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Calculating Roof Membrane Deformation Under Simulated Moderate Wind Uplift Pressures

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Abstract

Mechanically attached roof system has flexible membranes that are exposed to environmental elements to achieve the waterproofing function. Wind induced loads can lift the roof membrane between attachment locations and cause fluttering. The membrane under tension induced by wind forces transfers stresses through fasteners at the attachment locations. By characterizing the membrane deformation with its slope and using a force-vector diagram, one can predict the critical forces on fasteners. This paper presents the use of a three-dimensional finite element (3D-FE) model for predicting membrane deformation. To validate the model, a series of benchmark experiments have been performed at the Dynamic Roofing Facility of the National Research Council of Canada. The experimental data are also used to evaluate the validity of a mechanic model. From this comparative exercise between the existing model and the newly developed one, the paper offers the designer the limitations at which the simplified mechanic model can be used.

Keywords: Roofing, Wind Effects, Membrane Ballooning, 3D Finite Element Model, Membrane, Deflection, Mechanic based models, Fastener forces and Model validation

Nomenclature

2D	Two-dimensional
3D	Three-dimensional
3D-FE model	Three-dimensional finite element model
A	Membrane area (mm^2/in^2)
α	A radius for a circular membrane and one-half of the distance between supports in the short direction for long rectangular membrane
DRF	Dynamic Roofing Facility
$D_{1, 2, 3}$	Sensor distance (mm/in)
E	Modulus of elasticity (Mpa)
F_z	Force acting in Z direction (N/lbf)
F_{tensile}	Tensile force (N/lbf)
F_{tear}	Tear force (N/lbf)
F_x	Force acting in X direction (N/lbf)
h	Membrane deflection (mm/in)
h_{max}	Maximum deflection (mm/in)
L	Membrane length (mm/in)
L_l	A clear distance between fastener-edges and centerline of membrane (mm/in)
l	Distance between supports (mm/in)
MARS	Mechanically Attached Roofing Systems
NRC	National Research Council of Canada

p	Pressure applied (Pa/psf)
PVC	Polyvinyl chloride
t	Membrane thickness
ν	Poisson's ratio
X/L	Normalized ratio of sensor position to the membrane length

1. Introduction

More than 50% of the North American low-slope commercial buildings have their roof covered with flexible membranes [1]. These membranes provide the waterproofing function of the roof. The roof membranes are integrated with other roof components (insulation, barrier and deck) either with mechanical fastener and/or adhesives. In a Mechanically Attached Roofing Systems (MARS), membrane sheets are overlapped to form seams where fasteners are used at the seams to keep the membranes in place under the action of wind (Figure 1). Wind fluctuations (dynamic loading) cause the roof membranes to flutter, or rapidly flap up and down. This dynamic loading induces tension stresses on the membranes and fatigue at fastener deck engagement location. As shown in Figure 1, each of the roof components offers certain resistance to the wind uplift forces. A failure could occur when wind induced stresses exceed the resistance capacity of the roofing components. To avoid failure, the designer should identify the weakest link and increase its resistance.

Figure 2 depicts the membrane ballooned shape of the MARS from a field condition. The shape of the membrane ballooning can be simplified and illustrated as a second-order of a parabolic function equation in two-dimension (2D). Then, one can use a 2D-mechanic model to calculate the membrane deflection at various pressure levels. Using the deformed shape of the membrane, its slope (α) with respect to the original position (before ballooning) could be predicted. Incorporating the slope into a force-vector diagram, one could calculate approximately the critical forces on the fasteners. Due to the membrane physical properties, such as, thickness and flexibility, only the membrane is considered to be experiencing a large deflection and consequently creates tension forces in comparison to other roof components. The tensile forces on the membrane will be transferred to attachment location through fasteners. Once the slope is defined, the fastener critical forces (tension, shearing and peeling forces) can be predicted by dividing the max allowable fastener tensile force capacity (obtained from manufacture data sheet) by the ($\text{Sinus } \alpha$) which is the max slope angle as illustrated in Figure 2.

Literature review revealed that several researchers (Zarghammee [3], Baskaran and Borujerdi [4], Phalen [5] and Shi et al. [6]) developed numerical models to quantify membrane deformation. A critical review of numerical modeling effects can be found in Baskaran and Kashef [7]. Researchers (Gerhardt and Kramer [8], Kramer [9] [10]), Prevatt [11], Baskaran et al. [12] and Baskaran [13]) conducted experimental studies and measured membrane deformations. The present paper contributions are as follows:

- Carry out benchmark experiments in controlled laboratory conditions to quantify the membrane deflections.

- Using a 3D-FE model duplicate the benchmark experiments and numerically calculates the membrane deflections.
- Compare the measured and calculated membrane deflections with those obtained by the predicted mechanic models developed by Shi et al. [6].

This systematic approach offers designers, the validation of Shi et al. [6] numerical model and its limitations for calculating membrane deflections on roof.

2. Experimental Program for Model Benchmarking

2.1. Dynamic Roofing Facility (DRF)

A series of experiments were conducted using the Dynamic Roofing Facility (DRF) at the National Research Council of Canada (NRC). The DRF consists of a bottom frame of adjustable height upon which the roof specimen is installed, and a removable top chamber (Figure 3). The design of the DRF allows for the installation and study of roof assemblies of different insulation thicknesses up to 500 mm (18 in), as well as, the evaluation of sloped roofs. The bottom frame and top chamber are 6100 mm (240 in) long, 2200 mm (86 in) wide and 800 mm (32 in) high. The top chamber is equipped with six windows for allowing visual inspections, and a gust simulator, which consists of a flap valve connected to a stepping motor through a timing belt arrangement. A 37 KW (50HP) fan with a flow rate of 2500 L/sec (5300 cfm) produces pressure suction as high as 10 kPa (209 psf) over the roof assembly. A computer, using feedback signals, controls the operation of the DRF. The computer regulates the fan speed in order to maintain the required pressure level in the chamber. Operation of the flap valve simulates gusting in the

form of uniform cyclic pressure loading over the surface of the roofing assembly. Closing the flap valve allows pressure to build in the chamber, while opening the valve reduces the pressure. The test facility has instrumentation for measuring the dynamic response of the specimen, which was used in the current test investigation. More information of the DRF features is outlined in Baskaran et al. [14].

2.2. Experimental Set-Up

The roof system components used in the current experimental study consisted of steel joists, vapour barrier, insulation board and waterproof membranes. However, the focus of the present study was to investigate the maximum deflection of the membrane. Other components were treated as dummy to form a complete roofing system. As shown in Figure 4 (Top left photo), a rectangular hole was created in the middle of one side of the roof mock-up in the insulation board to accommodate ultrasonic sensor to capture the membrane deflections. Three ultrasonic sensors were installed along the rectangular hole. Three different sizes of waterproof membrane, 610 mm x 610 mm (2 ft x 2 ft), 1219 mm x 1219 mm (4 ft x 4 ft) and 1829 mm x 1829 mm (6 ft x 6 ft), were used. The membranes were categorized as reinforced Polyvinyl chloride (PVC) with the thickness of 1.14 mm (0.045 in) and having modulus of elasticity (E) of 300 Mpa (6265630 psf). The membranes were cut to the indicated sizes and placed on top of the insulation boards, and attached using metal battens and fasteners. This arrangement provided continuous support condition along the edges of the membranes. The top right photo of Figure 4 shows typical membrane layout attachment at the middle of the DRF table. Figure 4 also shows the detail arrangement and location of the three ultrasonic sensors that were used during the test. The

X and Y- axis represent the position of the ultrasonic sensor in terms of length and width positions of the DRF table respectively with the centre of the membrane placed at the centre of the DRF table. The ultrasonic sensor positions in terms of X and Y- axis for the three different sizes of the membranes used are summarized at the bottom of Figure 4.

2.3. Test Pressure Selection and Testing Procedure

Wind pressure loading on building envelopes are normally determined based on one or more of the following:

- Code recommendation
- Wind tunnel experiment
- Full scale measurement
- Computational Simulations.

The present study uses neither of those due to the fact that:

1. One of the purpose of this paper is to compare the data from a 3D finite element model with that of the 2D model developed by Shi et al. [6]. Therefore, the pressure levels were maintained similar to that of the Shi et al model.
2. To ensure that the pressures applied during the experimental testing will be within the elastic range of the simulated PVC membrane.

A test pressure of $9.57\text{E-}04$ Mpa (20 psf) was selected and a simplified form of CSA A123.21-04 dynamic wind testing procedure [15] was used by applying 10 gusts for each level. Thus the two numerical models as well as experimental testing were based on uniform static pressures that were simultaneously applied over the surface of the

membrane. Therefore, dynamic effects due to flow similar to the one that can be developed under boundary wind tunnels, effects of roof location and surface area were neglected. During the experiment, continuous time history of the membrane deflections corresponding to each pressure levels were measured and recorded. This facilitate simplification of variables involved and be able to compare deflection results obtained from 2D model against the 3D-FE model as well with the experimental data.

2.4. Experimental Results

Figure 5 shows the typical membranes ballooning condition during testing. The two photos show the ballooning condition for the 1829 mm x 1829 mm (6 ft x 6 ft) membrane size at the pressures of 2.39E-04 Mpa (5 psf) and 9.57E-04 Mpa (20 psf). The membrane deflections obtained from the test performed are plotted in Figure 6. The Y-axis describes membrane deflections and the X-axis provides the distance ratio of the ultrasonic sensor location to the membrane length. For example, the X-axis for the top graph (Fig. 6) illustrates the position of the ultrasonic sensor D-1 (Refers to Figure 4) was 305 mm (12.12 in) from the edge of the membrane. This number (305 mm) was divided by 610 mm (2 ft-membrane width), which gives a ratio of 0.5 in a normalized scale plotted at the X-axis. Following the same concept, the membrane deflections for D-2 and D-3 were also plotted. Detailed results of the membrane's deflection for the other membrane sizes, 1219 mm x 1219 mm (4 ft x 4 ft) and 1829 mm x 1829 mm (6 ft x 6 ft) were also plotted in the Figure 6. The maximum deflections obtained from testing the three different membrane sizes are summarized in Table 1.

3. Numerical Models Used for the Study

A simplified mechanic-based model developed by Shi et al. [6] was selected for the comparative exercise. Summaries of Shi's approach as well as predicted results correspondences to the current experimental program are presented in this section. In addition, a 3D-FE model was developed using commercially available finite element software (ABAQUS) to predict membrane deflections. The modeling details such as mechanical properties, boundary conditions and technique used for the simulation are also presented.

3.1. Two Dimensional (2D) Mechanic Model

Shi et al. [6] concluded that wind induced ballooning of certain two-dimensional membranes in building enclosure systems, such as in a wall system can be modeled as a second order parabola. By adopting this assumption, the maximum deflection of a membrane ballooning can be obtained and the relationship between the related variables is expressed in this following equation,

$$\frac{l(8Eth - pt^2)}{64Eth^2} \left[\ln \left(\frac{4h}{l} + \sqrt{\frac{16h^2}{l^2} + 1} \right) + \frac{4h}{l} \sqrt{\frac{16h^2}{l^2} + 1} \right] - 1 = 0 \quad (1)$$

Where:

l is the distance between supports,

t is membrane thickness,

E is membrane modulus of elasticity,

h is the membrane deflection and

p is the applied pressure.

In order to establish the 2D mechanic-model presented in the Equation 1, Shi et al. [6] conducted an experiment to compare the model deflection on a wall system. Figure 7 illustrates the Shi et al. [6] test set-up, as well as, its cross-section diagram which is shown by the left side photo, while the plotting curve on the right side of Figure 7 gives the results obtained from the test, as well as, from the 2D-model prediction. The X-axis represents the distance of deflection measured from the 2D strapping and the Y-axis represents the magnitude of the deflections. The test set-up by Shi et al. [6] was to predict the membrane deflections in a wall system. However, the current test set-up (Figure 4) represents the membrane deflection condition of a-mechanically attached roofing systems when subjected to wind pressures.

Using the Equation 1, the present study calculated the maximum deflections corresponding to the present test set-up parameters. Information needed in order to use Equation 1 was extracted from the experimental program section. The results of those calculated deflections are summarized in Table 2.

3.2. Three Dimensional Finite Element (3D-FE) Model

3D-FE Models for three different sizes of membranes were developed, aided by ABAQUS version 6.6-1 [16]. The models were assumed to be 3D- Linear Elastic model that consists of membranes and fasteners. The membranes were modeled as a shell type element (S4R) with a shell thickness of 1.143 mm (0.045 in). This shell element was modeled as a homogeneous elastic isotropic material that was restrained at two supports that were assumed to be fixed, while the other two supports were released (Figure 8). The mechanical properties of the membranes used are: Modulus of elasticity, E (300 MPa) and

Poisson's ratio ν (0.4), [7]. The fasteners around the membrane edges were modeled as spring type elements having a stiffness of 20 N/mm [4], placed at a distance of 305 mm (12 in) and having three degrees of freedom (Rotation X, Y, Z). The total number of springs used for the 610 mm x 610 mm (2 ft x 2 ft), 1219 mm x 1219 mm (4 ft x 4 ft) and 1829 mm x 1829 mm (6 ft x 6 ft) membrane sizes were 8, 16 and 24 respectively. The loads were applied to the model as uniform static pressures starting at 2.39E-04 MPa (5 psf) to 9.57E-04 MPa (20 psf) with increments of 2.39E-04 MPa (5 psf), which give a total of four steps to the model. Each step has initial increment size of 0.01 with a minimum of (1E-05) and a maximum of (1).

Figure 9 shows un-deformed 3D-FE model meshing layout. The shell size in the model was designed bigger than the original size by approximately 92903 mm² (1 ft²). This condition was taken to reflect the experimental test set-up as shown in Figure 4. Total numbers of nodes are 121, 289 and 1849 for 610 mm x 610 mm (2 ft x 2 ft), 1219 mm x 1219 mm (4 ft x 4 ft) and 1829 mm x 1829 mm (6 ft x 6 ft) membrane sizes respectively. This was based on a mesh sensitivity study carried out for the 610 mm x 610 mm (2 ft x 2 ft) membrane size as described below.

Mesh sensitivity study has been performed on the 3D-FE model to verify that all deflection results obtained from the finite element modelling simulations are mesh-independent. Since all 3D-FE models used the same size of mesh, the mesh sensitivity study was being performed only for the 3D-FE model using 2 ft x 2 ft membrane. Changing the mesh size means changing the number of element for the 3D-FE model. For the purpose of this verification, the number of element (3D-FE model - 2ft x 2 ft membrane) was

reduced to approximately 0.5, 0.75 from the optimized number of element. Similarly, number of elements was also increased to 1.25 and 1.5 times. By changing the numbers of elements (mesh size) and by maintaining other parameters constant, simulations were performed. Figure 10 illustrates that the deflection results depend on mesh size when the numbers of elements were reduced to 0.5 and 0.75 times from the original number of element . From the figure 10, it is clear that the mesh independency has been achieved using the mesh size of 100 and further increase in numbers of elements to 1.25 and 1.5 times were not significantly influencing the computed membrane deflections. Based on this mesh sensitivity verification, it has been concluded that further 3D-FE model simulation can use the same mesh size as for the 2ft x 2ft membrane model.

Figure 11 illustrates a typical deformed contour plot of the membrane when it is subjected to a pressure of $7.18\text{E-}04$ MPa (15 psf). The three photos in Figure 11 represent the three different membranes sizes. The legend on the left side of the photo shows the magnitude of the deflection obtained from the model according to the area viewed from a plane 3-direction. Three viewing planes (1, 2, and 3) are used as indicated in Figure 11. The magnitude of the differences in the membrane deflection is illustrated by different contour colours that are nominally defined by the number (mm) in the legends, at the left side of the photos (Figure 11). For the example, in the top left corner of Figure 10, the maximum deflection obtained for the 610 mm x 610 mm (2 ft x 2 ft) membrane due to $7.18\text{E-}04$ Mpa (15 psf) pressure is 35.25 mm (1.38 in). The maximum deflections of the membrane obtained from the 3D-FE models for the four different pressures applied on three different membrane sizes are summarized in Table 3.

4. Models Validation with Benchmark Data

This section presents the validation for the mechanic models using the present benchmark experimental data. The validation of the mechanic models is illustrated in terms of deflection ratio. This ratio was established by dividing the maximum membrane deflection obtained from the model prediction with that obtained from the experimental program. If the deflection ratio is:

- Equal to one, then the corresponding model correlates well with the experimental data (shown as equal line in figures).
- Less than one, then the corresponding model under estimates the membrane deflection.
- Greater than one, then the corresponding model over estimates the membrane deflection.

For example, in Figure 11, the deflection ratios obtained by the 3D-FE model to the benchmark experimental data for the membrane size of 610 mm x 610 mm (2 ft x 2 ft) are 0.96, 0.98, 0.97 and 0.98 respectively for the pressures of 2.39E-04 MPa (5 psf), 4.78E-04 MPa (10 psf), 7.18E-04 MPa (15 psf) and 9.57E-04 MPa (20 psf). These ratio values indicate that the 3D-FE model predicts well the maximum membrane deflections. Membrane deflection ratios were also calculated using Equation 1 [6] and presented in the Figure 11. It is clear that Equation 1 under estimates the membrane deflections. Following the same procedure, the membrane deflection ratios for the membrane sizes of 1219 mm x 1219 mm (4 ft x 4 ft) and 1829 mm x 1829 mm (6 ft x 6 ft) were calculated, and the results are presented in Figure 12 and Figure 13 respectively.

As shown in Figures 12 and 13, the deflection ratios of mechanic models in comparison to the experimental data were found to be less than one (< 1) in which it explains that the predictions of the membrane deflection from Equation 1 of the mechanic model is conservative. Other interesting observation was that the maximum membrane deflections ratio obtained using Equation 1 for 610 mm x 610 mm (2 ft x 2 ft) membrane sizes were found to be more conservative compared to that of 1219 mm x 1219 mm (4 ft x 4 ft) and 1829 mm x 1829 mm (6 ft x 6 ft) membrane sizes. In comparison, the deflection ratios obtained from Equation 1 were approximately 50% - 60% lower than the experimental data. This phenomenon indicates that Equation 1 is less accurate when used to predict maximum membrane deflection if the membrane size is less than 1219 mm x 1219 mm (4 ft x 4 ft). Results showed that the 3D-FE model compares well, irrespective of the membrane size and the pressure levels. It explains that the 3D-FE model predicts well the maximum membrane deflection for mechanically attached roofing systems compared to that of existing mechanic model (Equation 1). Based on the current study, it is recommended that Equation 1 be used only for predicting deflections, if the membrane size is greater than 1829 mm x 1829 mm (6 ft x 6 ft).

5. Conclusions

Characterizing the membrane deformation under wind uplift pressure can be used as a parameter for designers to determine the induced forces on the fasteners in a mechanically attached roof system. This paper presented data from benchmark experiments carried out to validate the finite element model that can predict the membrane deflections. Experimental data are also used to evaluate the validity of the existing 2D mechanic model (Equation 1).

From this comparative exercise, as an alternate to a more comprehensive finite element model, designers can use the Equation 1 to predict the membrane deflections for membrane sizes up to 1829 mm x 1829 mm (6 ft x 6 ft). Whereas in the present study the 3D-FE model overcomes this limitation. Nevertheless, the 3D-FE model requires validation with experimental data for its applicability towards time varying pressure fluctuations and this research is in progress.

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