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Impact of Table Size on the Performance of Thermo-Plastic Roofing Systems Under Wind Uplift Pressures

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Roofing systems have always been vulnerable to strong wind uplift pressures. Wind forces have dynamic effects on structures, as they change in time and space. Therefore, a dynamic means of evaluating roofing systems is necessary in order to identify the component of the system having the least resistance to wind uplift forces. Although researchers worldwide have conducted tests on roofing structures, they have all used various table sizes, as there is still no standard chamber size for experimental purposes. This paper aims to study the impact of table size on roofing system performance. To achieve this objective, extensive analytical work has been conducted 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. This paper presents some of these result comparisons. It was 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. Ideal table sizes were also suggested for various configurations having a TPO (Thermo-Plastic Olefins) membrane and correction factors were eventually developed for different table sizes.

INTRODUCTION-PROBLEM IDENTIFICATION

Wind effects must be taken into account when designing roofing systems, since, as in all structures, they are vulnerable to strong wind uplift pressures and severe damage [1]. The wind resistance rating of roofing systems is based on standardized test methods. In North America, existing test methods include Factory Mutual (FM 4470 and 4471) [2] and Underwriters Laboratories (UL 580 and 1897). In both cases, the manufacturer assembles the roofing system, together with its respective components in a test chamber as shown in Figure 1. To evaluate the wind uplift resistance, air pressure is applied until the structural failure of the system occurs, e.g. membrane tearing and/or fastener pull out.

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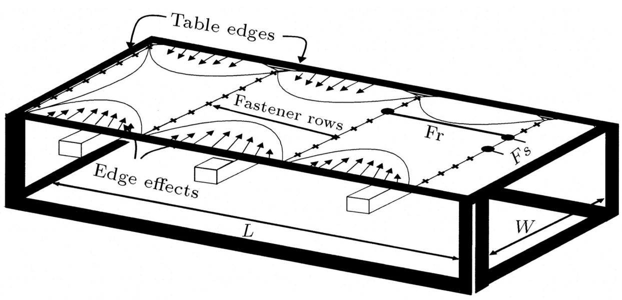


Figure 1. Effect of table size on the roofing system response.

For experimental purposes, roofing system specimens are generally placed in a testing apparatus whose size is normally far less than the size of the real roof. Although the system configuration (e.g. fastener spacing and membrane width) is the same as that of the real structure and the specimen is subjected to the same amount of suction pressure, the fastener load and membrane deflection might be different from real values. This is mainly because the testing rig edges would clamp the membrane and, therefore, resist some of the applied pressure, particularly so for narrower tables. If the testing table is wide enough, the results would be realistic and reliable. Nevertheless, how wide is adequate and how much does the answer to this question depend upon the roofing system configuration?

Current test methods consider different table sizes for the performance evaluation of roofing structures. For instance, FM tests use a table size of 5 ft by 9 ft (1524 by 2743 mm) or 12 ft by 24 ft (3658 by 7315 mm), depending on the roofing system. A chamber size of 10 ft by 10 ft (3048 by 3048 mm) is used by the UL standard. Figure 2 shows a number of existing chambers being used worldwide. Research efforts in recent decades 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, which makes it possible to evaluate roof systems dynamically [3]. A table size of 2000 by 6000 mm is used by the SIGDERS test protocol. The table size and its impact on the roofing system performance are questionable in order to achieve identical results by different testing methods. As a matter of fact, there is a need for testing standards and special guidelines to specify a unique table size and/or to recommend correction factors when chambers with other sizes have to be used.

Careful examination reveals that table size plays an important role in evaluating roofing systems and should be selected properly to obtain realistic wind uplift resistance. For example, the use of smaller tables would increase the edge effects on the results, particularly for roofing systems having larger membrane widths, i.e. spacing between fastener rows. On the other hand, using larger or wider tables would make the system response slower. Despite the significance of table dimensions to the author's knowledge, there still exist no clear criteria and/or specific standard to suggest an ideal table size. A number of parameters can influence the required table size, in particular Fastener Spacing (Fs), Fastener Row spacing (Fr) and membrane Elasticity (E), that would be closely related to fastener forces and membrane deflections. Zahrai and Baskaran developed an analytical model to investigate the wind resistance performance of Modified Bituminous (Mod-Bit) roofing systems [4,5]. 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.

In this paper, the testing facility, the SIGDERS dynamic load cycle and the Factory Mutual (FM), another evaluation method which is a static wind uplift test used commonly in North America, are briefly described. Using these tools and techniques, this paper studies the responses of roofing systems under uplift pressure conditions. The experimental results were subsequently used for comparison with those obtained by extensive analytical work, in order to validate the numerical modeling. In this way, the improved analytical model could be used to study the impact of table size on performance. The objectives of the present study in chronological order are:

- To develop a numerical model simulating experimental results,
- To investigate the effect of table size on roofing system responses,
- To identify an ideal table size for which no changes are introduced into the system response,
- To develop correction factors for tables smaller than the ideal one.

APPLIED LOAD PROCEDURE

Factory Mutual Standard

The standard test currently in most common use in North America is the FM static test (FM 1986). In this static test, a pressure of 1436 Pa (30 psf) is applied from the bottom of the test specimen and held for one minute. The pressure is increased by 718 Pa (15 psf) each minute until the test specimen fails [2]. A test assembly that successfully sustains a pressure of 4309 Pa (90 psf), for example is given a windstorm classification of I-90.

SIGDERS Load Cycle

The SIGDERS load cycle was developed based on extensive wind tunnel studies of full-scale roofing systems measuring 3048 mm by 3048 mm (10 ft by 10 ft). These studies were carried out in the NRC's 9000 mm by 9000 mm (30 ft by 30 ft) wind tunnel. The load cycle consists of eight load sequences with different pressure ranges. The eight load sequences can be divided into two groups: Group 1 represents wind-induced suction over a roof assembly and Group 2 represents the effects on a building of exterior wind fluctuations, combined with constant interior pressure [6]. Internal pressure variations have been explicitly codified in the recent North American Wind Standards by ASCE 1997, NBCC 1995 [7,8]. Details of the method by which the load cycle was developed can be found elsewhere [9].

The above test methods can be conducted in the Dynamic Roofing Facility (DRF) established at the Institute for Research in Construction at the National

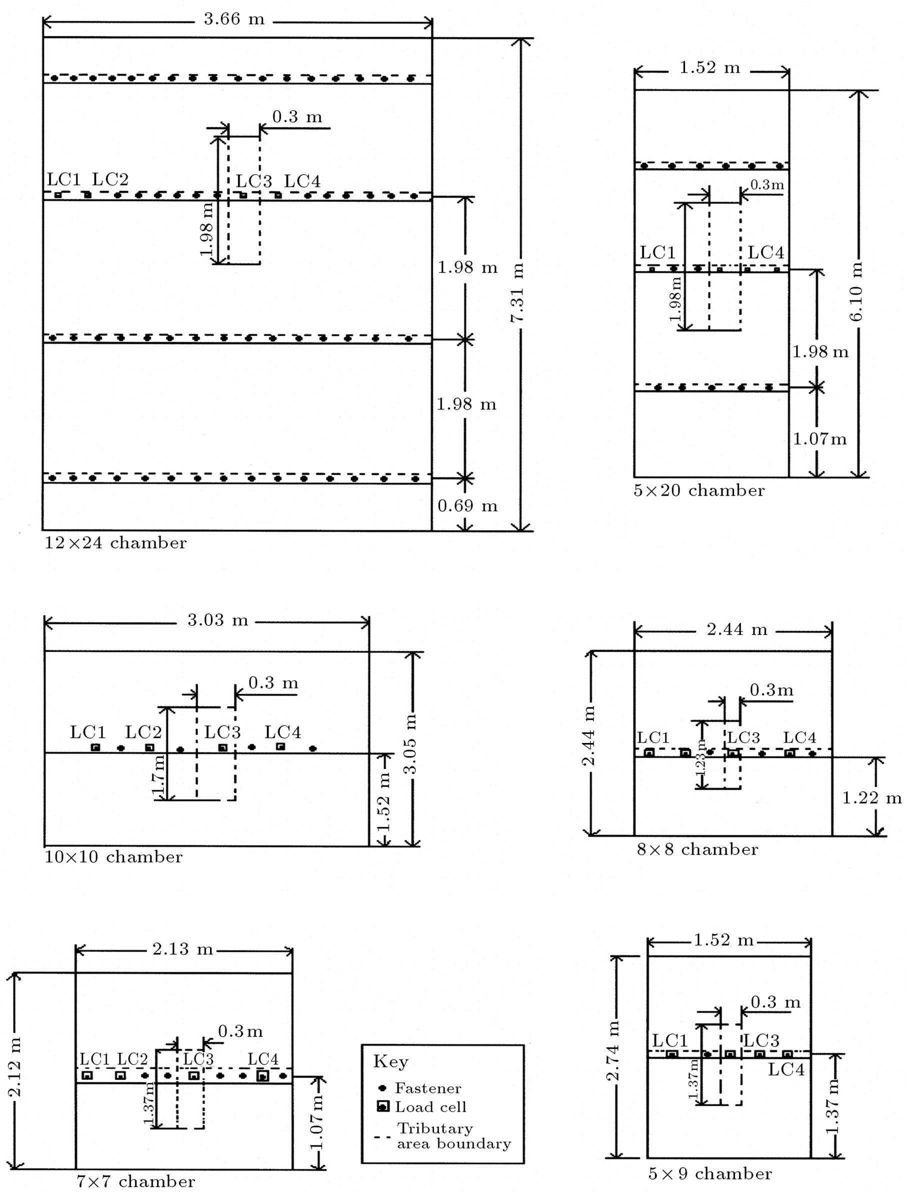


Figure 2. Tested table sizes for evaluation of roofing system performance.

Research Council of Canada (IRC/NRC). The DRF consists of a bottom frame of adjustable height upon which roof specimens are installed and a movable top chamber (see [3] for more details). The DRF operation is controlled by a HP mainframe computer using feedback signals. The computer regulates the fan speed, in order to maintain the required pressure level in the chamber. Operation of the flap valve simulates the gusts. Closing the flap valve allows pressure existence in the chamber and opening the valve bleeds the pressure.

EVALUATION OF TPO SYSTEM

System Details

TPO roof assemblies with various configurations were evaluated under the two different testing methods

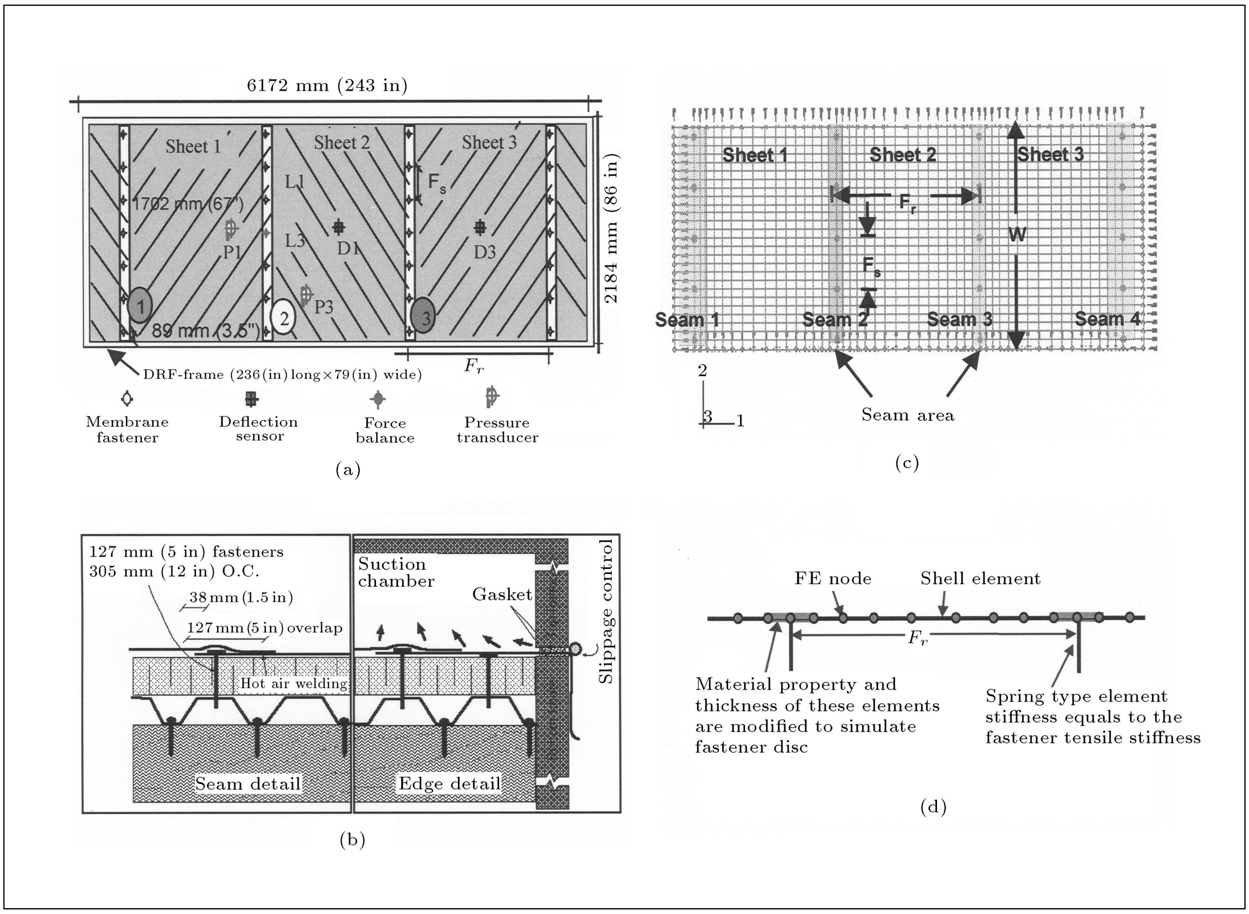


Figure 3. (a) Roofing system layout for thermoplastic membranes; (b) Longitudinal section of TPO roofing system; (left) seam detail, (right) edge detail; (c) The enhanced finite element model; (d) Seam details considered in the proposed numerical model.

(FM and SIGDERS). Similar system layout and instrumentation locations were used for the specimens. To monitor the response of the roof system, typical design parameters of pressure, force and deflection were measured (Figure 3a). Load cells and optical deflection sensors, respectively, measured the tensile forces in the fasteners and in the uplift movement of the membrane center point. As shown in Figures 3a and b, the tested roofing system consisted of all three main roofing components: A 0.76 mm (22-Ga) thick steel deck with a profile height of 38 mm (1.5 in) and a flute width of 150 mm (5.9 in), 100 mm by 1500 mm by 3000 mm (4 in thick by 4 ft by 8 ft) polyisocyanurate (ISO) insulation boards, mechanically attached to the steel deck, and membrane.

Membrane

The present study focuses on the behavior of those roofing systems in which thermoplastic membranes are used as the waterproof component. Two main kinds of thermoplastic membrane: PolyVinyl Chloride (PVC) and ThermoPlastic olefins (TPO) are used in single-ply roofs. In this study, 1829 mm (6 ft) wide reinforced polyethylene-based TPO membrane sheets are used. In the early 1990's, TPO was introduced into the roofing market, due to its outstanding ecological profile with regard to environmental aspects [10]. A complete overview of PVC and TPO roofing membrane performance has been documented by Rossiter and Paroli [11] and Beer [12], respectively.

The details of a typical seam are shown in Figure 3b, where the seam has an overlap of 127 mm (5 in), with the fastener placed 38 mm (1.5 in) from the edge of the under sheet and 89 mm (3.5 in) from the edge of the overlapping 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 in).

Figure 3b also shows a typical detail at the edge of the DRF frame. Gaskets were placed above and below the membrane, between the membrane and the frame, to ensure the air-tightness of the chamber. Pieces of wood, 76 mm (3 in) in diameter, were fixed to

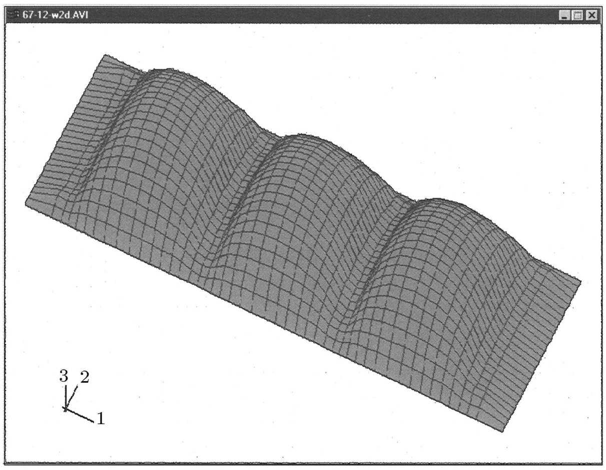


Figure 4. Typical deflected shape of the proposed numerical model.

the membrane outside the chamber, to prevent the membrane from slipping during the test. The four seams shown in Figure 4 indicate the fastener locations. For the tested system, membrane sheets were fastened at 152, 305 and 457 mm (6, 12 and 18 in for different configurations) intervals along the seam. Fasteners were 127 mm (5 in) long with a plastic disc of 51 mm (2 in) in diameter.

NUMERICAL MODELING APPROACH

To achieve the objectives of this paper, the present study takes advantage of the numerical modelling approach. Finite Element (FE) analysis is generally done by dividing the whole assembly model of concern into many smaller parts. FE techniques afford large flexibility in exploring scenarios which are too expensive or, in some cases, impossible to set up experimentally. In addition to economical advantages, the analytical models are generally faster for solving complex problems where there is a need to investigate the impact of various influencing parameters.

Roofing can be a good application for FE analysis, as some membrane materials have large deformations that make some conventional analysis methods inappropriate. The FE model is also helpful for studying the roofing performance using larger test tables where there is less edge effect and the holding fasteners take more load than the table edges. Keeping the above advantages in mind, a three-step approach is followed in this study: (i) Development of a FE model, as typically shown in Figure 4, (ii) Verification of the FE model with experimental data for limited benchmark configurations and (iii) Investigation of the effect of table size on the roofing system performance, using the validated FE model.

FE Model

Figure 3c shows the FE model, being 6 m in length and 2 m wide (the same as the roofing system dimensions in the experimental program shown in Figure 3a), proposed to simulate the behaviour of roof specimens in the lab. For simplicity, the membrane alone was considered in the numerical modelling, due to its much greater flexibility compared to those of the insulation and steel deck. In other words, the deflection of the steel deck was ignored and fasteners were assumed as spring supports for the membrane, in addition to the edge supports.

For each case, a rectangular grid of nodes and elements was used in order to discretize the membrane. Numerical modelling grids, consisting of 4-node shell elements for the membrane (about 1.04 mm thick with an equivalent modulus of elasticity of 300 MPa) and springs for the fasteners (axial stiffness of 20 N/mm), were located in the seam areas. The membrane at the fastener locations was modelled to represent the hard plastic fastener discs (3 mm thick with a diameter of 50 mm (2 in) and a modulus of elasticity of 500 MPa).

ABAQUS version 5.7 [13] is a commercially available finite element program with nonlinear analysis capability, which was used to carry out all the analyses and obtain numerical results. The large strains and deformations that occur during the loading of the membrane require that a geometry nonlinearity (large deformation theory) be considered. Small load increments were considered to accommodate the flexibility of the single-ply membranes.

Some of the features of the FE model development are briefly explained in the following. The geometry nonlinear behaviour of the membrane was accounted for by using finer meshes, particularly around the seam areas and end supports. Larger size elements could cause the FE equations not to converge. Seam details were simply modelled by doubling the thickness of the shell element at the seam areas, as schematically illustrated in Figure 3d, in order to simulate the spliced region of the membrane. Different material properties were simulated for fastener discs in the seam areas using shell elements. Fixed bar type elements were used to simulate fastener attachments with the steel deck.

VALIDATION OF THE PROPOSED MODEL

A roofing system with a single-ply TPO membrane was initially selected to validate the finite element model. Three Fr/Fs configurations (67 in/12 in, 48 in/18 in, and 72 in/18 in) or (1700/300, 1220/460 and 1830/460 in mm) were considered. A typical deflected shape for the membrane is shown in Figure 4, where membrane ballooning occurs between fastener rows and table edges. To collect benchmark data, experiments were carried out for these systems at the Dynamic Roofing Facility (DRF), using FM and SIGDERS test protocols described in the previous sections. This testing program provided six sets of data to validate and improve the FE model.

RESULTS AND DISCUSSION

The average values of two characteristic parameters, i.e. fastener loads at the center of the seam and deflections at the center of the membrane width, measured from the DRF experiments, were compared with the output of the FE analyses. These comparisons demonstrated that the FE analytical model is a valid tool that can be used to predict the fastener forces of test specimens at any pressure level. A typical example of the fastener load comparison is shown in Figure 5a, for the first configuration (Fr/Fs = 67 in/12 in). For this case, an under-estimation of 7% by the FE model has been noticed. Similar comparisons for the 48 in/18 in and 72 in/18 in configurations, respectively, revealed 2% and 10% deviations (this time, over-estimations as presented in Figures 5b and 5c) of the analytical model from the measured fastener loads in the DRF experiments. As illustrated in Figure 6, more difference was observed in the membrane deformations, due to some slippage that occurred in the tests, particularly for the roofing configurations with smaller membrane width. Therefore, the tensile forces of the fasteners were usually considered for comparison purposes.

DEVELOPMENT OF TABLE SIZE CORRECTION FACTORS

As mentioned earlier, each test protocol has its own table size, giving some related results not necessarily identical to those obtained by other testing methods. In this section, the focus is to determine ideal table size and develop corresponding correction factors. It is noteworthy that changing table length does not significantly affect the wind resistance response (see the membrane ballooning between two rows of fasteners in Figure 1) and here, accordingly, was kept constant (2 m, the same as DRF tests). The above-validated FE model was used to investigate the effect of table width on the system performance. The ideal table width must demonstrate no changes in the roofing system response. While maintaining the same TPO roofing system and the same applied pressure (30 psf), the table width was changed by 12 ins (305 mm) increments, in order to carry out several simulations for different Fr/Fs configurations. A range of 31 in to 199 in was considered for the table width.

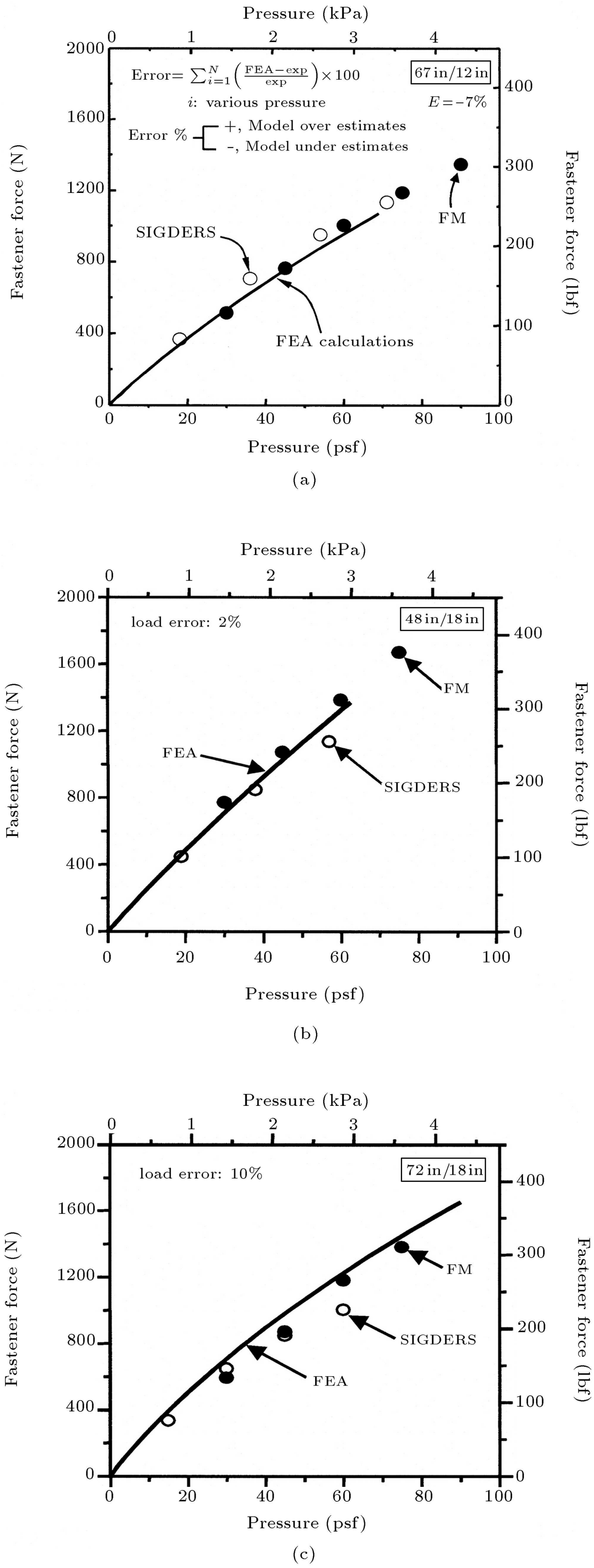
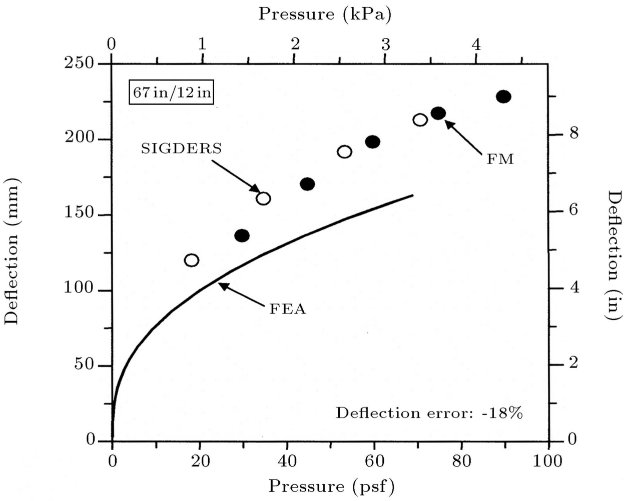
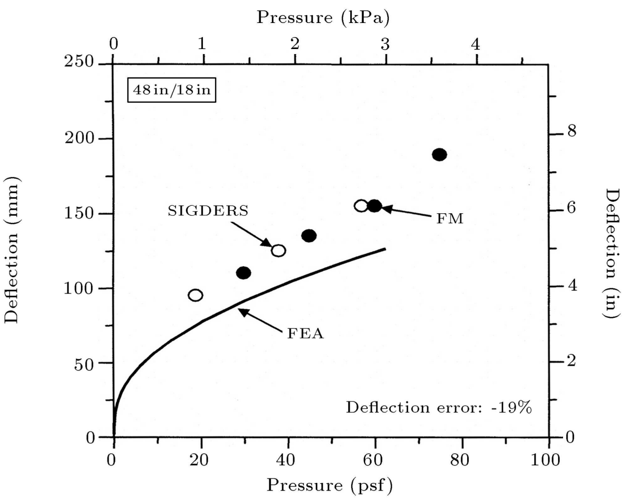


Figure 5. Model validation; comparison of the FE simulation results for fastener tensile force with experimental data: (a) 67 in/12 in, (b) 48 in/18 in and (c) 72 in/18 in configurations.



(a)



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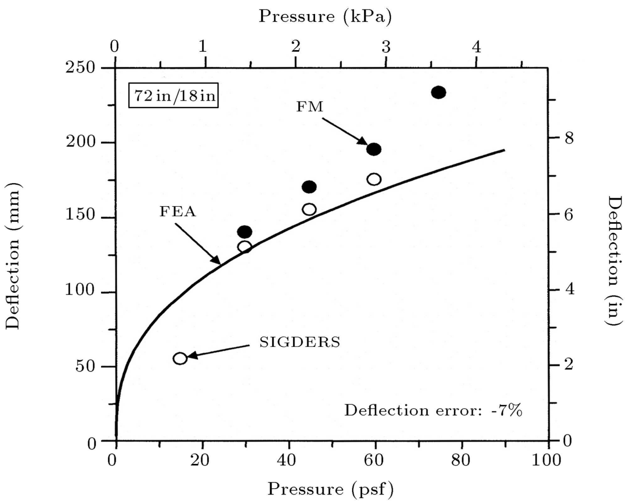

(c)

Figure 6. Model validation; comparison of the FE simulation results for membrane deflection with experimental data; (a) 67 in/12 in, (b) 48 in/18 in and (c) 72 in/18 in configurations.

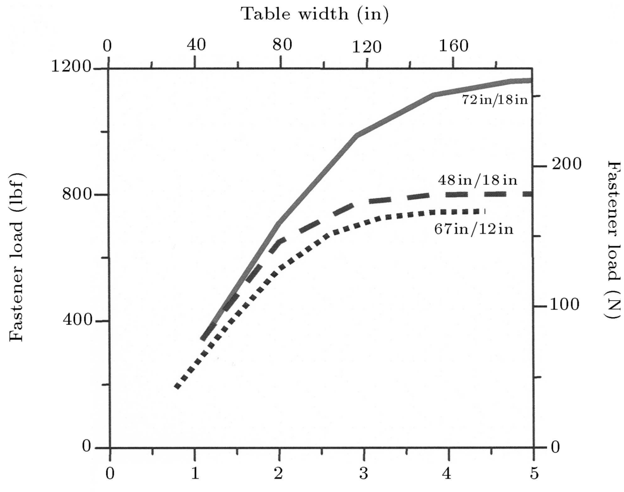

Figure 7. Fastener tensile load versus table width for three roofing system configurations.

The impact of table width on the fastener forces for the three Fr/Fs configurations considered here, is presented in Figure 7, where the rate of fastener load change is high for a table width less than 3 m. In all cases, increasing the table width, made the fastener forces approach the tributary load (i.e. pressure multiplied by the tributary area) for that fastener. Also, note that having the same size fastener spacing, Fs, a larger membrane width (fastener row spacing, Fr), increases the width of the ideal table. The following criteria were used to identify the appropriate table width: "Fastener load is constant or change in the fastener load is within 5% from the one table width to the next". In other words, if the change in the fastener tensile force is less than 5% while increasing the table width by 12 in, the new table width is ideal and there is no need to further increase the width. For instance, 115 in was obtained as the ideal table width for the 67 in/12 in configuration, with 4% change in fastener force (Figure 7).

With this approach, correction factors should be considered for tables smaller than the ideal one. Based on the relationship between fastener load and table width (Figure 8a), the fastener load should be multiplied by the correction factor, C_f , for tables with a smaller width. A typical example is also shown in Figure 8a for a 67 in/12 in configuration. In such a case, while the ideal table width is 115 in (2.92 m), a correction factor of 1.26 should be applied to the fastener force if a table width of 78 in (2 m) is used. Note that the other parameters, such as the applied pressure and membrane layout, were kept constant. Figure 8b shows a comparison of the correction factor curves for various configurations in an attempt to achieve characteristic curves and generalized guidelines. Complementary research is underway to investigate the issue for other

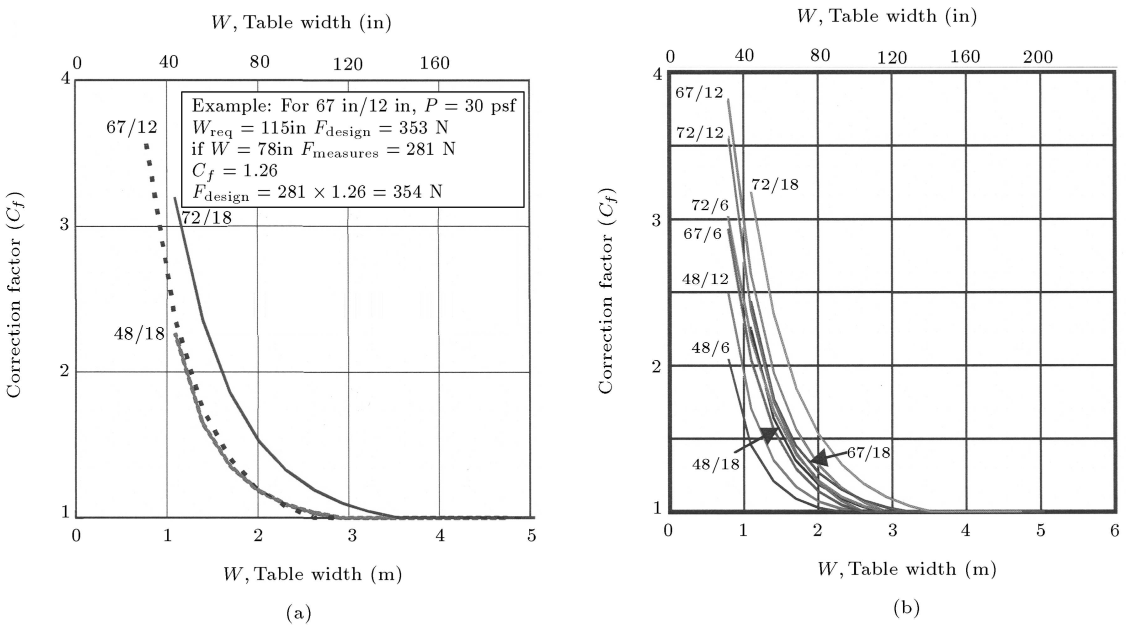

Figure 8. Developed correction factors for various table sizes for (a) Three considered system configurations; (b) Different cases for comparison.

membranes through dynamic analyses.

CONCLUSIONS

An analytical model was developed to simulate the wind resistance response of single-ply roofing systems used frequently in building structures subjected to wind loads. Numerical results for various system configurations compared well with those obtained by experimental work, based on different test protocols (average values for the results of dynamic testing by SIGDERS method were considered for comparison purposes). The analytical model was also used to investigate the effect of table size on the roofing system performance. It was found that an increase in table width beyond a certain level (e.g. about 3 m for the cases considered in this study) 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, having the same size of fastener spacing, a larger membrane width (fastener row spacing) increases the width of the ideal table.

Several numerical analyses were carried out to obtain the relationship between fastener force and table width for various configurations and developed table size correction factors applicable to smaller tables. More research considering other membranes and dynamic analyses has been in progress at IRC/NRC, in order to establish guidelines for table size correction factors to be applied to the results given by different test protocols. It is ideal for roofing designers to have software capable of performing complete system designs.

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