and a modulus of elasticity of 500 MPa. The geometric non-linear behavior of the membrane was also taken into account using finer meshes particularly around the seam areas and end supports.

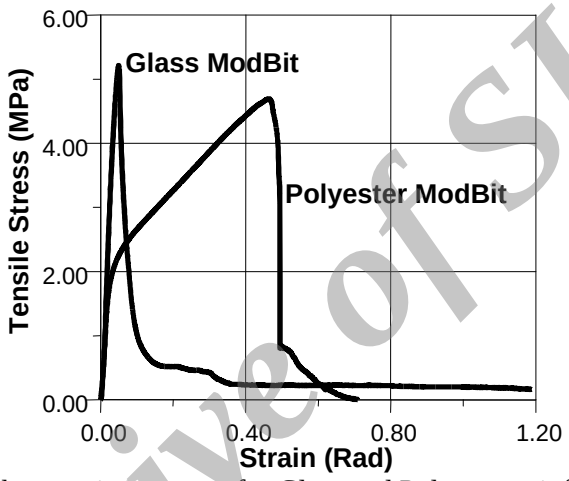


Figure 6. Stress-strain characteristic curves for Glass and Polyester reinforced membranes used in group#2 and 3 considered in this numerical study

Seam details were modeled by doubling the thickness of the shell element at the seam areas as schematically illustrated in Figure 5, to simulate the spliced region of the membrane. Fixed bar type element were used to simulate fastener attachments with the steel deck. Fasteners were assumed as spring supports with axial stiffness of 20 N/mm.

A typical computed membrane deflected shape is shown in Figure 7 where the membrane ballooning occurs between fastener rows and table edges. Computed fastener forces for three configurations are presented in Figure 8 where the rate of fastener load change is high for a table width less than 1.7 m. In all cases, with increasing the table width, the fastener forces approach to the tributary loads (i.e., pressure multiplied by the tributary area) for that fastener. Also, note that for Group#3 roofing system configurations (Figure 8b) where there is no middle seam and practically the membrane width (fastener row spacing, F_r) is larger, the width of the ideal table would increase.

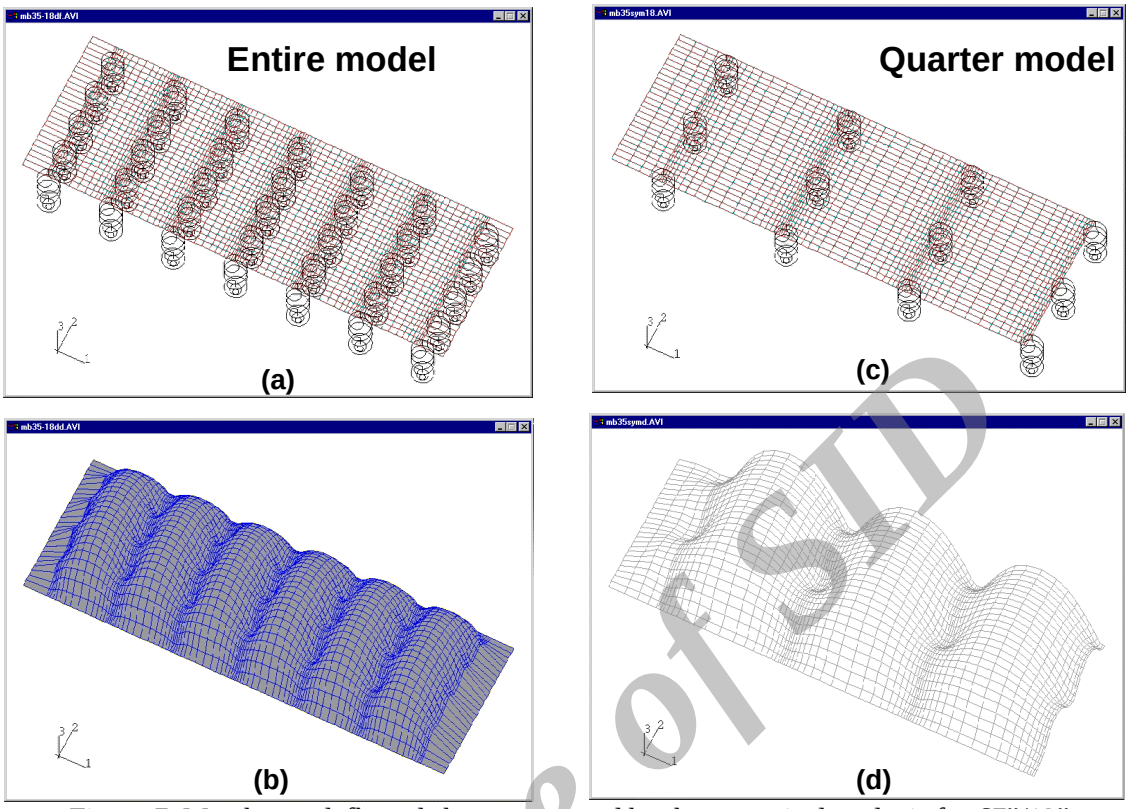
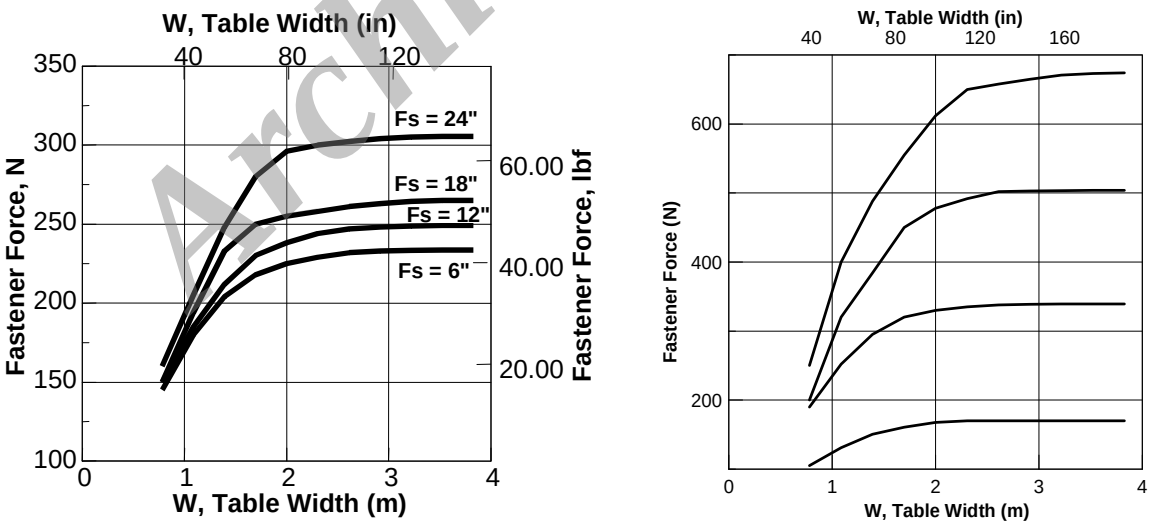


Figure 7. Membrane deflected shape computed by the numerical analysis for 67”/12” configuration (maximum deflection of 117 mm (4.6”) due to a suction of 1436 Pa (30 psf)).



(a) (b)

Figure 8. Computed fastener tensile force versus table width for four roofing system configurations in two considered groups

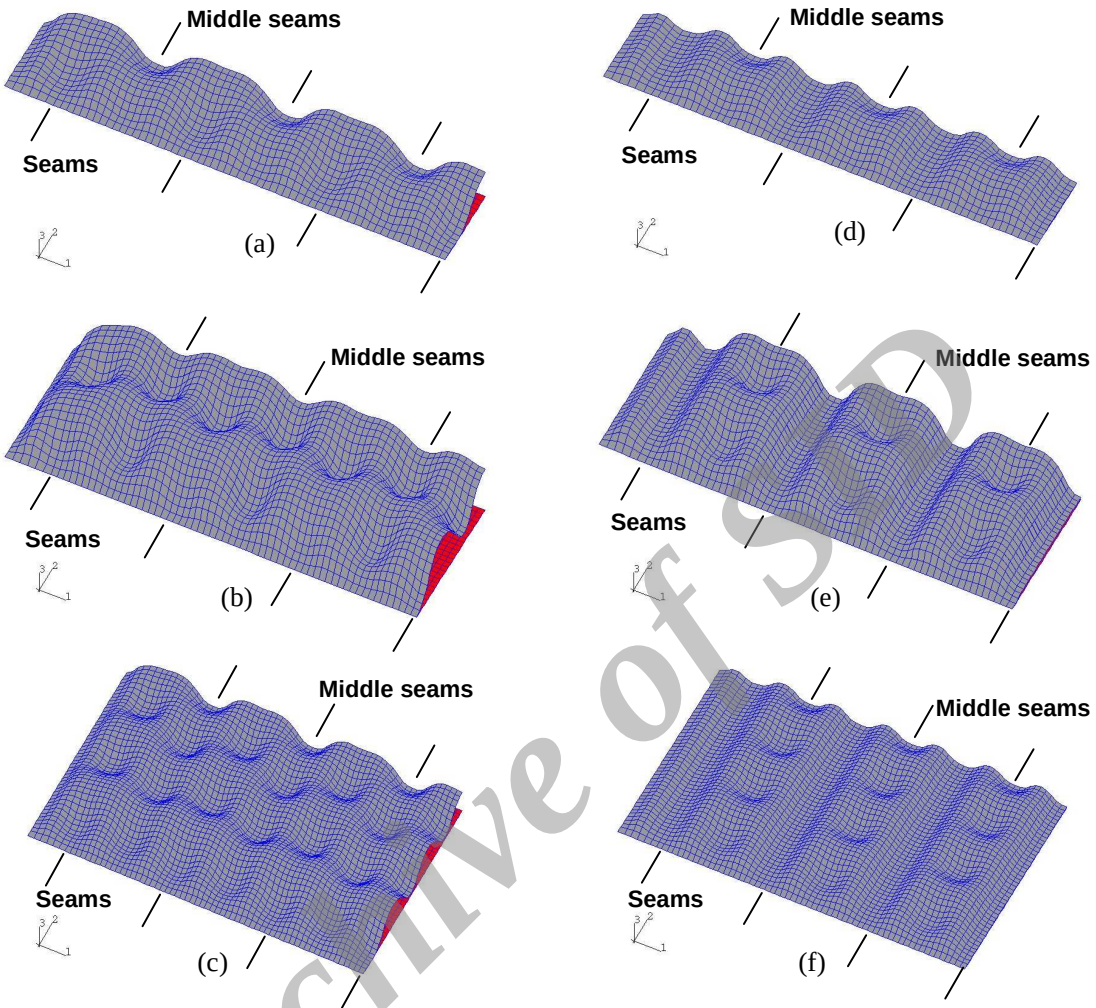


Figure 9. Deflected shapes for Group#2 using a quarter model having fastener spacing of 24" and tables width of: (a) 43", (b) 79", (c) 139"; and fastener spacing of 6" and tables width of: (d) 43", (e) 79", (f) 139"

3. BENCHMARKING THE ADOPTED MODEL

To collect benchmark data and verify the analytical model, experiments were carried out at the Dynamic Roofing Facility (DRF) applying two (FM and SIGDERS) test protocols. A roofing system with single-ply TPO membrane was initially selected to validate the finite element model. Three F_r/F_s configurations, 1700/305, 1220/460, and 1830/460 mm, (67"/12", 48"/18", and 72"/18") were considered. This testing program provided six sets of data to validate the FE model. Average values of two characteristic parameters, i.e., fastener loads at the center location of the seam, L1, and deflections at the center location of the membrane width, D1, measured from the DRF experiments were compared with the output of the FE analyses. Refer to the Figure 3 for the details of the L1 and D1 locations.

Fastener force comparisons are shown in Figure 10, where the horizontal axis represents the applied suctions on the roof assembly. In the experiments, based on the test protocols (FM or SIGDERS) the required pressures are applied and maintained for specific duration. During the model, simulations were performed at 718 Pa (15 psf) increments. The vertical axis presents fastener forces to represent the roofing systems response for the applied pressure. These comparisons demonstrated that the FE model is a viable tool that can be used to predict the fastener forces of test specimens at any pressure level.

To establish deviations between the two data sets (experiments versus model), the following expression was used:

$$\Delta F = \sum_{i=1}^{N} \left(\frac{F_{FE} - F_{EXP}}{F_{EXP}} \right) \times 100 \qquad (1)$$

F_{FE} is the fastener force obtained from the FE model,

F_{EXP} is the fastener force measured at the DRF,

N is the number of cases (pressure levels) considered for each configuration, and ΔF is the fastener force deviation between F_{FE}, and F_{EXP}. ΔF with a negative sign (-) means that the model underestimates the roofing system response compared to the experimental approach and vice versa.

Using Equation (1), for the case of F_r/F_s = 67”/12”, an under-estimation of 7% by the FE model has been noticed (Figure 6a). Similar comparisons for the Group#2 35”/12” and Group#3 35/18” roofing system configurations respectively revealed 2% and 10% deviations (over-estimations as presented in Figures 10a and 10b) of the analytical model from the measured fastener loads with the DRF experiments.

Similar to the format of Figure 10, Figure 11 presents the model validation for the prediction of the membrane deflection. Using deflection instead of forces in the equation (1), deviations are calculated. Computed displacement deviations (Δd) are also inserted in Figure 7.

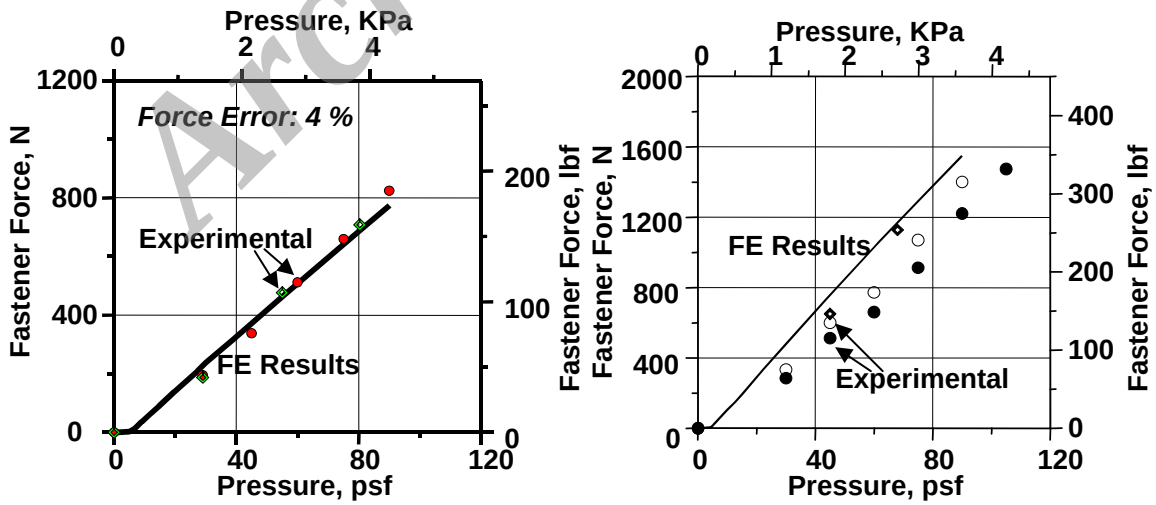


Figure 10. Model Validation – Comparison of the FE simulation results for fastener tensile force with Experimental Data: (a) Group#2 35”/12” configuration, (b) Group#3 35”/18” configurations.

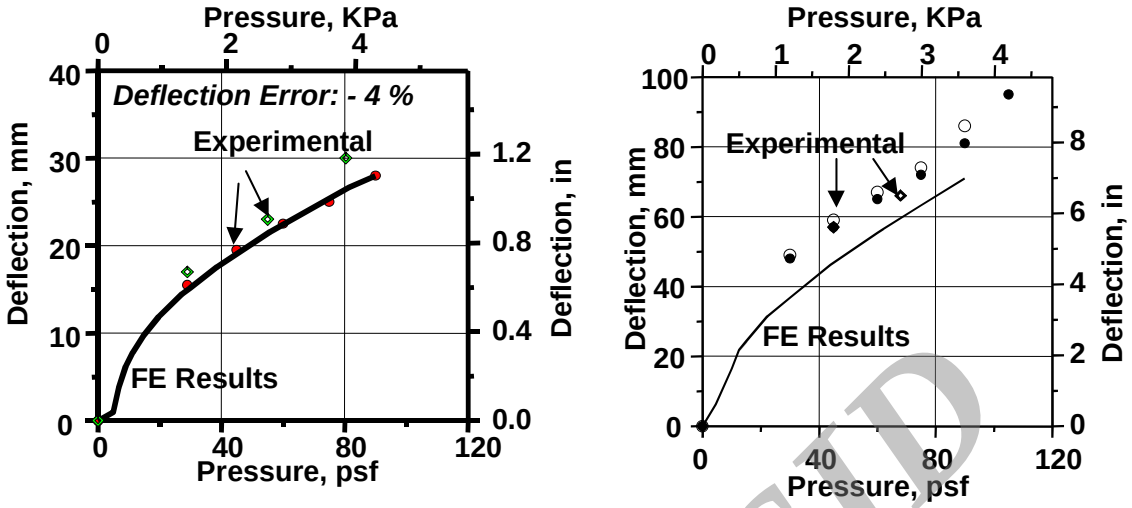


Figure 11. Model Validation – Comparison of the FE simulation results for membrane deflection with Experimental Data: (a) Group#2 35”/12” configuration, (b) Group#3 35”/18” configurations

Irrespective of the roofing system configurations, the membrane deflections are always underestimated by the numerical model. As shown in Figure 11, values of Δd ranged from –7 % to –19% and the cause for the difference between the data sets can be mainly grouped in two factors:

1. Edge Conditions: In the model, all four edges are restrained from any movements, whereas membrane slippage from the edges of the test frame was noticed during the experiments.

2. Membrane *Stiffness*: In the experiment, de-pending on the elasticity, the membrane undergoes stretching from its original stage. Also it uplifts for the applied suctions. Thus, the measured deflection is the summation of the membrane stretching and membrane uplift. In the simulation, only the membrane uplift is accounted for in the calculation of membrane deflection.

4. DEVELOPMENT OF TABLE SIZE CORRECTION FACTORS

4.1 Required table width

This section focuses on the required table size and development of corresponding correction factors. All three dimensions (i.e., length, width and depth), as shown in Figure 1, may be referred to as the table size. However, as discussed, during the system installation, components similar to those of the field systems are used. In other words, there is no variation from the field system on the thickness of components such as the insulation and membrane. Also, the effect of the table length is a minimum due to the fact that during the system installation on the table, membrane width forms parallel to the table width. Therefore, the present investigation focuses on identifying only the effect of table width on the system response using the validated FE model. Required Table Width (RTW) can introduce only minimum changes, if any, in the roofing system response. Maintaining all the

other parameters constant for the TPO roofing systems, the table width was increased by 305 mm (12") increments. Changing the table width from 781 to 5048mm (31" to 199") carried out several simulations, for different F_r/F_s configurations. The following criterion was used to identify the RTW:

"The table with RTW should provide no change in the fastener forces or change in the fastener force should be within 5% compared to those obtained from the smaller table".

In other words, if the change in the fastener tensile force is less than 5% while increasing the table width by 305 mm (12"), the new table width is the RTW and there is no need to increase the width any more.

4.2 Numerical examples

Computed fastener loads for two typical configurations (48"/18" and 72"/18") are shown in Tables 2 and 3. Using the above established criterion, it is clear that 2610 mm (103") is the RTW for the 48"/18" configuration. Also, increase in the fastener row spacing from 1220 to 1830 mm (48" to 72") increases the RTW from 2610 to 3219 mm (103" to 127"). Note that both these systems have the same fastener spacing of 457 mm (18") along the seam.

From the established RTW, one can develop correction factors (F_c) for the smaller tables. In Table 2, 2610 mm (103") is identified as the RTW with 748 N as fastener force. Using a 2000 mm (79") table reduces the fastener force to 650 N. To correct this reduction, a magnification factor of 1.15 (748/650) is needed. Thus, a correction factor of 1 is assigned to the 2610 mm table whereas a correction factor of 1.15 is developed for the 2000 mm table.

Table 2: Fastener forces for Mod Bit Group#2 (Glass base sheets and Polyester cap sheets, 3" square metal disks) with main fasteners at 24", 18", 12" and 6", and middle fasteners at 20", due to 1436 Pa (30 psf) pressure obtained by changing the table width

No.	Table Width mm (in)	F_s=24" Max. Force N (lbf)	Change (%)	F_s=18" Max. Force N (lbf)	Change (%)	F_s=12" Max. Force N (lbf)	Change (%)	F_s=6" Max. Force N (lbf)	Change (%)
1	4134 (163)	305.5 (68.6)	0	265 (59.5)	0	249 (55.9)	0	233.5 (52.4)	0
2	3829 (151)	305.5 (68.6)	0	265 (59.5)	0	249 (55.9)	0	233.5 (52.4)	0
3	3524 (139)	305.5 (68.6)	0	265 (59.5)	0	249 (55.9)	0	233.5 (52.4)	0
4	3219 (127)	305 (68.5)	0.2	264.4(59.4)	0.2	248.6(55.8)	0.1	233.3 (52.4)	0
5	2914 (115)	304 (68.2)	0.3	263(59.0)	0.5	248 (55.7)	0.2	233 (52.3)	0.1
6	2610 (103)	302.3 (67.9)	0.6	261 (58.6)	0.8	247 (55.5)	0.4	232 (52.1)	0.4
7	2305 (91)	300 (67.4)	0.8	258 (57.9)	1.1	244 (54.8)	1.2	229 (51.4)	1.3
8	2000 (79)	296 (66.5)	1.3	255 (57.2)	1.2	238 (53.4)	2.5	225 (50.5)	1.7
9	1695 (67)	280 (62.9)	5.4	250 (56.1)	2.0	230 (51.6)	3.4	218 (48.9)	3.1
10	1390 (55)	248 (55.7)	11.4	233 (52.3)	6.8	212 (47.6)	7.8	204 (45.8)	6.4
11	1086 (43)	205 (46.0)	17.3	194 (43.6)	16.7	185 (41.5)	12.7	180 (40.4)	12.7
12	781 (31)	160 (35.9)	22.0	150 (33.7)	22.7	150 (33.7)	18.9	145 (32.6)	18.5

For engineering design purposes, the F_c can be useful in two folds:

1: To calculate the design load, the fastener forces should be multiplied by the F_c's.

2: If one assumes, induced forces (F) are directly proportional to the applied pressure (P) via tributary area (P = F.A), then the roofing system's sustained pressures on smaller tables should be divided by the F_c to correct the pressure for the effect of RTW.

At this stage it is worth to mention the benefits of a numerical model. The data in Tables

2 and 3 represent 30 numerical experiments. As discussed in section 1, engineering solutions for problems of this nature can only be obtained through numerical modeling. Experimental approach would not be economically feasible.

Varieties of simulations were performed for the variations of the two influencing factors, namely, fastener row spacing (F_r) and fastener spacing (F_s). Three F_r configurations 1830, 1700 and 1220 mm (72", 67" and 48") with three F_s configurations 152, 305 and 460 mm (6", 12" and 18") are considered. These F_r/F_s combinations represent most of the TPO systems currently available in the roofing industry. However, recently, membrane widths as high as 3048 mm (120") were introduced and F_s of 610 mm (24") were also incorporated in the design of large roof areas. For each configuration, fastener forces are calculated. By applying a procedure similar to that used in Tables 2 and 3, correction factors were developed. The results are presented in the Figure 12 for the Group#2 35"/12" and Group#3 35"/18" roofing configurations. Figures 13 and 14 shows the changes in the fastener forces and membrane deflection respectively, versus applied pressure for the four configurations in those two group of Mod-Bit roofing systems considered here.

Table 3: Fastener forces for Mod Bit Group#3 (Polyester base cap sheets, 2" round metal disks) with fasteners at 24", 18", 12" and 6", due to 1436 Pa (30 psf) pressure obtained by changing the table width

No	Table Width mm (in)	F_s=24" Max. Force N (lbf)	Change (%)	F_s=18" Max. Force N (lbf)	Change (%)	F_s=12" Max. Force N (lbf)	Change (%)	F_s=6" Max. Force N (lbf)	Change (%)
1	4134 (163)	674 (151.3)	0	504 (113.1)	0	339 (76.1)	0	170 (38.2)	0
2	3829 (151)	674 (151.3)	0	504 (113.1)	0	339 (76.1)	0	170 (38.2)	0
3	3524 (139)	673 (151.1)	0.1	504 (113.1)	0	339 (76.1)	0	170 (38.2)	0
4	3219 (127)	671 (150.6)	0.3	503.5 (113)	0	339 (76.1)	0	170 (38.2)	0
5	2914 (115)	665 (149.3)	0.9	503 (112.9)	0.1	338.6 (76)	0.1	169.8 (38.1)	0
6	2610 (103)	658 (147.7)	1.1	502 (112.7)	0.2	337.7 (75.8)	0.3	169.8 (38.1)	0
7	2305 (91)	650 (145.9)	1.2	492 (110.5)	2.0	335 (75.2)	0.8	169.7 (38.1)	0
8	2000 (79)	612 (137.4)	5.8	478 (107.3)	2.8	330 (74.1)	1.5	167.4 (37.6)	1.4
9	1695 (67)	555 (124.6)	9.3	450 (101.0)	5.9	320 (71.8)	3.0	160.8 (36.1)	3.9
10	1390 (55)	488 (109.6)	12.0	384 (86.2)	15.0	295 (66.2)	7.8	150.5 (33.8)	6.4
11	1086 (43)	400 (89.8)	18.0	320 (71.8)	17.0	252 (56.6)	14.6	130.8 (29.4)	13.0
12	781 (31)	250 (56.1)	37.0	200 (44.9)	37.0	190 (42.7)	25.0	105 (23.6)	20.0

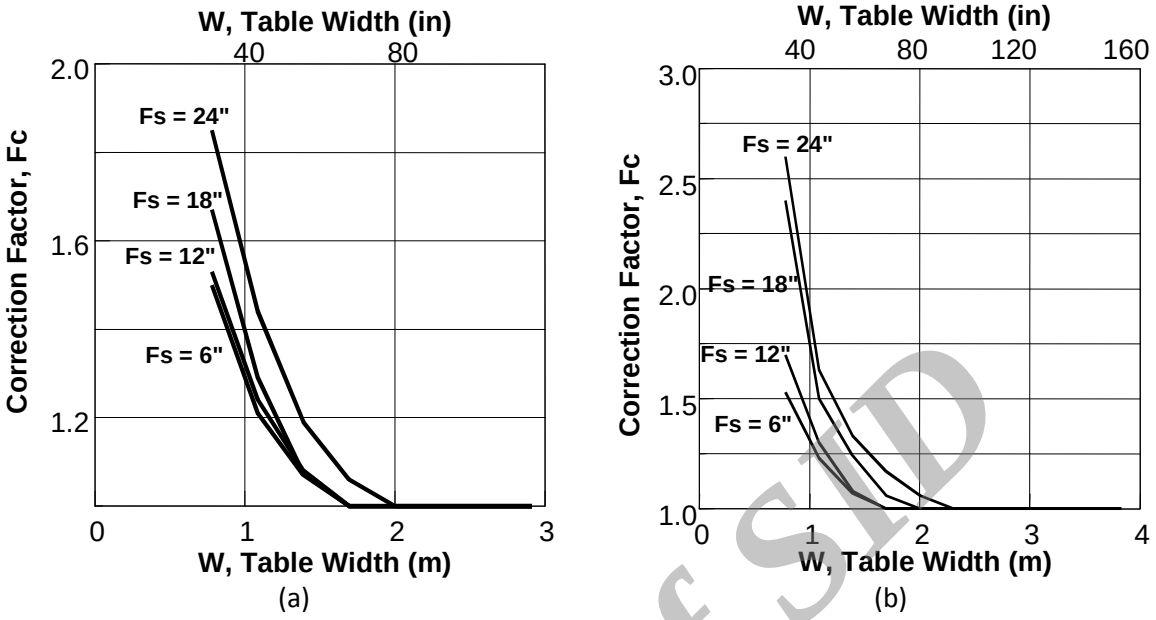


Figure 12. Developed Correction Factors: (a) Group#2 35”/12”; (b) Group#3 35”/18” roofing configurations

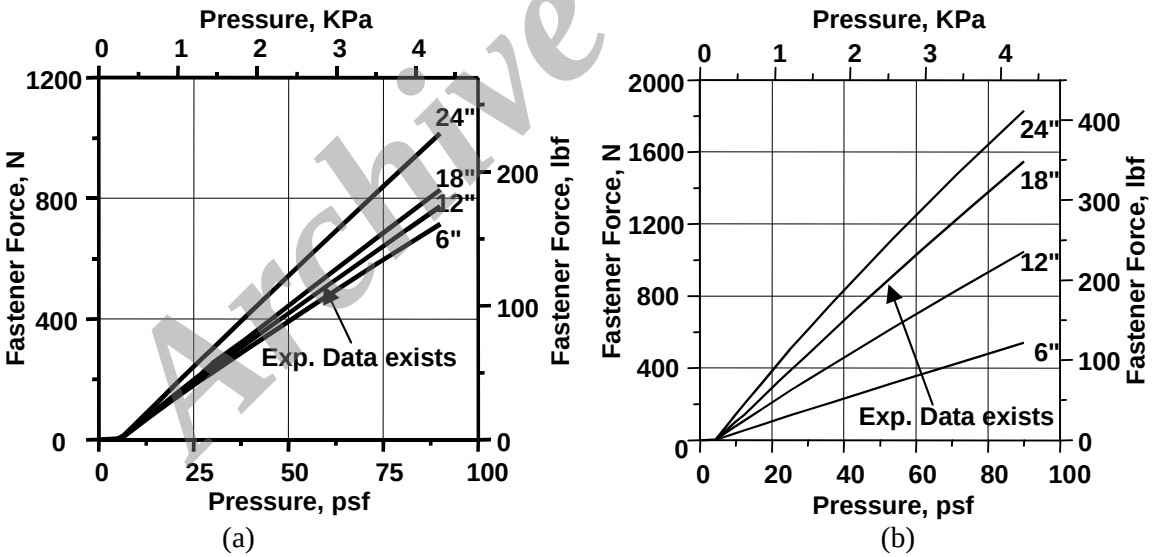


Figure 13. Fastener forces versus applied pressure for four roofing system configurations: (a) Group#2; (b) Group#3

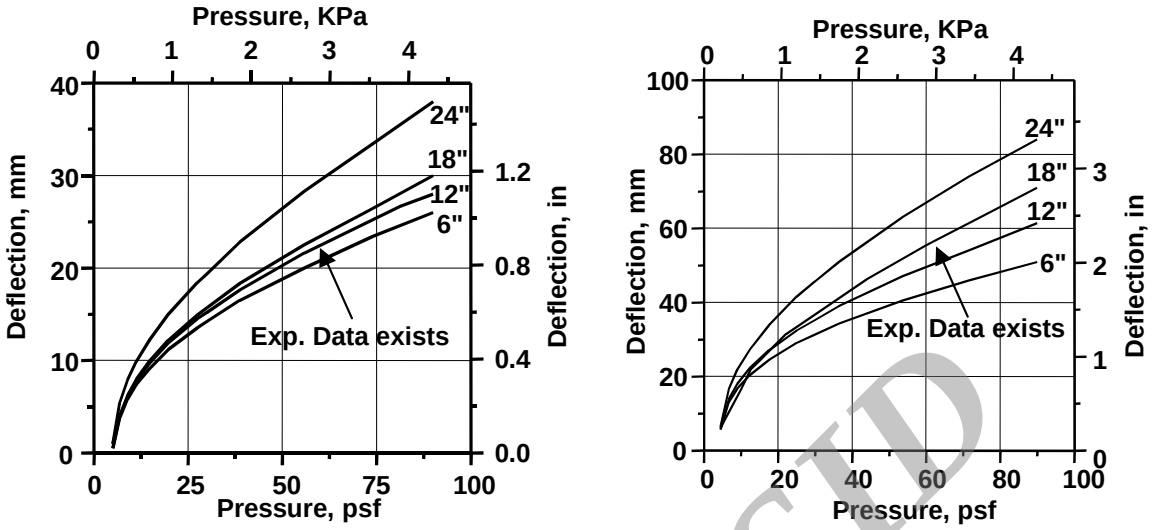


Figure 14. Membrane deflection versus applied pressure for four roofing system configurations: (a) Group#2; (b) Group#3

Figures 8 to 10 present an attempt to achieve characteristic curves such that generalized guidelines can be developed for the F_c. These Figures show that the correction factors are higher for the wider membranes and influence of the F_s on the development of F_c is less than that of F_r. Therefore, in the development of generalized F_c, one can assign higher importance factor for F_r compared to F_s.

6. CONCLUSIONS

An analytical model was developed to investigate the wind resistance performance of single-ply roofing systems. Numerical results for various system configurations compared well with those obtained from the experimental studies carried out using the Dynamic Roofing Facility.

The analytical model was also used to investigate the effect of table size on the roofing system performance. Attempts were made to identify the required table width. It was found that an increase in the table width beyond a certain level did not significantly change the system response. This specific limit depends on the system configurations. Systems with wider membranes (fastener row spacing) would generally increase the required table width.

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Canada Post Corporation, Department of National Defense, Public Works and Government Services Canada and Associations: Canadian Roofing Contractors' Association, Industrial Risk Insurers, National Roofing Contractors' Association and Roof Consultants Institute.

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