BUILDING CODES QUEENSLAND

Investigation on Wind Loads Applied to Solar Panels Mounted on Roofs

Report No. TS821

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EXECUTIVE SUMMARY

This study was commissioned to investigate the wind loading applied to photovoltaic solar panels mounted on roofs. It was undertaken to determine the wind pressure coefficients that apply to solar panels mounted on the roofs of residential (Part A of the study) and commercial (Part B of the study) buildings in Australia. It has been prepared in response to concerns about the structural integrity of their installation on a roof to withstand high wind loads during a cyclonic event.

The installation of solar panels will alter the air flow and influence the wind loads acting on the supporting building surface near the panels. The air flow over the panels and through the gaps influences the load on the panel. Net pressures acting on the panel system are transmitted to the roof structure via the fixings (typically brackets and rails or racking frames).

A literature review of readily available data on wind loading design parameters used for solar panels on mounted roofs was initially conducted. This study indicated that there was limited information relevant to wind loads on photovoltaic installations. Then a wind tunnel study was performed to measure the wind pressure coefficients that apply to typically installed photovoltaic solar panel systems mounted on the roof of residential and commercial buildings. The results are presented in a form consistent with the wind loading standard, (AS/NZS) 1170.2: 2011.

In Part A of the wind tunnel study, three gable-end roof model buildings with 7.5°, 15° and 22.5° roof slopes were tested in a boundary layer flow. Tests were carried out, firstly on a baseline building (no panels fitted) and then with an array of panels fixed at a range of locations on the roof and fixed parallel to the roof surface with two gaps (100 mm and 200 mm) between the roof and the underside of the panel array. The effect of roof slope, panel location on the roof, gap between the roof and the panels, and the influence of the addition of an immediately adjacent second array were studied.

The results for Part A show that:

- The measured external pressures on the baseline (no panels fitted) building roof with slopes of 7.5°, 15° and 22.5° were similar to the data in AS/NZS 1170.2. The largest negative pressures occur near the leading edges of the roof and the ridge-line on higher pitch roofs.
- When panels are located near the leading gable end of the roof, these panels experience negative net pressures similar to the external pressure on that part of the roof. The largest peak negative (uplift) aerodynamic shape factor measured for these panel locations was -1.7.
- Panels located in the central part of the roof can experience net pressures that are larger than the external pressure on the corresponding part of the roof without solar panels. The largest net aerodynamic shape factors measured for these panel locations were -1.2 and +0.5.

In Part B of the study, the wind loads on a baseline (no panels fitted) building with a flat roof were measured. Following this measurements were taken with an array inclined at 15° and 30° to the horizontal and fixed on various positions of the roof. The results for this part of the study indicate that:

- The measured external pressures on the flat roof baseline building are similar to the pressures given in AS/NZS 1170.2. The largest suction pressures occur near the leading edges of the roof.
- When panels are located on the roof with an orientation such that the wind flows towards the downward inclined face of the array, large net positive and negative design pressures are generated on the panel array.
- Panels with an inclination of 30° experience the largest peak negative and positive pressures.

Net pressure coefficients for the panel and building configurations investigated in this study are presented in a similar format to that used in AS/NZS 1170.2. The study identifies pressure coefficients that can be used to design panels and their structural support systems to withstand the expected wind loads.

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1. INTRODUCTION

The Cyclone Testing Station (CTS) at James Cook University was commissioned by Building Codes Queensland (BCQ) to determine the wind pressure coefficients that apply to solar panels mounted on the roofs of residential and commercial buildings.

Pressure coefficients for calculating wind loads are currently available in AS/NZS 1170.2 [1] and AS 4055 [2] for building design, in accordance with the National Construction Code of Australia (NCC) [3]. However, structural wind load design data on roof mounted solar panel systems are not available, which makes it difficult to design systems that are both safe and economical. This study aims to produce pressure coefficients that apply to roof mounted panel systems typical of those used in Australia. These coefficients will also be submitted for consideration and possible inclusion in AS/NZS 1170.2, so that this data is readily available to designers.

The study consists of:

- a literature review and desk-top study to identify any readily available data on wind loading design parameters for solar panels mounted on roofs and
- a wind tunnel study conducted, in two parts:
  Part A – Residential Buildings: investigated the wind loads applied to solar panels that are installed parallel to a range of pitched gable roofs of residential buildings, typical of detached residential houses, (Class 1 and Class 10 buildings as defined by the NCC).
  Part B – Commercial Buildings: investigated the wind loads applied to solar panels fitted at inclined angles to a flat roof of a buildings, more typical of commercial applications, (Class 5 to 9 buildings as defined by the NCC).

2. LITERATURE REVIEW

Structural design wind load data for solar panel systems installed on buildings is scarce, and in many cases, assumptions (based on data on the building or from similar shapes) are made when calculating wind loads on solar systems.

Recent studies have addressed some of these limitations by deriving wind loads on a range of panel configurations and arrangements. Studies by Wood et al [4], Stenabaugh et al [5] and Ruscheweyh and Windhovel [6] etc have provided some limited data that could be developed in a codified form. Wood et al [4] studied the loads on panels mounted parallel to a flat roof and extending over the whole roof. They found large wind loads at the leading edge, and significantly lower loads elsewhere. Ruscheweyh and Windhovel [6] showed that numerous parameters affect the wind load applied on inclined panels located on a flat roof. They found that only panels close to the edge of the roof experience large loads.

A survey and calculation method based on British Standards has been produced by the Building Research Establishment of the U.K. (Blackmore, [7]). However, the Building Research Establishment Digest also stated that, “There is very little information and no authoritative guidance about wind loads on roof based photovoltaic (PV) systems…”.

A report from Virginia Tech University in the United States (Tieleman *et al.*, [8]) did provide reasonably comprehensive data for wind loads on solar panels mounted parallel to roofs. This provides some indication of the probable magnitude of pressure coefficients by stating that:

"For the common situation of panels mounted parallel to roofs, the upper surface of the solar panel array will experience similar pressures to an equivalent roof cladding upper surface in the same location. The net pressures across a solar panel array will not be the same as the net pressures across the adjacent roof surface, since the solar panel array has two sides exposed to wind flow. This is unlike the roof cladding which has one external side exposed to wind flow pressures, and one internal side exposed to building internal pressures."

"Net wind loads on solar panels attached parallel to roofs can, to a first approximation, be estimated from the external roof pressure coefficients in codes and standards. Some previous studies have shown that some pressure equalization can occur across the solar panel depending on the panel offset distance. Roof aerodynamic shape factors (including local pressure factors , K_l as appropriate) may be applied to determine solar panel net pressure coefficients for typical cases, where the solar panel arrays are mounted parallel to, and between 50 and 150mm above, the plane of the roof surface" according to the Virginia Tech study.

"The possibility exists that a solar panel located close to the edge of a roof may affect the wind flow over the roof itself, and possibly increase the wind loads on the roof; it is therefore advisable not to mount panels close to a roof edge if possible."

These previous international studies give some indication of the anticipated magnitude of pressures applying to solar panels installed on residential and commercial roofs. One clear indication is that the net pressure on panels installed parallel to the roofing plane may be similar to the pressure that would apply to the upper surface of the roof prior to the installation of the panels, including any local pressure factors that may apply.

While this information provides useful guidance for any further study, it is not sufficiently comprehensive as it does not determine the wind pressure coefficients for typical Australian installations.

3. TYPICAL AUSTRALIAN SYSTEMS

A typical type of solar panel system used in Australia is an array of panels attached to support rails that align with roofing battens on domestic houses. Here the rails are screwed to the battens or trusses thus sandwiching the roof cladding. Individual panels (nominally 1.7m × 1.0m) are often fixed to the rails with a series of brackets, as shown in Figure 1. The panels are parallel to the corresponding roof surface and form a gap between the rails that provide blockage between the roof and the underside of the panel. A larger gap is formed when brackets are used to stand the panels on the rail which also provides more space for venting above the rails. The gap could typically vary from about 75mm to 300mm.

Figure 1. Typical layout of solar panel arrays on the roof of houses and structural support system for solar panels mounted parallel to pitched roofs

On flat roof commercial type buildings, arrays of panels are installed on racks at an angle of typically between 15^{o} and 30^{o}.

The installation of solar panels will alter the air flow, and influence the wind loads acting on the building. The air flow over the panels and through the gaps influences the load on the panel. Net pressures acting on the panel system are transmitted to the roof structure via the fixings (brackets and railing). The changes to the wind loads on the roof of the building and the net loads on the solar panels must be analysed to determine the effect of the solar panels on the building's structural system. Partial equalisation of pressures acting on the building roof with that on the bottom of the solar panel may tend to minimise the overall changes in load experienced by the roof structure.

4. WIND TUNNEL STUDY

The study, carried out in two parts, (Part A – Residential Buildings and Part B – Commercial Buildings), quantifies the wind loads acting on solar panels and their effect on the building. Wind tunnel tests were conducted to establish pressure coefficients, in a form consistent with AS/NZS 1170.2 [1]. The measured pressure coefficients can be combined with the design wind speed for a given location to obtain the net design pressure on the solar panels and the external design pressure on the roof of the building.

Wind tunnel studies using scale models of buildings and panel arrays were carried out in the 2.0m high, 2.5m wide, 22.0m long boundary layer wind tunnel in the School of Engineering & Physical Sciences at James Cook University. An approach atmospheric boundary layer flow representing an open terrain, as defined in AS/NZS1170.2 [1], was simulated at a length scale of 1:20 over the fetch by using a 250mm high trip-board at the upstream end followed by an array of blocks on the tunnel floor. The range of building types (with solar panels attached and without) were constructed at a length scale of 1:20 and tested in this flow. A model scale solar panel thickness of about 5 mm was required to accommodate the overlapping tubes that were used to measure net pressures across the panel. This set-up satisfactorily represents typical full scale panels, and the flow over the roof surface as well as the gap between the roof surface and panels.

External pressures were measured on the roof of the buildings for approach wind directions $\theta = 0°$ to $360°$ in steps of 15° intervals, for the building without solar panels ("baseline" building). Tests were repeated with solar panel arrays at each of the nominated locations, and the external pressures on the roof surface and the top and bottom surfaces of the solar panels were measured. Pressure taps in each case were connected to a transducer using a tubing system. The fluctuating pressures, *p(t)* were sampled at 1250 Hz for 30 seconds and presented as pressure coefficients $C_p(t) = p(t) / \frac{1}{2}\rho\overline{V}_h^2$. These pressure coefficients were statistically analyzed to get mean ($C_{\bar{p}}$), maximum ($C_{\hat{p}}$) and minimum ($C_{\breve{p}}$) pressure coefficients in a single run;

$$C_{\bar{p}} = \frac{\bar{p}}{\frac{1}{2}\rho\overline{V}_h^2}, \quad C_{\hat{p}} = \frac{\hat{p}}{\frac{1}{2}\rho\overline{V}_h^2}, \quad C_{\breve{p}} = \frac{\breve{p}}{\frac{1}{2}\rho\overline{V}_h^2} \tag{1}$$

where $\frac{1}{2}\rho\overline{V}_h^2$ is the mean dynamic pressure at mid roof height *h*. Three runs were conducted for each approach wind direction to obtain repeat sets of pressure coefficients.

The mean and peak (i.e. maximum and minimum) pressure coefficients presented in the study are the averages from the repeat runs. Area-averaged net pressure coefficients on each 1.7m × 1.0m panel were obtained by combining the simultaneous pressures on all taps within each panel. The net (i.e. (top-bottom)) pressure coefficients, C_{pn} across the solar panels were also derived.

Wind loads for the design of structures and cladding are usually calculated from pressures derived from nominal shape factors or pressure coefficients, provided in AS/NZS 1170.2. The external design pressures are calculated from Equation 2, where ρ is the density of air, and $C_{fig} = C_{p,e}(K_a \times K_c \times K_l \times K_p)$ is the aerodynamic shape factor. The quasi-static external and net pressure coefficients, $C_{p,e}$ and $C_{p,n}$ respectively are obtained from Section 5, and Appendix C in AS/NZS 1170.2. K_a, K_c, K_l and K_p are factors for area-averaging, load combination, local-pressure effects, and cladding permeability. The dynamic response factor C_{dyn} is taken equal as 1.0 for these types of structures, and V_h is the peak design gust wind speed at mid roof height.

$$p_{design} = 0.5\rho V_h^2 C_{fig} C_{dyn} \qquad (2)$$

These design external (or net) pressures derived from AS/NZS 1170.2 can be equated to the values obtained from the wind tunnel tests as shown in Equation 3, where $\overline{V}_h$ is the mean wind speed at mid-roof height.

$$p_{design} = 0.5\rho V_h^2 C_{fig} = 0.5\rho \overline{V}_h^2 C_{peak} \qquad (3)$$

The effective shape factors can be calculated in a form consistent with AS/NZS 1170.2 as $C_{peak} / G_U^2 = C_{fig}$. Here, $G_U = (V_h / \overline{V}_h)$, is the velocity gust factor, or the ratio of the gust wind velocity to the mean wind velocity at the reference mid-roof height. From the 1989 version of AS 1170.2, G_U ranges from 1.65 for h = 10m to 1.8 for the domestic houses.

4.1 Part A – Residential Buildings

The study investigated the influence of roof slope, solar panel position, size of panel array, approach wind direction, and the gap between the panel and the roof surface.

The wind loads on solar panels mounted parallel to the gable roof of houses with slopes of 7.5°, 15° and 22.5° were determined in the wind tunnel study in Part A, using 1:20 scale models intended to represent typical low, medium and high roof pitch Australian houses. The houses modelled have plan dimensions of 10m × 21m, an eaves height of 2.7 m. A total of 32 taps were installed on the roof surface of the models, as shown in Figure 2, to measure external roof surface pressures.

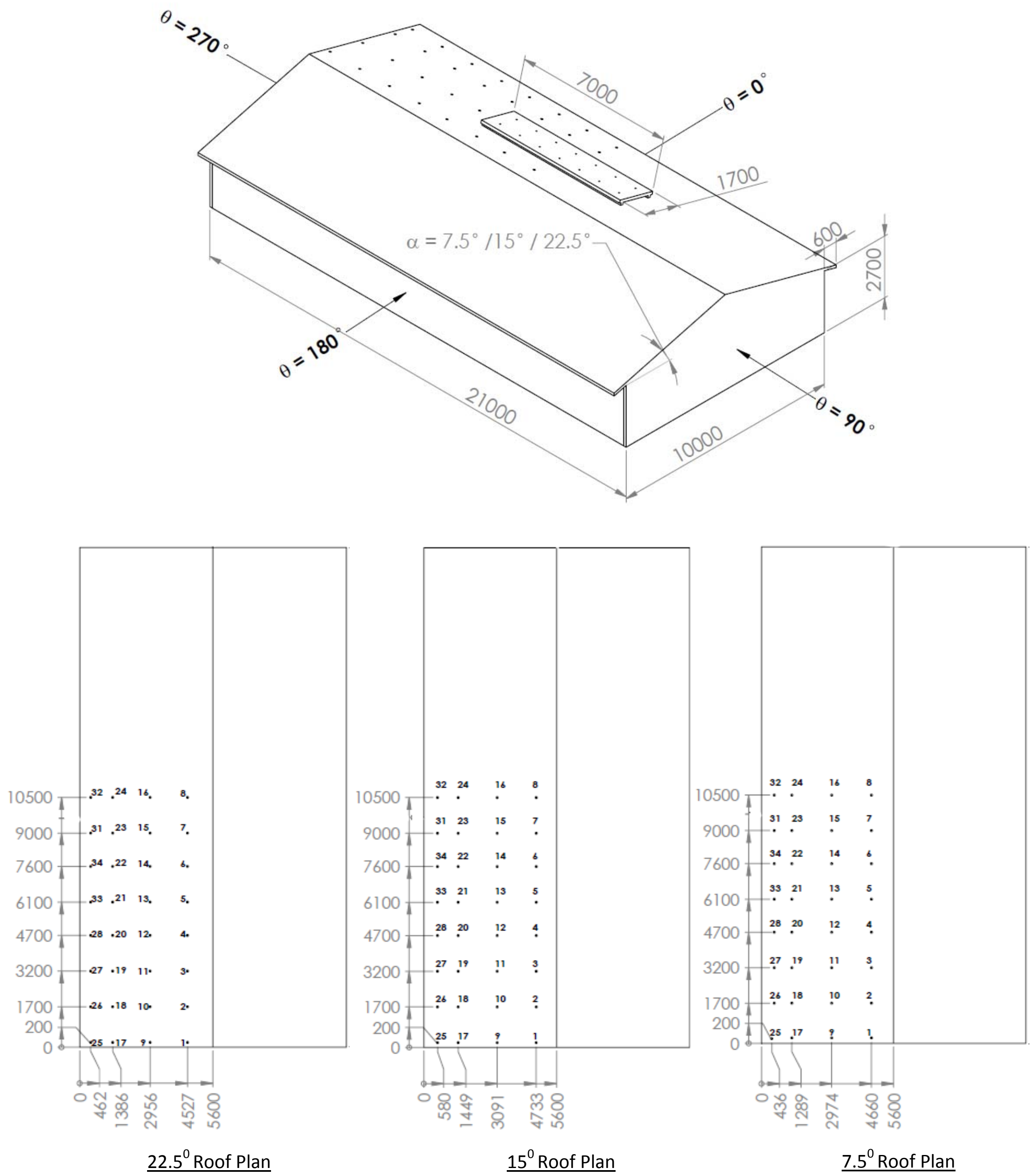


Figure 2. 10m × 21m × 2.7m low medium and high, roof pitch gable end houses showing pressure tap locations for Part A of project.

The solar panel system was modelled as an array consisting of seven panels, each with full-scale dimensions of 1.7m × 1.0m. A configuration of the panels (one panel deep by seven panels long, 1 × 7) forming an array of 1.7m × 7.0m was tested in six positions on the roof, identified as A, B, C, D, E and F, as shown in Figure 3.

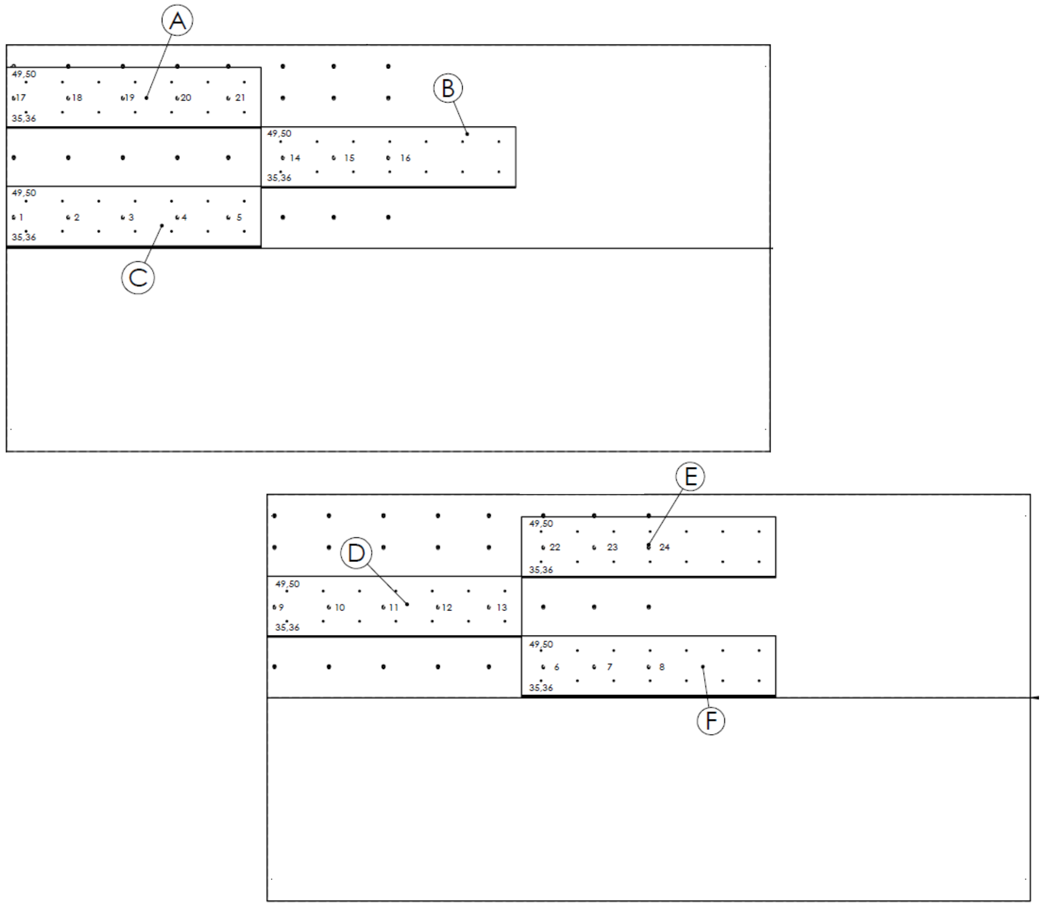


Figure 3. Locations of 1 ×7 solar panel arrays on the roof of buildings for Part A of project.

To investigate the effect of panel array size, studies were also performed using an array that was twice the area, which is a 2 × 7 configuration of the panels forming an array of 3.4m × 7.0m. This was tested in four positions on the roof, identified as A-d, C-d, B-e and B-f, as shown in Figure 4.

Note that the additional configuration of a bank of 1 × 7 panels was a "*Dummy Panel*" and was not fitted with pressure taps. The locations of this Dummy Panel have been identified by lower case letters "d", "e' and "f" in Figure 4.

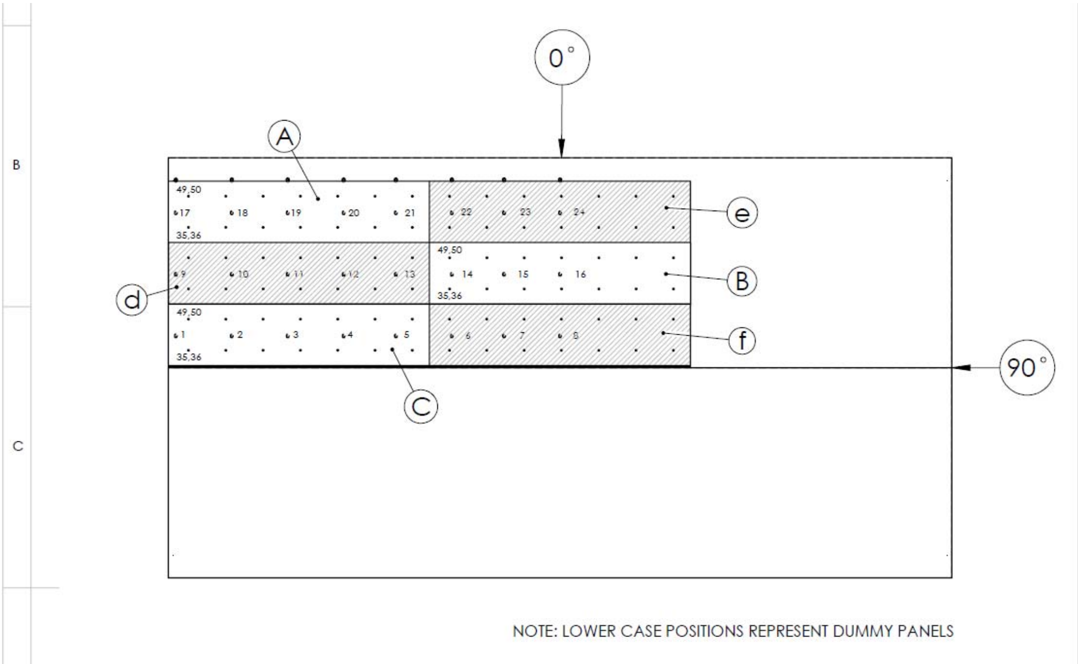


Figure 4. Locations of 2×7 solar panel arrays on the roof of buildings for Part A of project.

The support system was modelled, such that the panels were mounted onto rails fixed to the roof at a spacing of 1300mm. This allowed the PVC tubes used for pressure measurements to be connected to the transducers located below the wind tunnel via the support rail and brackets and slots on the roof. A total of 28 taps were installed on the top and bottom surfaces of the panel array as shown in Figure 5. Fourteen pressure taps to both the top and bottom panel surfaces of the 1×7 array aligned with each other (i.e. twenty-eight pressure taps in total) were used to obtain net (i.e. (top-bottom) pressure coefficients, C_{pn} on each 1.7m × 1.0m module.

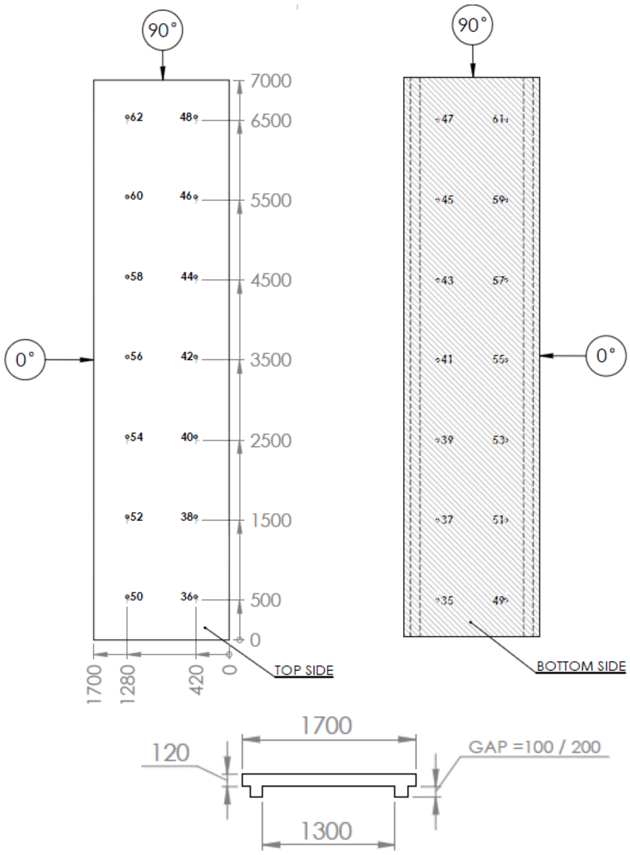


Figure 5. 1 × 7 module array and support system showing pressure tap locations on top and bottom surfaces

Figure 6 shows a solar panel array attached on a house model in the wind tunnel.

a) **b)**

Figure 6. a) 7.5° roof pitch base building model in the wind tunnel. b) 22.5° roof pitch building model with a 1×7 solar panel array located at position D, in the wind tunnel.

4.2 Part B – Commercial Buildings

Part B of this study investigated the influence of the panel slope and position on the wind loads applied to solar panels fitted at inclined angles to the flat roof of a commercial building, using a 1:20 scale model. The building modelled had a plan size of 12 m × 12 m and a height of 10 m, as shown in Figure 7.

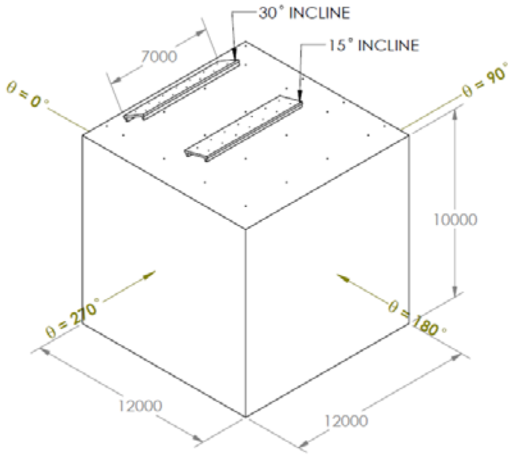


Figure 7. 12m × 12m × 10m Commercial building for Part B of project.

For Part B, the 1 × 7 panel was used, that is an array consisting of seven panels, one panel deep by seven panels long, with each panel having full-scale dimensions of 1.7m × 1.0m. This formed an array with a total plan size of 1.7m × 7.0m This one size of rectangular solar panel, of about 12 m^2 in area, was tested at two panel inclinations to the roof; 15° and 30°. Figure 5 shows the location of the twenty-eight pressure taps fitted to the solar panel array.

The panels were positioned at four locations on the roof, at the midline edge of the roof, adjacent to the corner of the roof (orientated in plan view, parallel to an edge and at 45° to an edge), the centre of the roof and adjacent to a corner, but parallel to an edge of the roof (positions A, B, C and D as shown in Figure 8). Twenty three pressure taps on the roof were used to measure the external surface pressures.

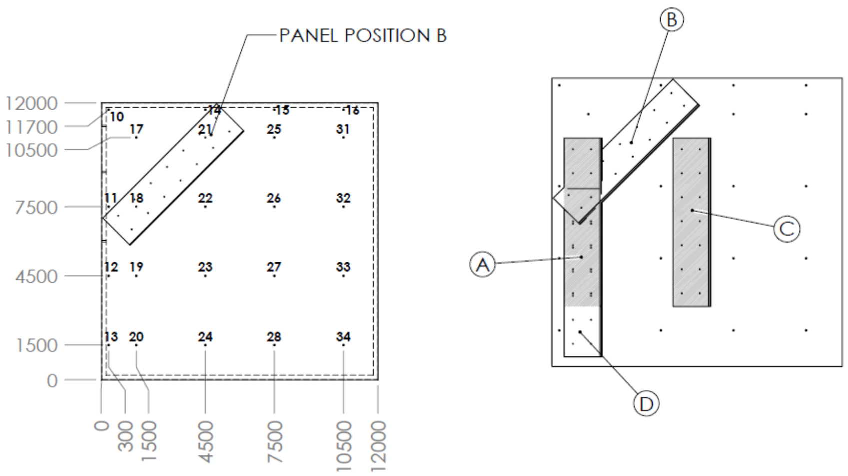


Figure 8. Inclined solar panels attached to a flat roof building showing pressure tap locations for Part B of project.

5. RESULTS AND ANALYSIS

5.1 Part A - Panels parallel to pitched roof- Residential Buildings

- **Results for all combinations**

For this part of the study, a total of 1440 different combinations were investigated. This involved two panel sizes, two gaps between the roof and the underside of the panel, three roof slopes and either six positions (for the single panel) or four positions (for the double panel) on the roof, with each of these combinations being run in the wind tunnel for twenty-four different wind directions, plus an additional 72 combinations for the three "Baseline" buildings without solar panels fitted. These results are presented in the form of mean ($C_{\bar{p}}$), maximum ($C_{\hat{p}}$) and minimum ($C_{\breve{p}}$) pressure coefficients, as defined in Equation 1 of Section 4. These results show that the net pressures on the panels are similar for gaps of 100mm and 200mm, and for 1 × 7 and 2 × 7 arrays. The external pressures on the surface of the building roof are influenced by the array of panels in its vicinity.

The results from all of these combinations are included in an addendum to the report, as the data is extensive. Table 1 provides a brief description of the number of pages (one page for each combination) used for the different arrangements reported in each Section of the addendum.

Table 1: Table of Mean and Peak Pressure Coefficients Presented in Addendum to Report for Part A-Residential Buildings

Section No.	Brief Description of Arrangement Reported in Each Section	No. of Pages
A	Single Array with 100 mm Gap - Mean and Peak C_ps and C_{pn}s	432
B	Single Array with 200 mm Gap - Mean and Peak C_ps and C_{pn}s	432
C	Double Array with 100 mm Gap - Mean and Peak C_ps and C_{pn}s	288
D	Double Array with 200 mm Gap - Mean and Peak C_ps and C_{pn}s	288
G	Baseline Building No Panels - Mean and Peak C_ps	72

- **Aerodynamic Shape Factors**

These results were then analysed to calculate the effective aerodynamic shape factors (C_{fig}), as described in Section 4. In order to consolidate the results from this analysis, critical values (maximum or minimum) from each of the twenty-four different wind directions were grouped into four main orthogonal directions, namely; $0^o \pm 45^o$, $90^o \pm 30^o$, $180^o \pm 45^o$ and $270^o \pm 30^o$.

The external aerodynamic shape factors on gable roof slopes of 7.5^o, 15^o and 22.5^o of buildings without solar panels ("baseline" buildings) for the ranges of wind approach directions $0^o \pm 45^o$, $90^o \pm 30^o$, $180^o \pm 45^o$ and $270^o \pm 30^o$ are shown in Appendix A (Figures A1, a-l).

The external aerodynamic shape factors on the roof of 7.5^o, 15^o and 22.5^o buildings with solar panels and the net aerodynamic shape factors on rectangular solar panel arrays of 1.7 m × 7.0 m mounted with a gap of 100mm, for configurations A, B, C, D, E and F for the ranges of wind approach directions 0 ± 45^o, 90 ± 30^o and 180 ± 45^o and 270 ± 30^o are shown in 72 diagrams in

Appendix A (Figures A2-7 a-l). These diagrams show the maximum and minimum aerodynamic shape factors (C_{fig}) acting on the external roof surface, with the dotted lines indicating the location of the solar panel array on the roof. Each diagram also includes two separate plan views of the 1.7m × 7.0 m solar panel arrays to show the minimum and maximum net aerodynamic shape factors ($C_{fig,n}$) acting on seven panels along the array. Note that upwards values for the net aerodynamic shape factor ($C_{fig,n}$) applied to the panels are shown as negative (as they act in a direction away from the top surface).

The approach wind directions between 240° and 300° (i.e. direction ~ parallel to the ridge-line) generate large net suctions on the leading module of the array, especially when it is located close to the gable edge (i.e. positions A, D and C). These wind directions may also generate net downwards pressures on the surface of building roof. Panels on the internal part of the roof generally experience lower positive and negative net pressures.

- **Recommended Net Aerodynamic Shape Factors Applicable for Solar Panels**

All of the data from Part A of this study has been analyzed to determine the wind loading parameters that are applicable for any of the solar panel configuration investigated in this study. For simplicity, each half of the roof (either side of the ridge-line) has been sub-divided into thirds. Then the critical (both minimum and maximum) net aerodynamic shape factors ($C_{fig,n}$) that are applicable for solar panels located in each area, for each of the three roof slopes, have been determined.

These values have been consolidated into maximum and minimum values that are applicable for the two orthogonal design wind directions, which is wind blowing within a sector of ± 45° in directions parallel to the ridge and perpendicular to the ridge of the gable roof building. These values are summarized for three roof slope ranges (α) in Figures 7 to 9. This summary is recommended for inclusion in a standard such as AS/NZS 1170.2. As shown in these figures, the largest net negative (uplift) aerodynamic shape factor is -1.7.

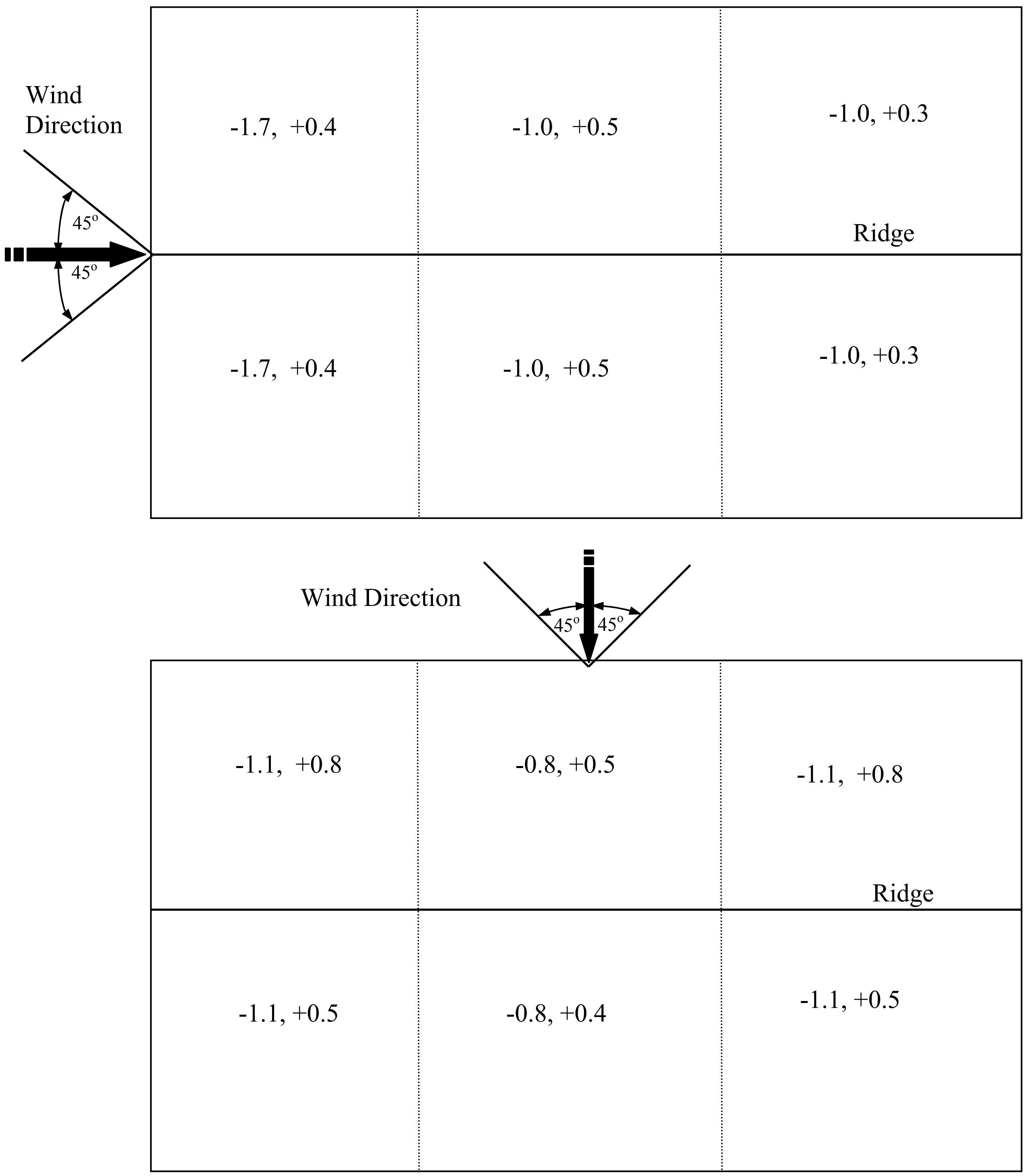


Figure 7. Suggested net aerodynamic shape factors ($C_{fig,n}$) for Panel array on Low Pitch roof ($\alpha \leq 10^o$)

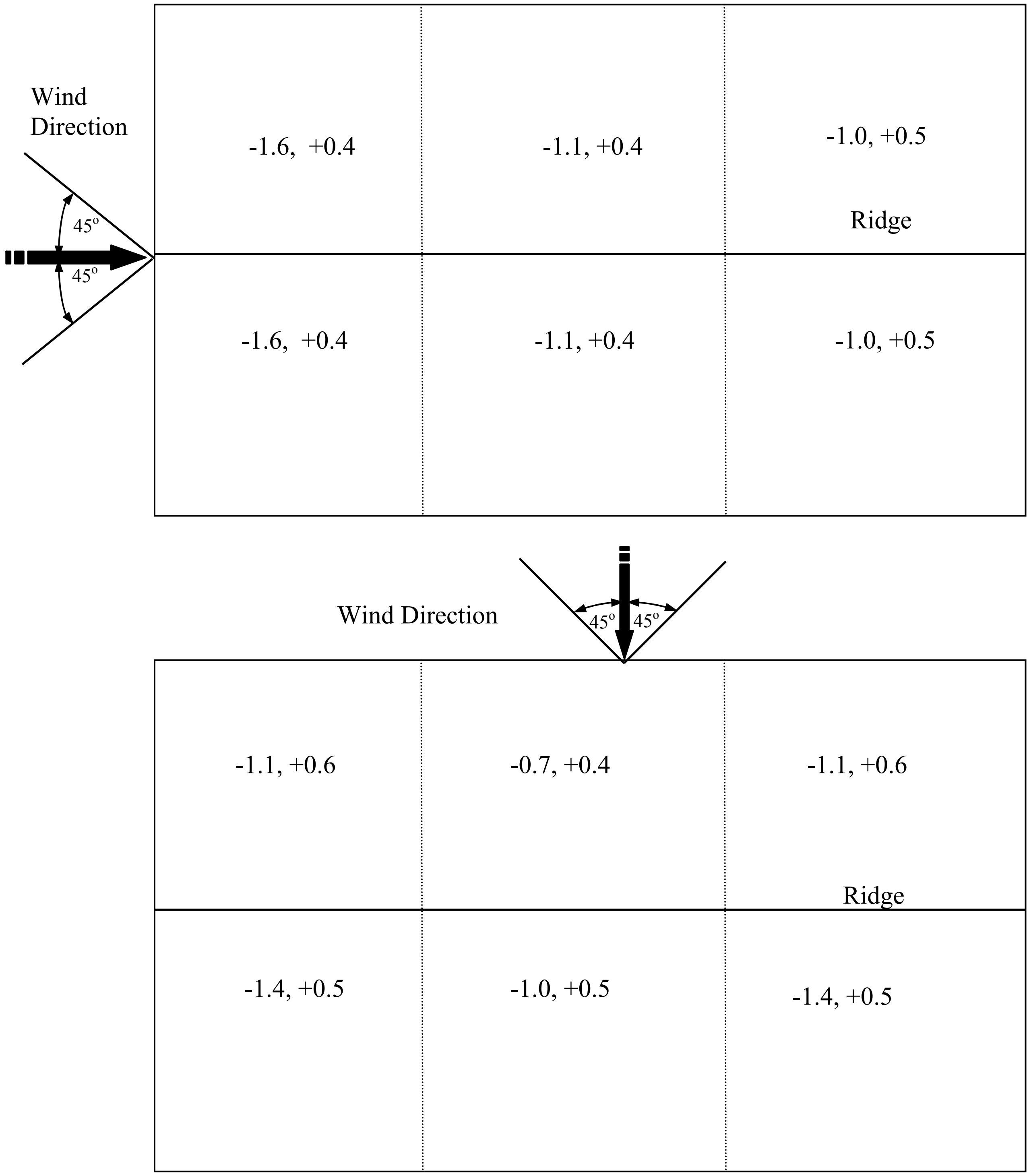
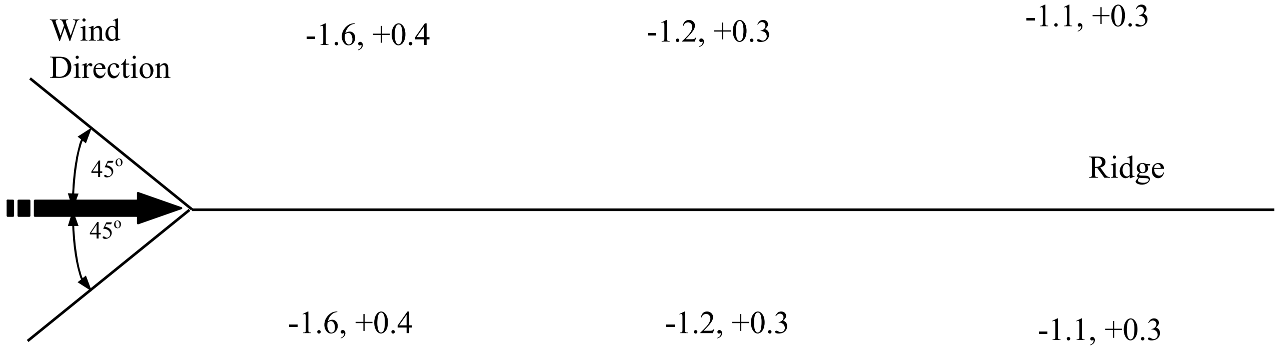


Figure 8. Suggested net aerodynamic shape factors ($C_{fig,n}$) for Panel array on Medium Pitch roof ($10^o \leq \alpha \leq 20^o$)



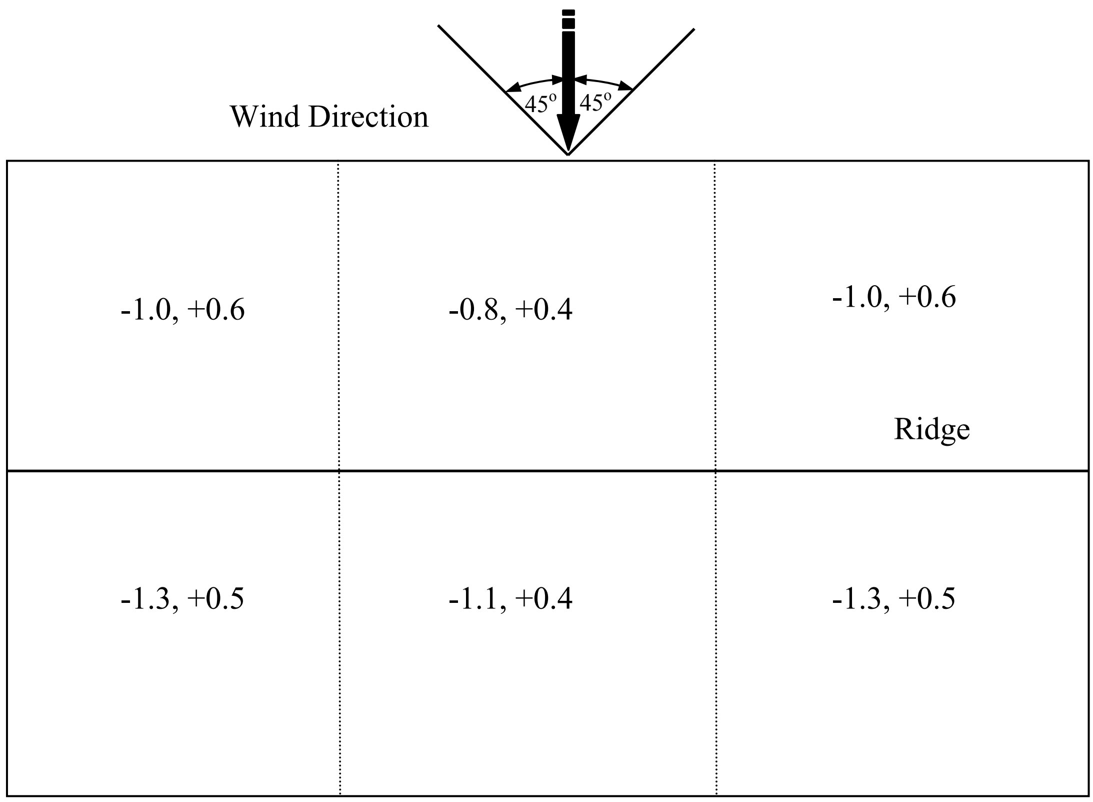


Figure 9. Suggested net aerodynamic shape factors ($C_{fig,n}$) for Panel array on High Pitch roof ($20^o \leq \alpha \leq 30^o$)

- **Sample design calculations**

Sample design calculations are included in Appendix B to demonstrate how design pressures on panel systems can be calculated using the information contained in this report, along with a knowledge of the design wind speed for a given location or range of locations. In Appendix B the net pressures across the panel array are compared to upper surface pressures on the roofs derived from AS/NZS 1170.2. This information is useful in determining the next steps in simplifying the process of designing panel systems.

5.2 Part B - Panels inclined to a flat roof-

- **Results for all combinations**

For this part of the study, a total of 192 different combinations were investigated. This involved one panel size, two panel inclinations to the roof and four positions on the flat roof, with each of these combinations being run in the wind tunnel for twenty-four different wind directions, plus an additional 24 combinations for the "Baseline" building without solar panels fitted. These results are presented in the form of mean ($C_{\bar{p}}$), maximum ($C_{\hat{p}}$) and minimum ($C_{\breve{p}}$) pressure coefficients, as defined in Equation 1 of Section 4. These results show that the net pressures on the panels depend on the location and inclination of the array to the roof and the approach wind direction. The array that is inclined at 30^{o} to the roof is generally subjected to the largest negative peak pressure coefficients, when the array is located close to the windward edge of the roof for winds approaching towards its downwards inclined face. The array that is inclined at 30^{o} to the roof also experiences larger peak positive pressure coefficients compared to an array that is inclined at 15^{o} to the roof.

The results from all of these combinations are included in an addendum to the report, as the data is extensive. Table 2 provides a brief description of the number of pages (one page for each combination) used for the different arrangements reported in each Section of the addendum,

Table 2: Table of Mean and Peak Pressure Coefficients Presented in Addendum to Report for Part B – Commercial Buildings

Section No.	Brief Description of Arrangement Reported in Each Section	No. of Pages
E	Single Array with 15° Incline - Mean and Peak C_ps and C_{pn}s	96
F	Single Array with 30° Incline - Mean and Peak C_ps and C_{pn}s	96
H	Baseline Building No Panels - Mean and Peak C_ps	24

- **Aerodynamic Shape Factors**

Similarly to Part A, these results were then analysed and consolidated into four main orthogonal directions, namely; $0^{o} \pm 45^{o}$, $90^{o} \pm 30^{o}$, $180^{o} \pm 45^{o}$ and $270^{o} \pm 30^{o}$.

The external C_{fig}s on the flat roof of the building without solar panels (baseline building) for the ranges of wind approach directions 0° ± 45°, 90° ± 30°, 180° ± 45°, and 270o ± 30° are shown in Appendix C (Figures C1- a-d).

The external C_{fig}s on the flat roof building with solar panels and the $C_{fig,n}$s on rectangular solar panel arrays, of 1.7m × 7.0 m mounted with inclinations of 15° and 30° at positions A, B, C and D for the ranges of wind approach directions 0 ± 45°, 90 ± 30°,180 ± 45° and 270 ± 30° are shown in Appendix C (Figures C2-5 a-h).

The minimum values for these $C_{fig,n}$ values on the solar arrays are summarized in Table 3.

Table 3: Minimum Net Aerodynamic Pressure Coefficients on 1.7m × 7.0 m Solar Arrays

Panel Location	Panel Inclination	Minimum Net Aerodynamic Pressure Coefficient $C_{fig,n}$ on Array			
		0 ± 45°	90 ± 30°	180 ± 45°	270 ± 30°
A	15°	-0.82	-1.41	-1.72	-1.57
	30°	-0.66	-1.42	-1.60	-1.37
B	15°	-0.75	-1.29	-1.58	-1.31
	30°	-0.67	-1.72	-2.35	-1.61
C	15°	-0.86	-0.91	-1.69	-1.68
	30°	-1.02	-0.78	-1.43	-1.48
D	15°	-0.81	-1.46	-1.64	-1.23
	30°	-0.57	-1.67	-2.02	-0.94

The maximum values for these $C_{fig,n}$ values on the solar arrays are summarized in Table 4.

Table 4: Maximum Net Aerodynamic Pressure Coefficients on 1.7m × 7.0 m Solar Arrays

Panel Location	Panel Inclination	Maximum Net Aerodynamic Pressure Coefficient $C_{fig,n}$ on Array			
		0 ± 45°	90 ± 30°	180 ± 45°	270 ± 30°
A	15°	+1.01	+0.98	+0.37	+0.81
	30°	+1.14	+0.94	+0.34	+0.99
B	15°	+0.88	+0.69	+0.66	+0.70
	30°	+1.14	+0.96	+0.67	+0.91
C	15°	+0.67	+0.66	+0.59	+0.57
	30°	+0.91	+1.00	+0.64	+0.52
D	15°	+0.84	+0.76	+0.39	+0.90
	30°	+0.95	+0.90	+0.48	+1.16

These aerodynamic shape factors, $C_{fig,n}$s, along with the appropriate design wind speeds can be used by the method given in AS/NZS 1170.2 [1] to determine the design wind loads that will be applied to solar arrays.

6. CONCLUSIONS

A study was carried out to determine wind loads on roof-mounted photovoltaic solar panel systems. The study comprised of two parts: Part A - Panel arrays on Residential Buildings and Part B - Panel arrays on Commercial Buildings

In Part A, three gable-end 1:20 scale models with 7.5°, 15° and 22.5° roof slopes were tested in a boundary layer wind tunnel. Tests were carried out with an array of panels fixed at a range of locations on the roof and two gaps between the roof and the underside of the panel array. The impact of roof slope, panel array location on the roof, array size, gap of the panels above the roof surface, and the influence on wind loading due to the addition of the array were examined.

This first part of the study found that the wind loads on the panels were higher when the array is located at the gable-end edge of the roof and that the leading edge panel experiences the largest net upwards load. The gap between the array and the roof did not have a significant effect over the range studied, nor were the overall roof uplift wind loads significantly altered with the addition of the solar array.

The results for Part A show that:

- The measured external pressures on the baseline (no panels fitted) building roof with slopes of 7.5°, 15° and 22.5° were similar to the data in AS/NZS 1170.2. The largest negative pressures occur near the leading edges of the roof and the ridge-line on higher pitch roofs.
- When panels are located near the leading gable end of the roof, these panels experience negative net pressures similar to the external pressure on that part of the roof. The largest peak negative (uplift) aerodynamic shape factor measured for these panel locations was -1.7.
- Panels located in the central part of the roof can experience net pressures that are larger than the external pressure on the corresponding part of the roof without solar panels. The largest net aerodynamic shape factors measured for these panel locations were -1.2 and +0.5.

For Figures 7, 8 and 9, pressure coefficients are presented in a format similar to pressure coefficients for other elements in AS/NZS 1170.2. These pressure coefficients can be used to calculate the wind loads on the panels and the structural support system. It is intended that the pressure coefficients developed in this report will be submitted for inclusion in the next revision of AS/NZS 1170.2, to support the process of designing panels systems that are both safe and economical.

In Part B, a 1:20 scale model with a flat roof was tested in a boundary layer wind tunnel. Tests were carried out with an array of panels fixed at a range of locations on the roof and two inclinations to the roof. The impact of panel array location on the roof, and the inclination of the array, and the influence on wind loading due to the addition of the array were examined.

The second part of the study showed that the net loads acting on the array are influenced by the angle of inclination to the flat roof, and large net negative pressures are experienced on panels located near the windward roof edge when the flow is directed towards the face of the array.

The results for Part B of the study indicate that:

- The measured external pressures on the flat roof baseline building are similar to the pressures given in AS/NZS 1170.2. The largest suction pressures occur near the leading edges of the roof.
- When panels are located on the roof with an orientation such that the wind flows towards the downward face of the array, large net positive and negative design pressures are generated on the panel array.

- Panels with an inclination of 30^o experience the largest peak pressures.

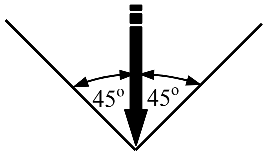
A complete set of pressure coefficients obtained in Part A and Part B of this study are provided in the addendum to this report.

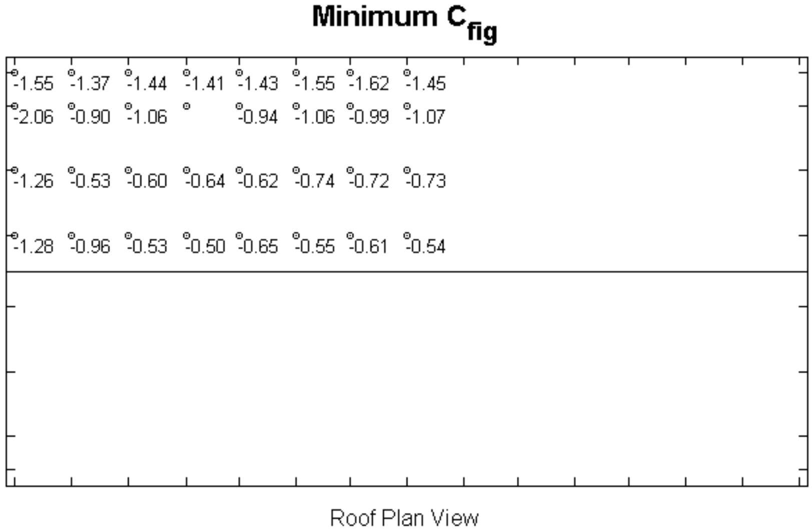
7. REFERENCES

[1] Standards Australia/Standards New Zealand (2011), "*AS/NZS 1170.2:2011 Structural design actions – Part 2: Wind actions*", Standards Australia, Sydney, NSW.
[2] Standards Australia (2006), "*AS 4055-2006 Wind loads for housing*", Standards Australia, Sydney, NSW.
[3] National Construction Code (2011) "*NCC 2011 Volumes One and Two*" ed., Australian Building Codes Board, Canberra, ACT.
[4] Wood, G.S., Denoon, R.O. Kwok, K.C.S., (2001), "*Wind loads on industrial solar panel arrays and supporting roof structure*". Wind and Structures 4, 481-494.
[5] Stenabaugh S. E., Karava P. and. Kopp G. A., (2011), "*Design wind loads for photovoltaic systems on sloped roofs of residential buildings*", Proceedings 13ICWE, Amsterdam.
[6] Ruscheweyh H. and Windhövel R., (2011) "*Wind loads at solar and photovoltaic modules for large plants*", Proceedings 13ICWE, Amsterdam.
[7] Blackmore P., (2004), "*Wind loads on roof-based photovoltaic systems*", Building Research Establishment, Digest 489.
[8] Tieleman, H.W., Akins, R.E. and Sparks P.R., (1980), "*An investigation of wind loads on solar collectors*", Virginia Polytechnic Institute and State University, Report VPI-E-80-.

APPENDIX A – PRESSURE COEFICIENTS

PART A – BASELINE BUILDING & BUILDING WITH 1 × 7 PANELS PARALLEL TO ROOF SLOPE





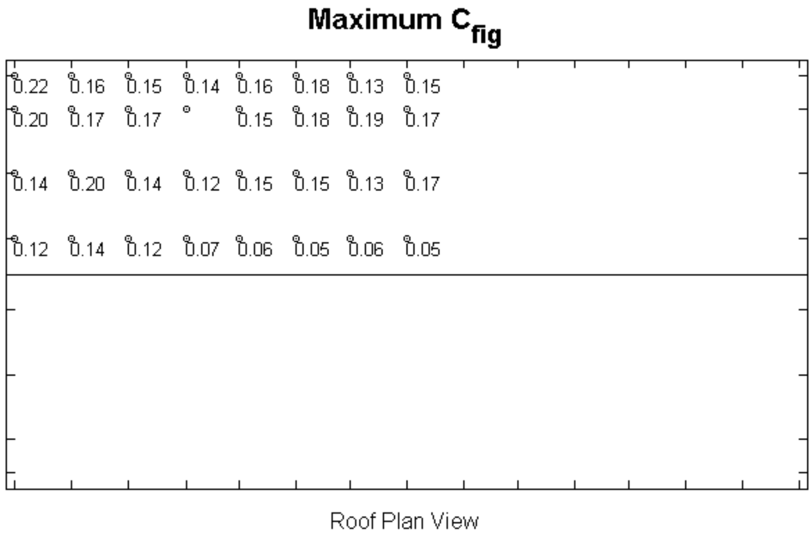


Figure A1-a. C_{fig} - Baseline building - Roof Pitch 7.5°, Wind Direction 0° ± 45°

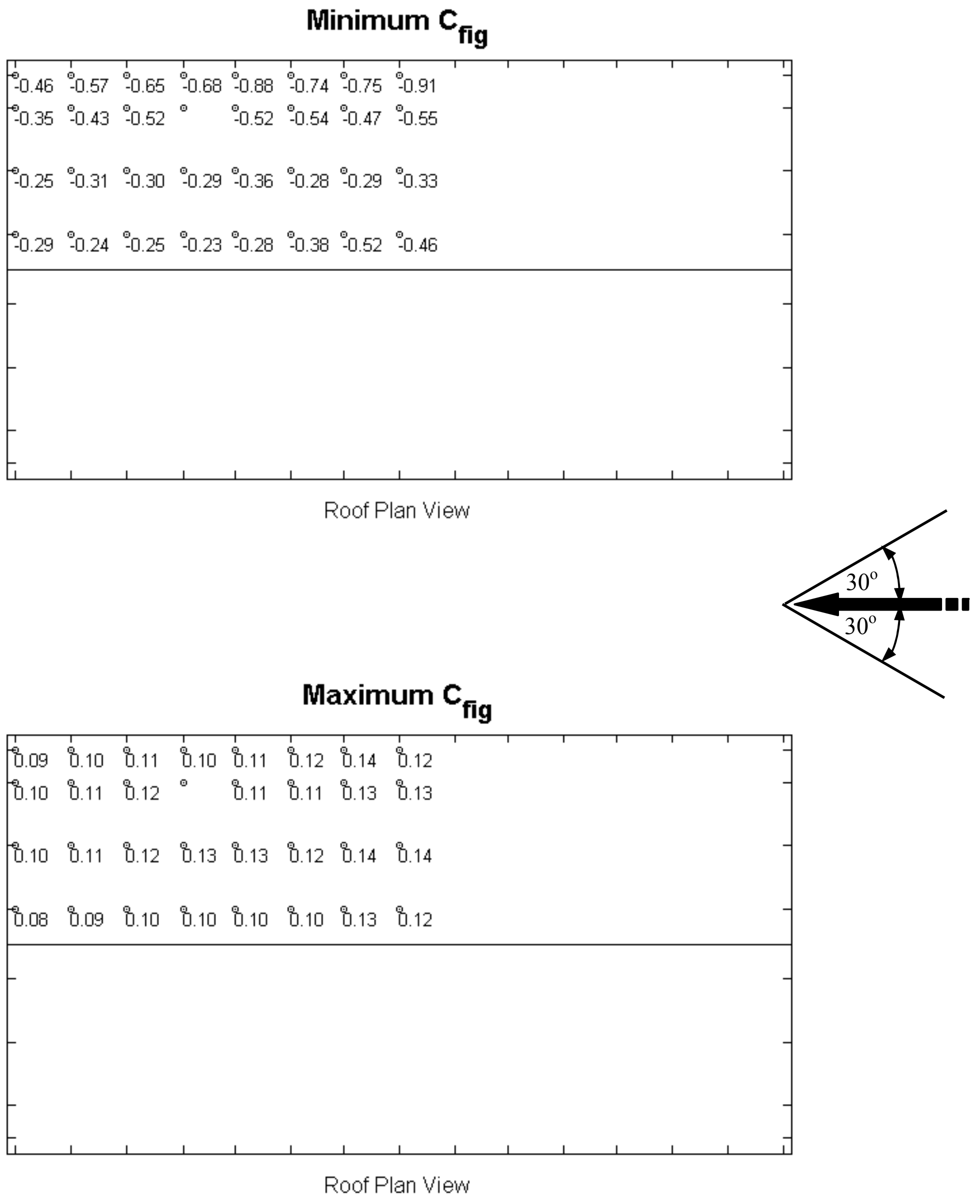
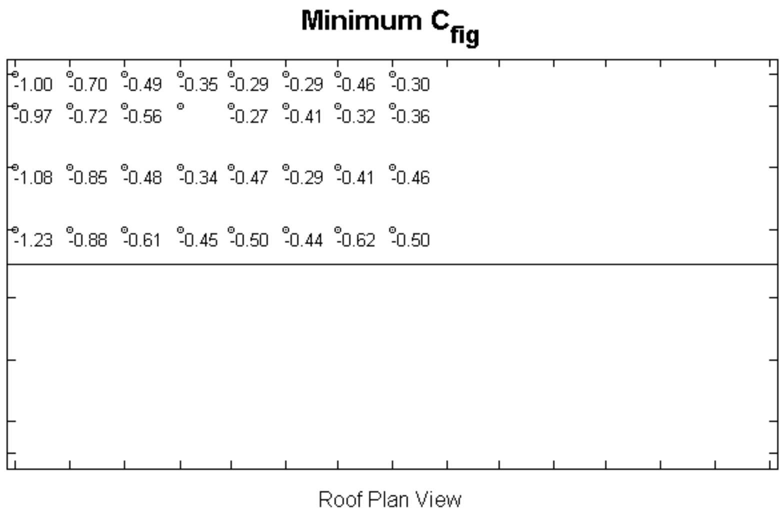
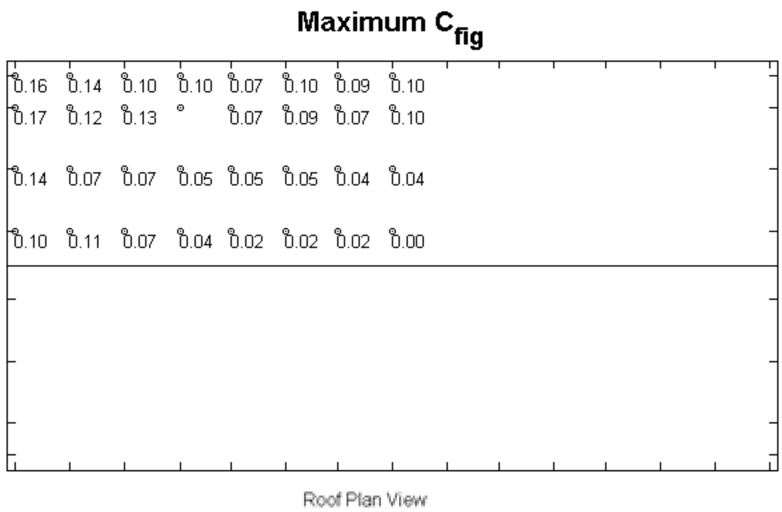


Figure A1-b. C_{fig} - Baseline building - Roof Pitch 7.5°, Wind Direction 90° ± 30°





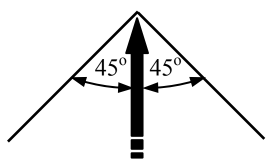


Figure A1-c. C_{fig} - Baseline building- Roof Pitch 7.5°, Wind Direction 180° ± 45°

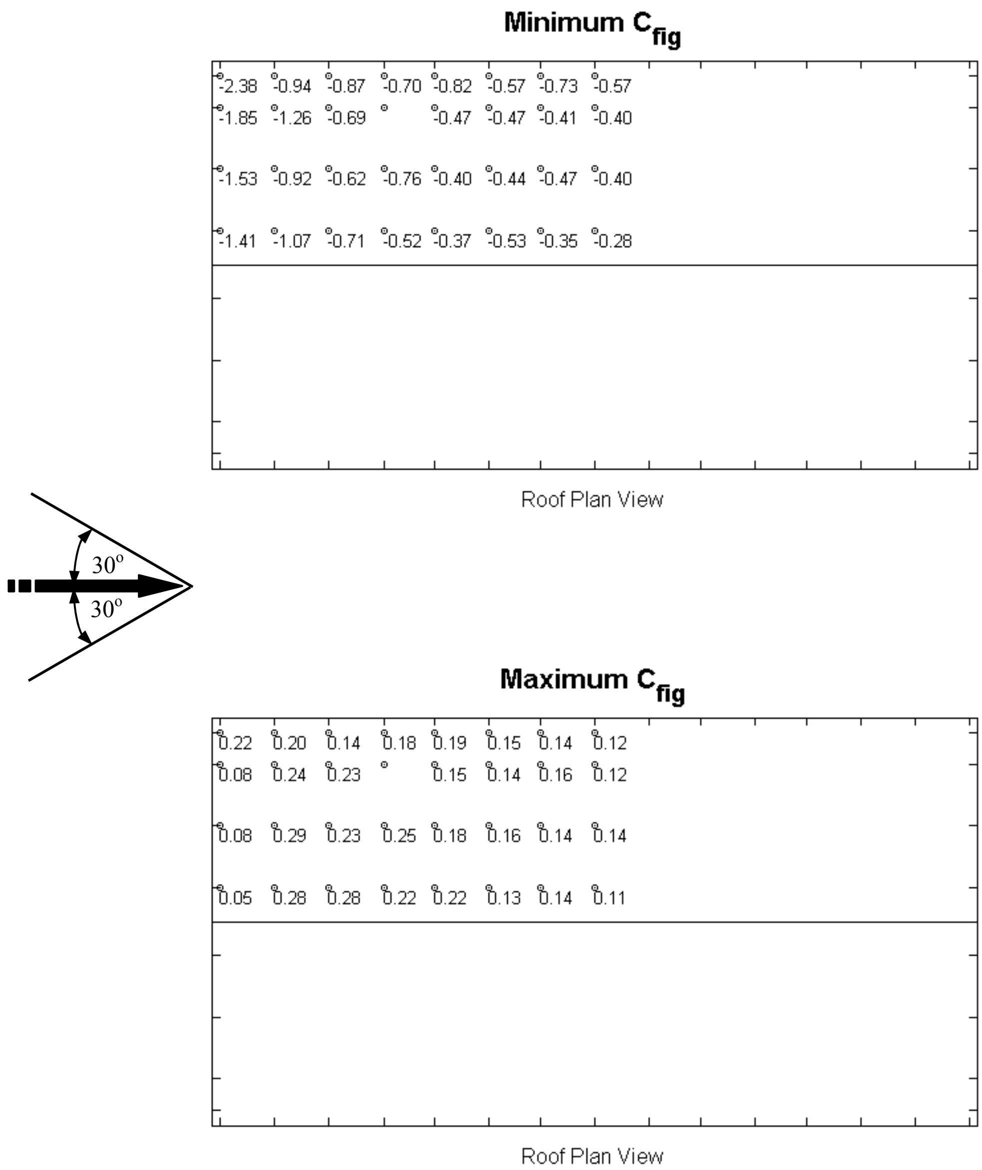
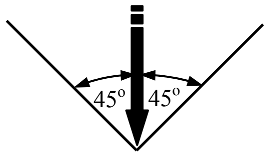
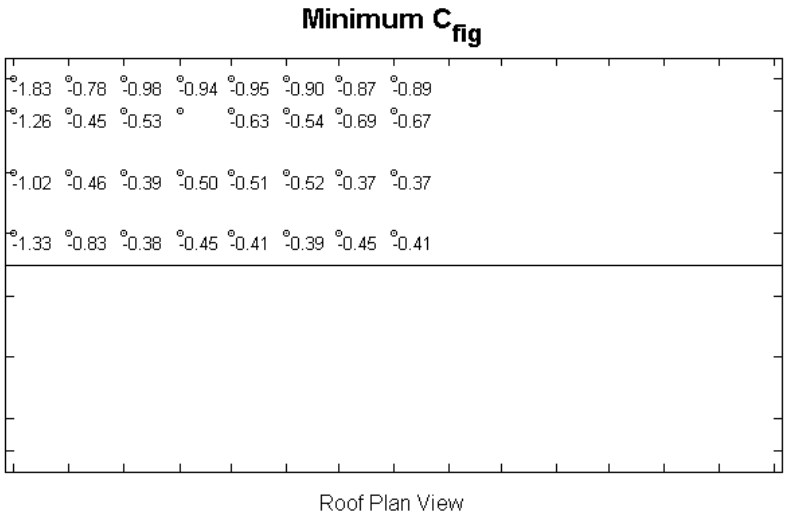


Figure A1-d. C_{fig} - Baseline building - Roof Pitch 7.5°, Wind Direction 270° ± 30°





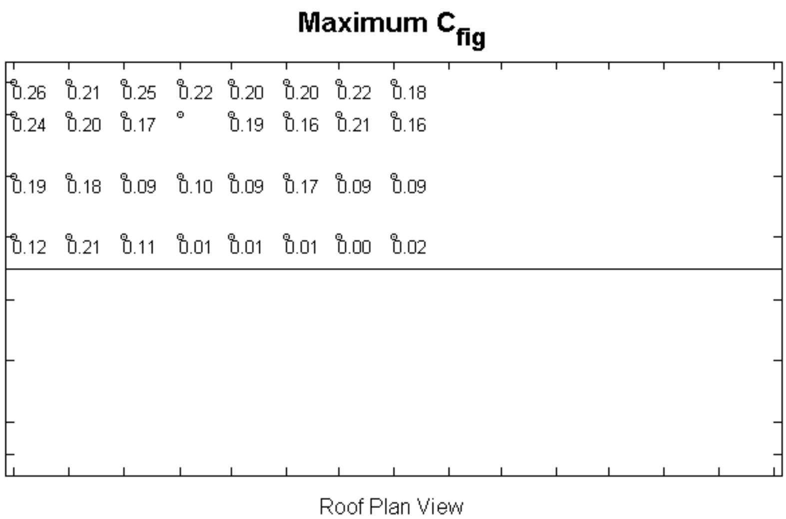


Figure A1-e. C_{fig} - Baseline building - Roof Pitch 15°, Wind Direction 0° ± 45°

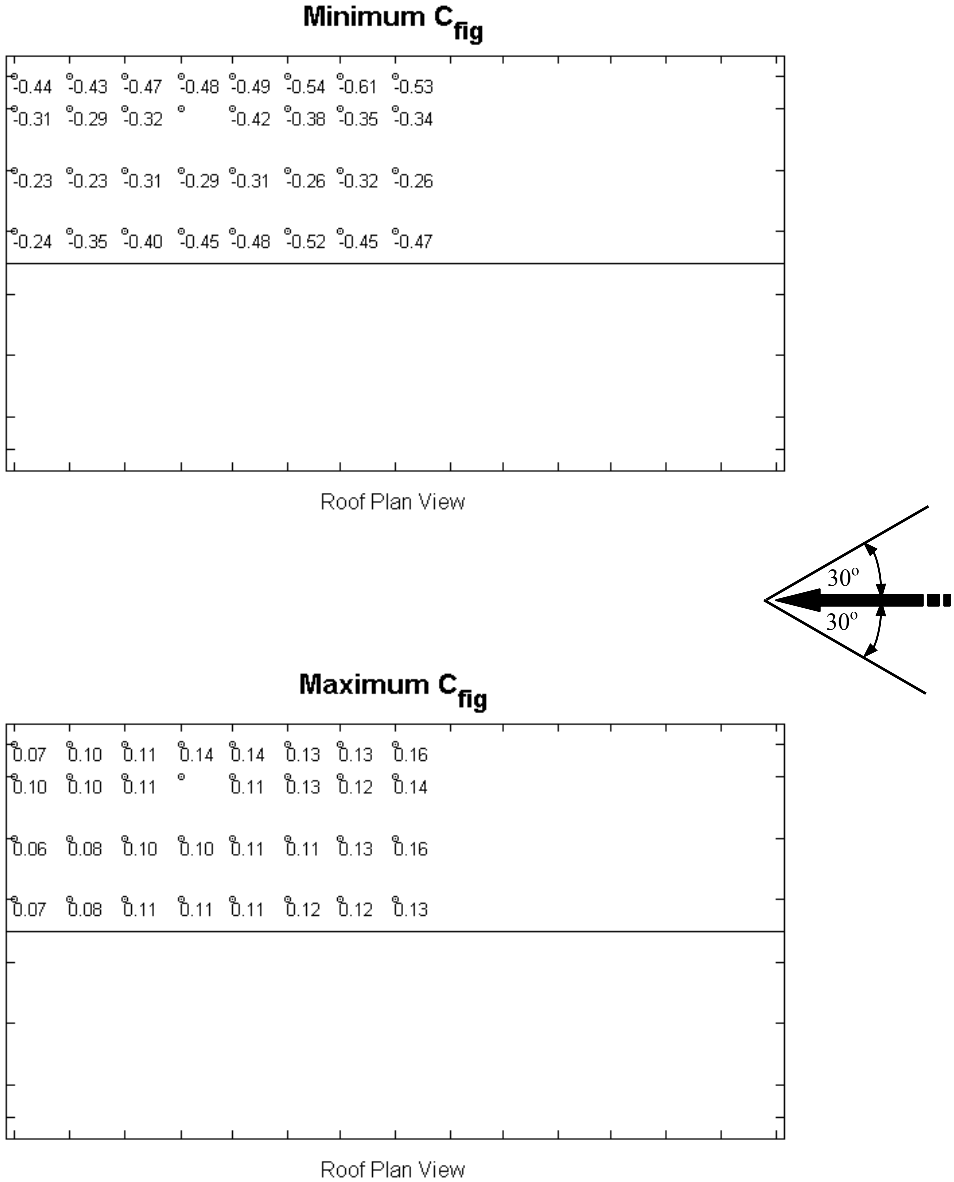


Figure A1-f. C_{fig} - Baseline building - Roof Pitch 15°, Wind Direction 90° ± 30°

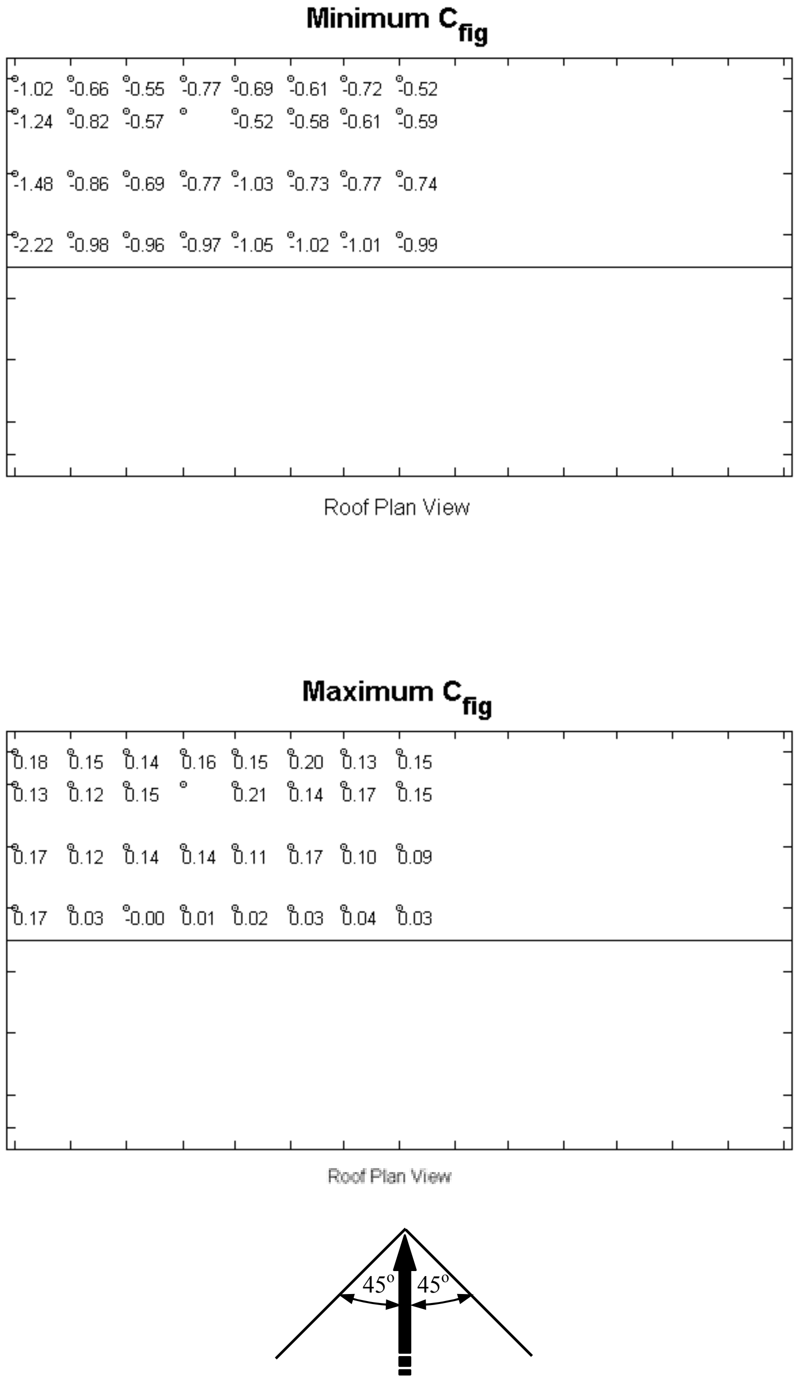


Figure A1-g. C_{fig} - Baseline building - Roof Pitch 15°, Wind Direction 180° ± 45°

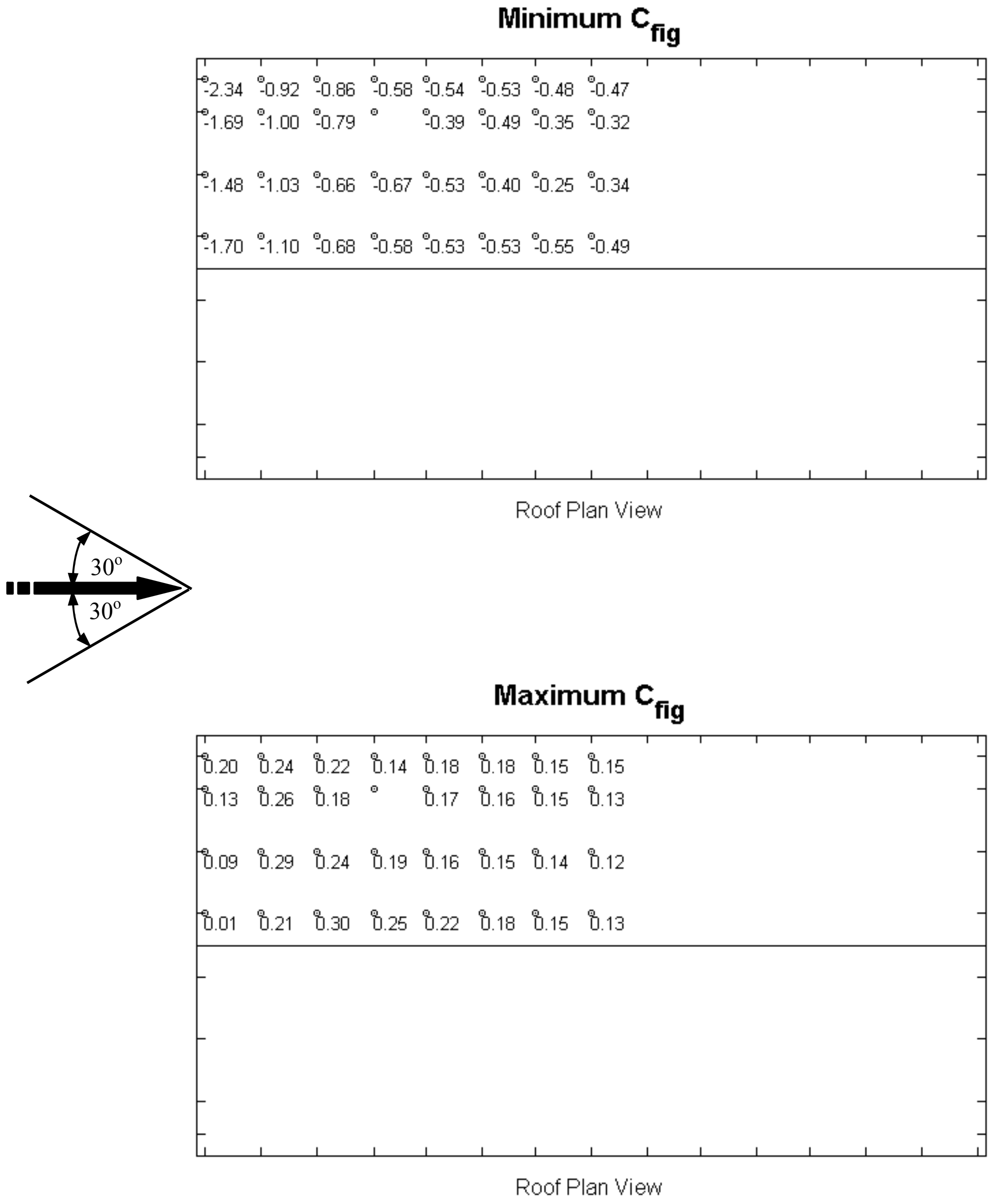
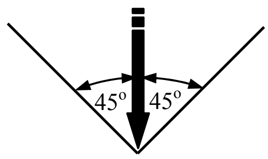
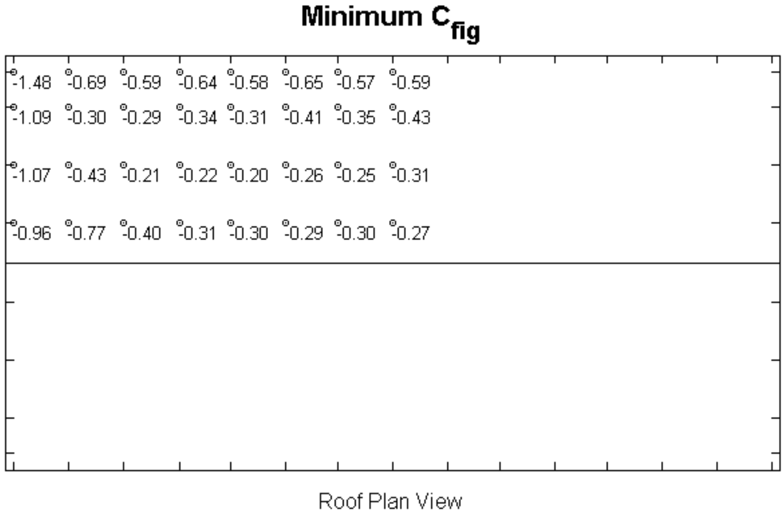


Figure A1-h. C_{fig} - Baseline building - Roof Pitch 15^o, Wind Direction 270^o ± 30^o





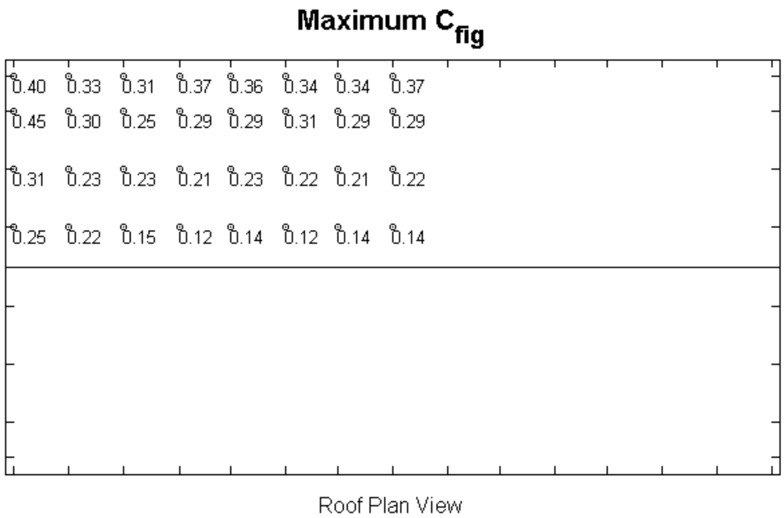


Figure A1-i. C_{fig} - Baseline building - Roof Pitch 22.5°, Wind Direction 0° ± 45°

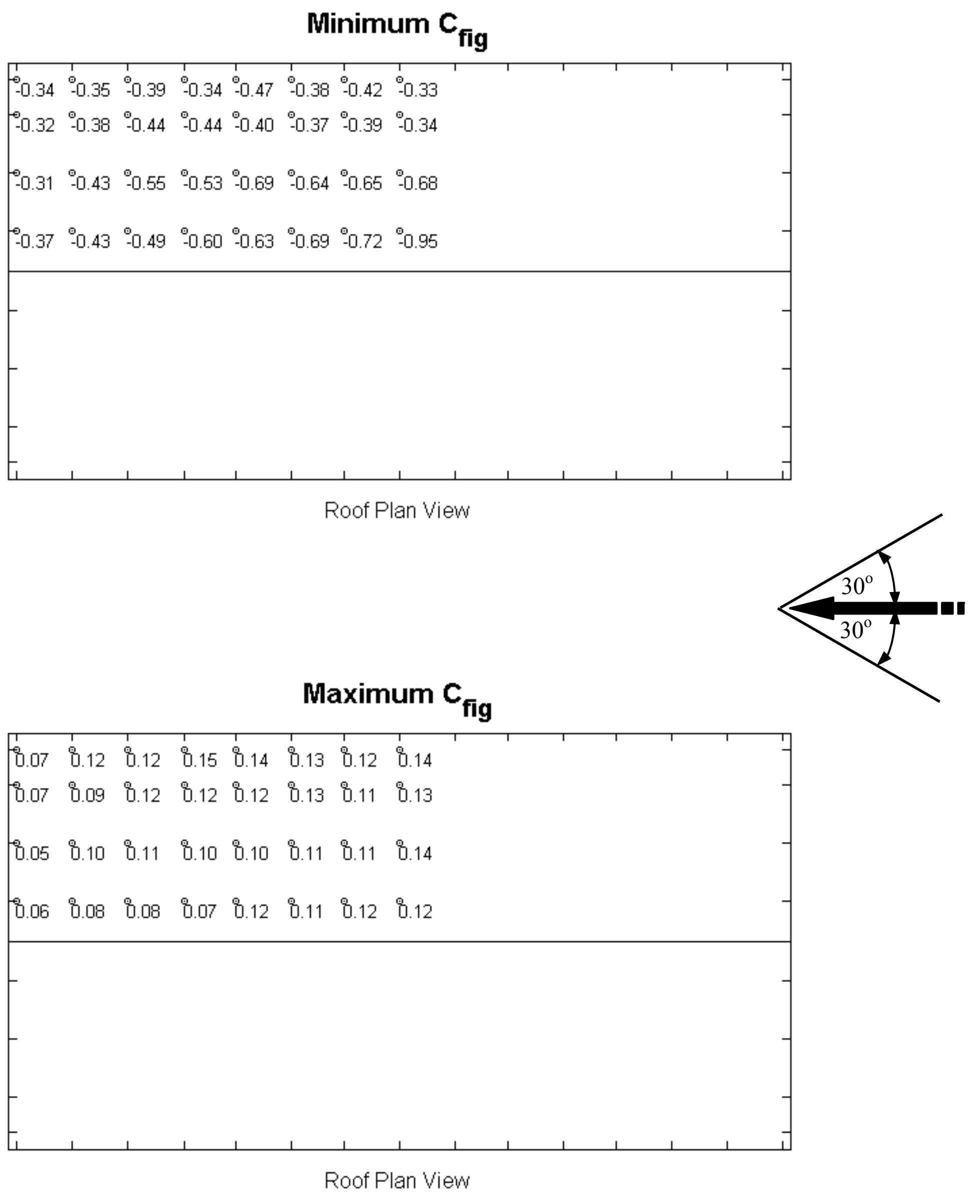


Figure A1-j. C_{fig} - Baseline building - Roof Pitch 22.5°, Wind Direction 90° ± 30°

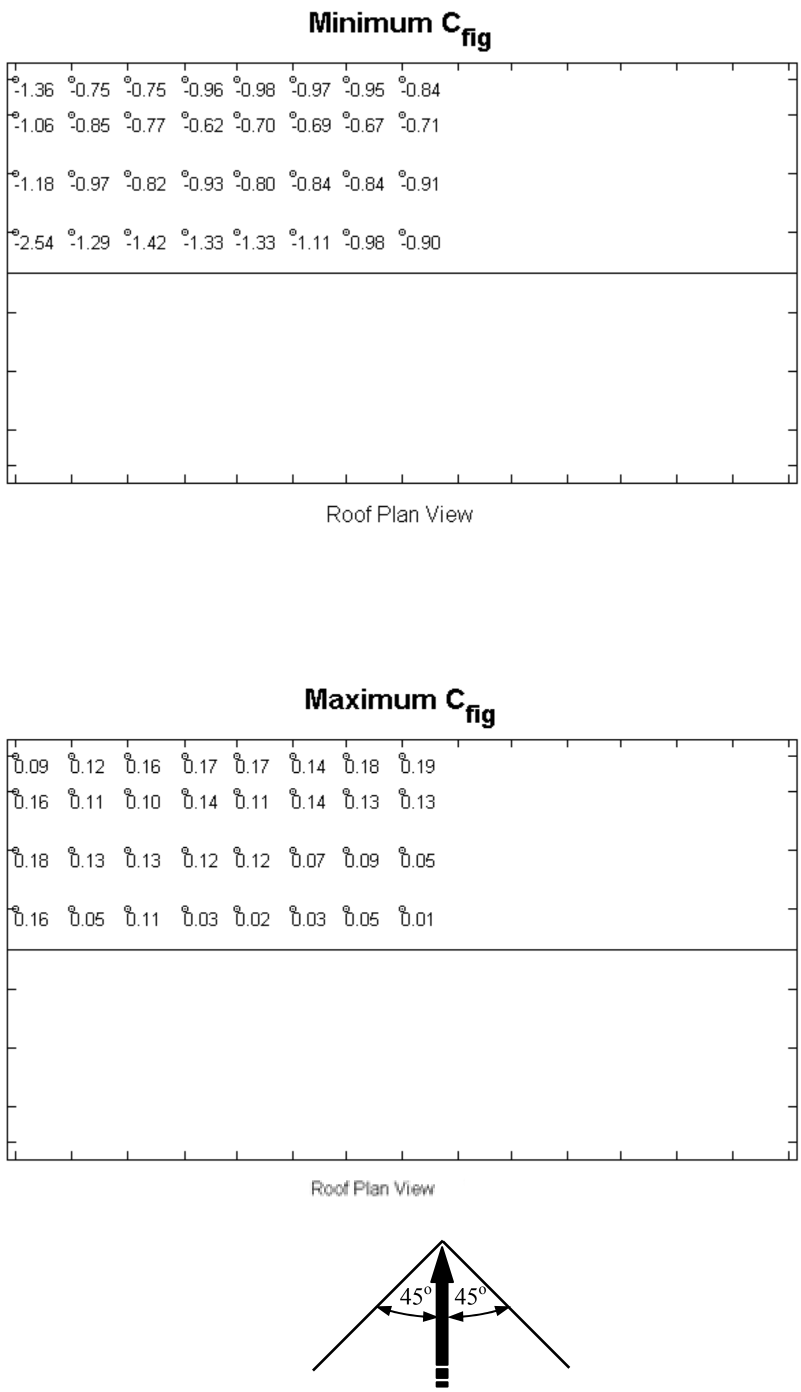


Figure A1-k . C_{fig} - Baseline building - Roof Pitch 22.5°, Wind Direction 180° ± 45°

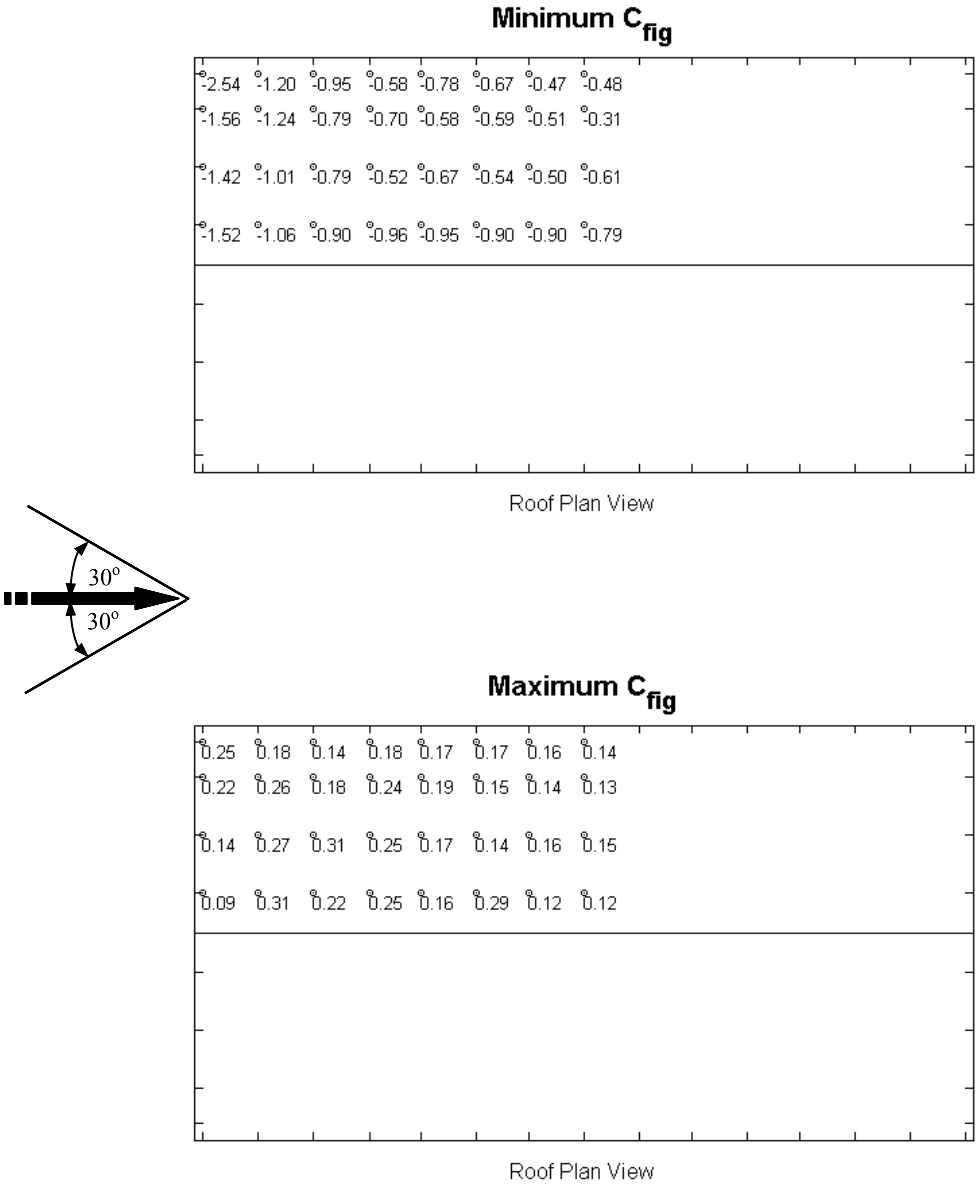


Figure A1-l. C_{fig} - Baseline building - Roof Pitch 22.5°, Wind Direction 270° ± 30°

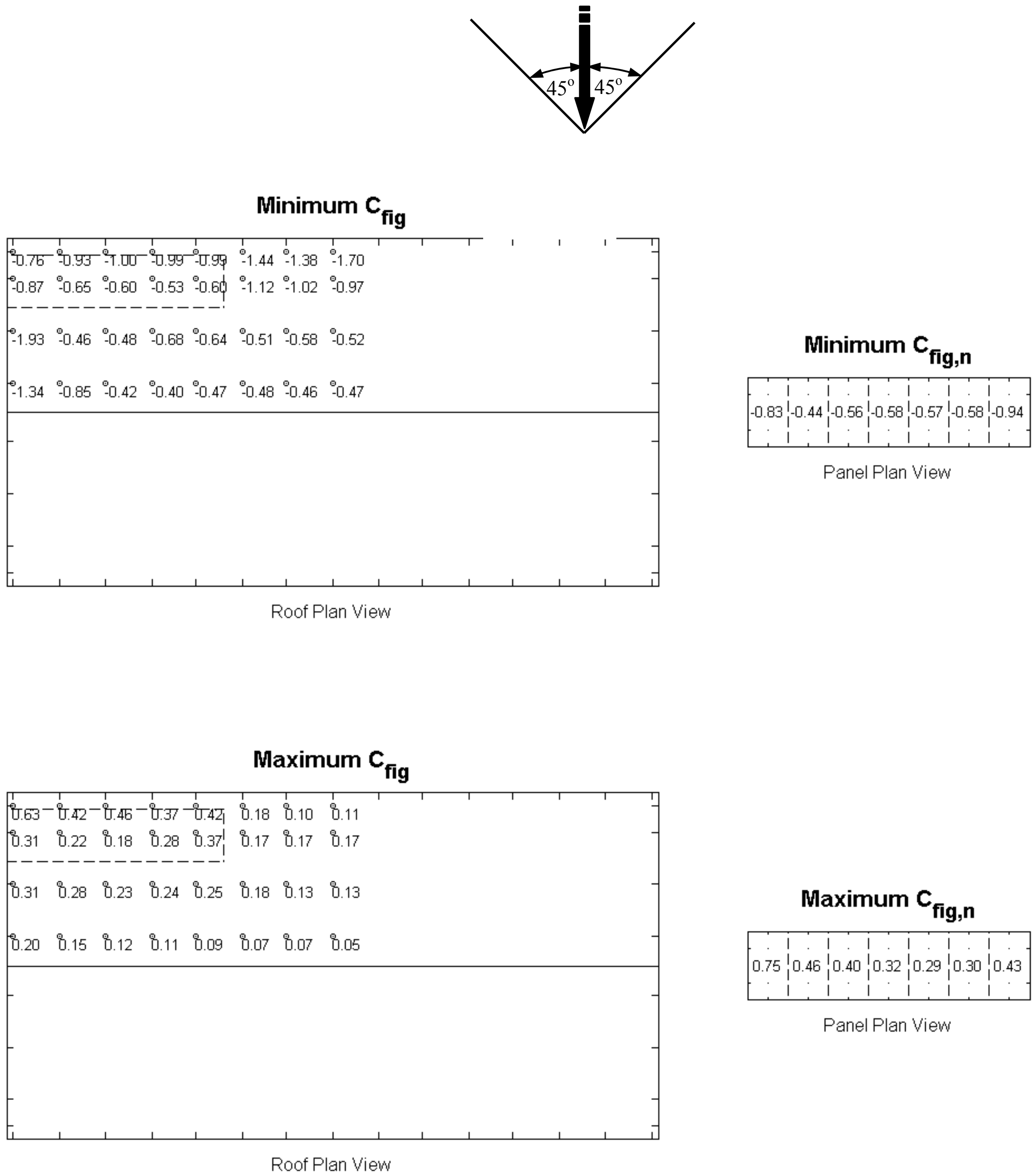
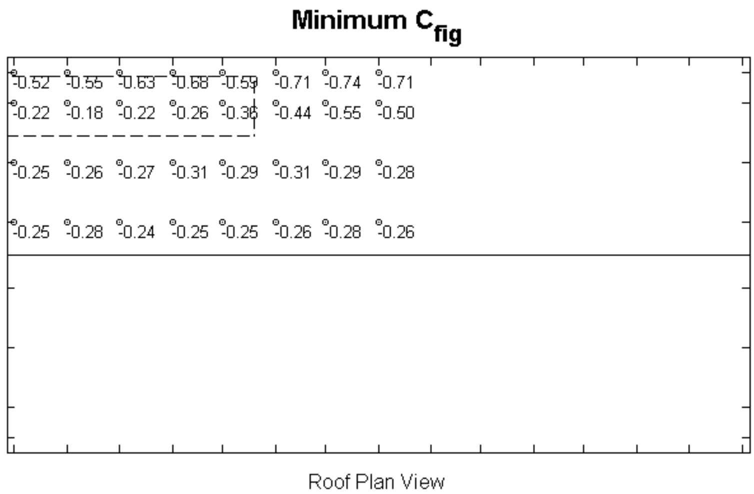
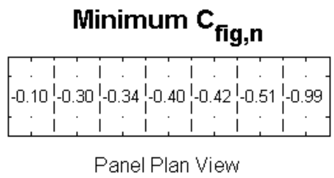
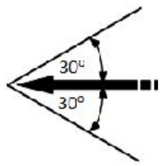
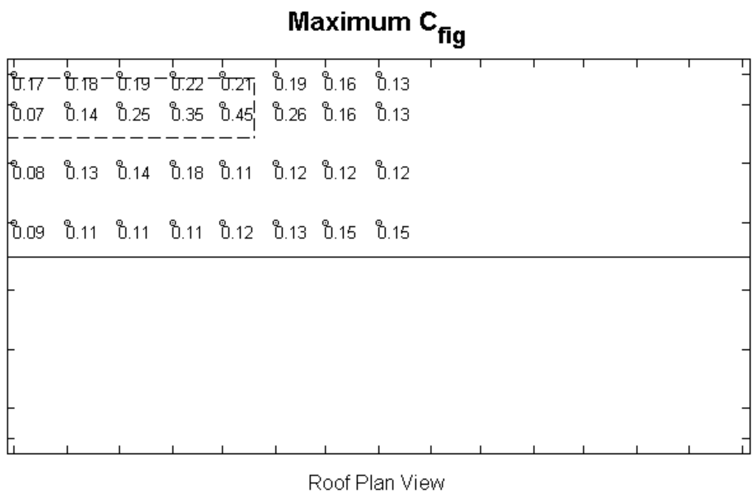


Figure A2-a. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 7.5°, Wind Direction 0° ± 45°









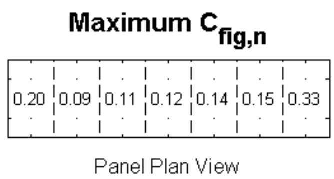


Figure A2-b. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 7.5°, Wind Direction 90° ± 30°

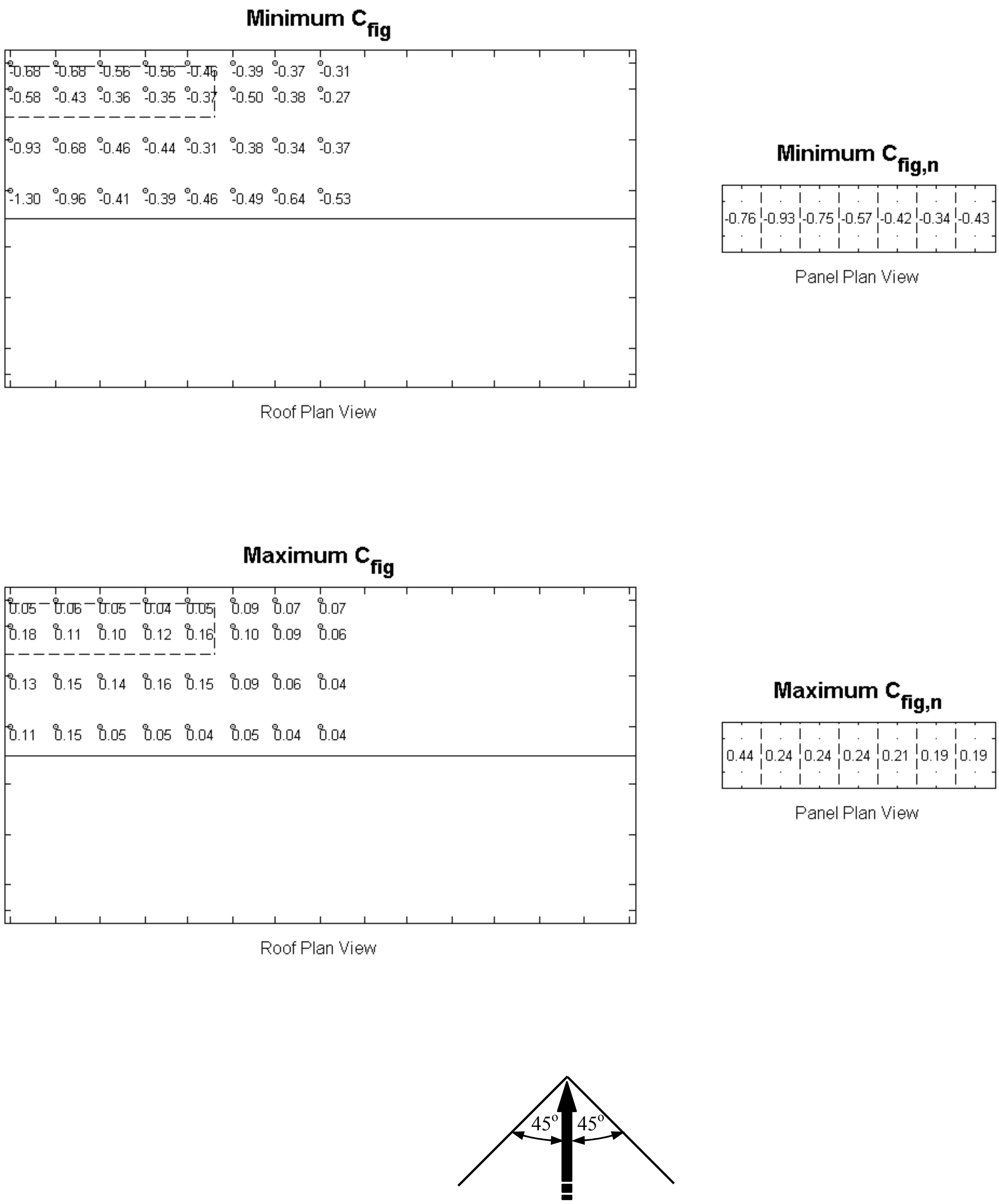


Figure A2-c. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 7.5°, Wind Direction 180° ± 45°

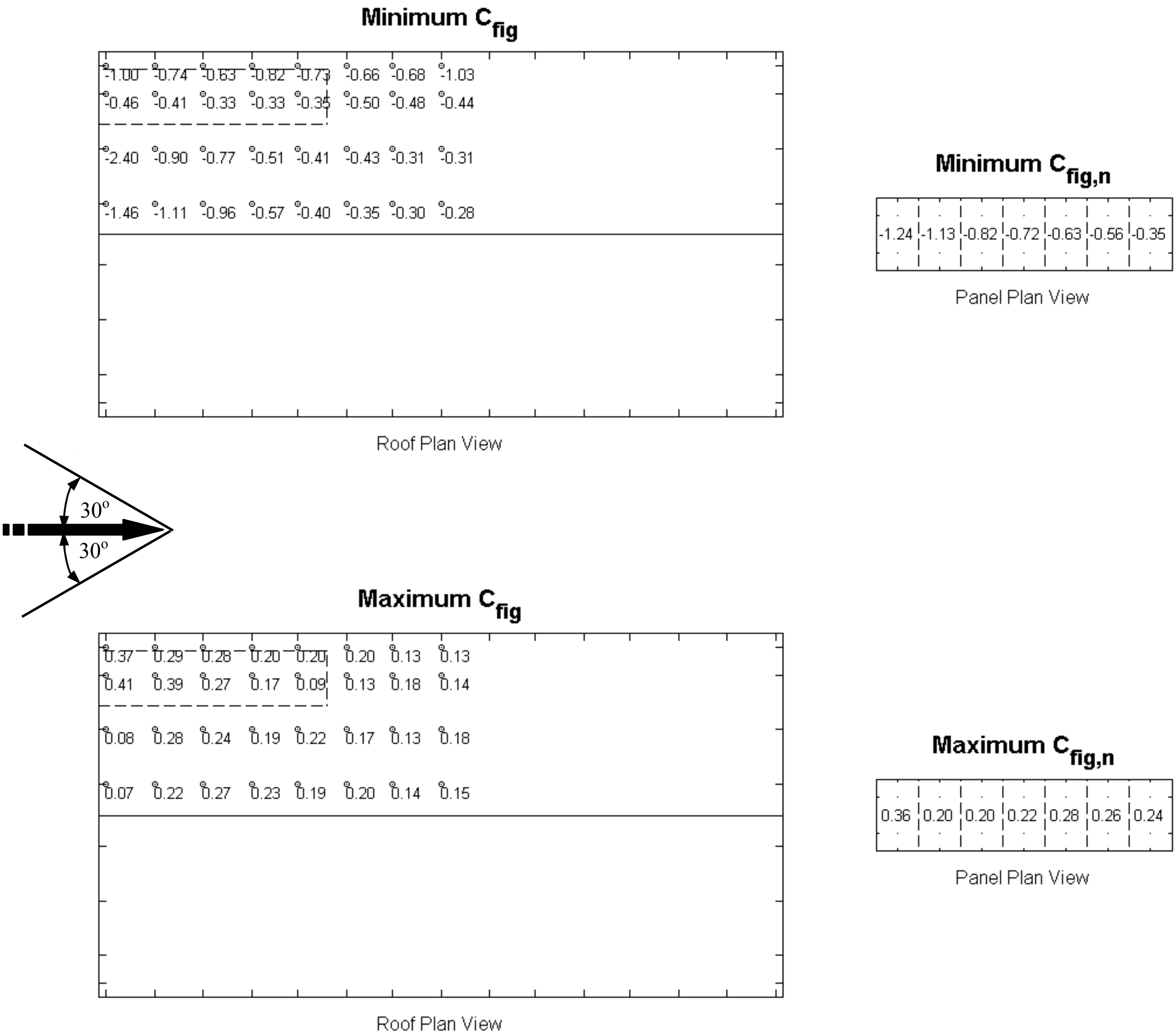


Figure A2-d. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 7.5°, Wind Direction 270° ± 30°

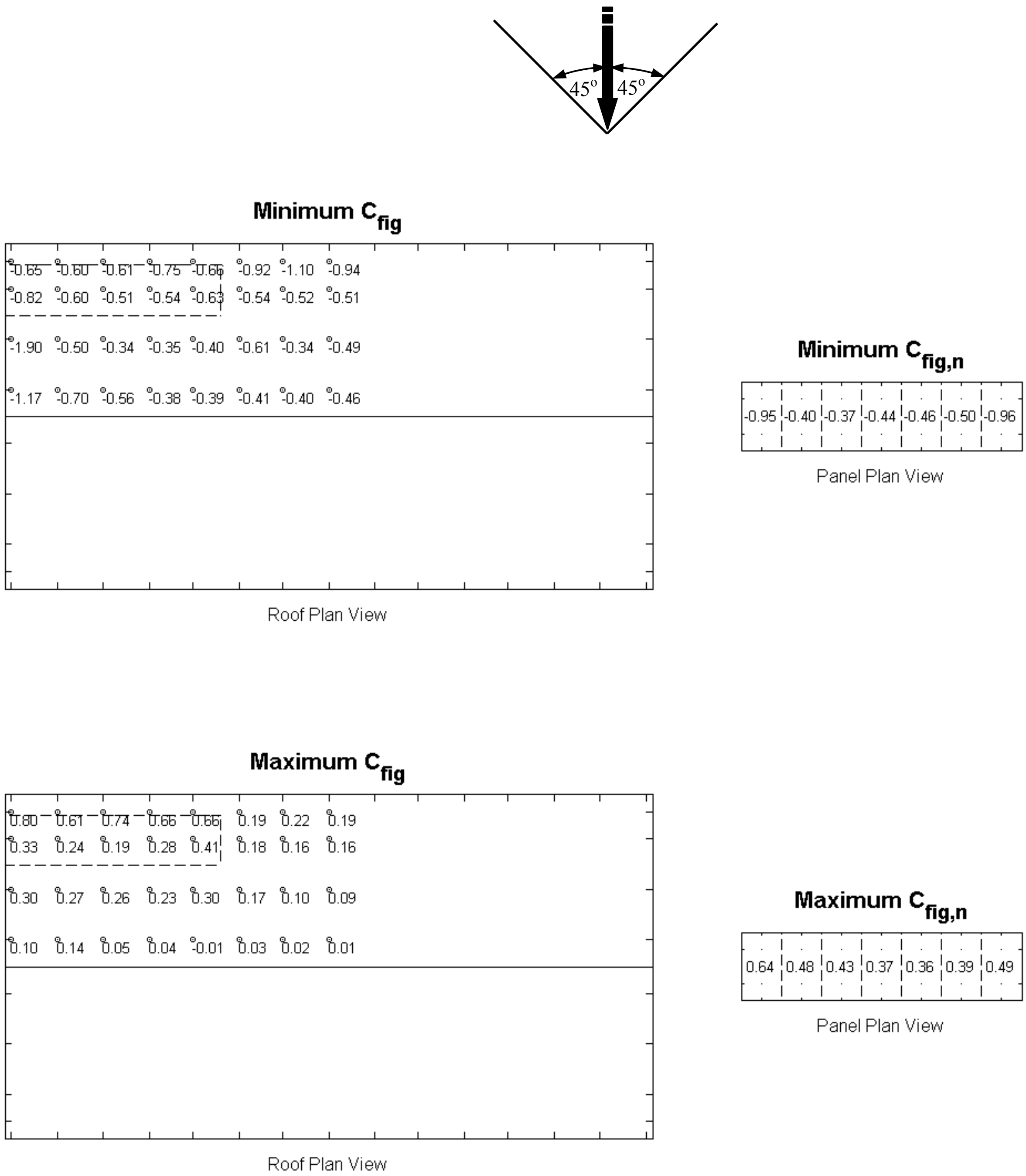


Figure A2-e. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 15°, Wind Direction 0° ± 45°

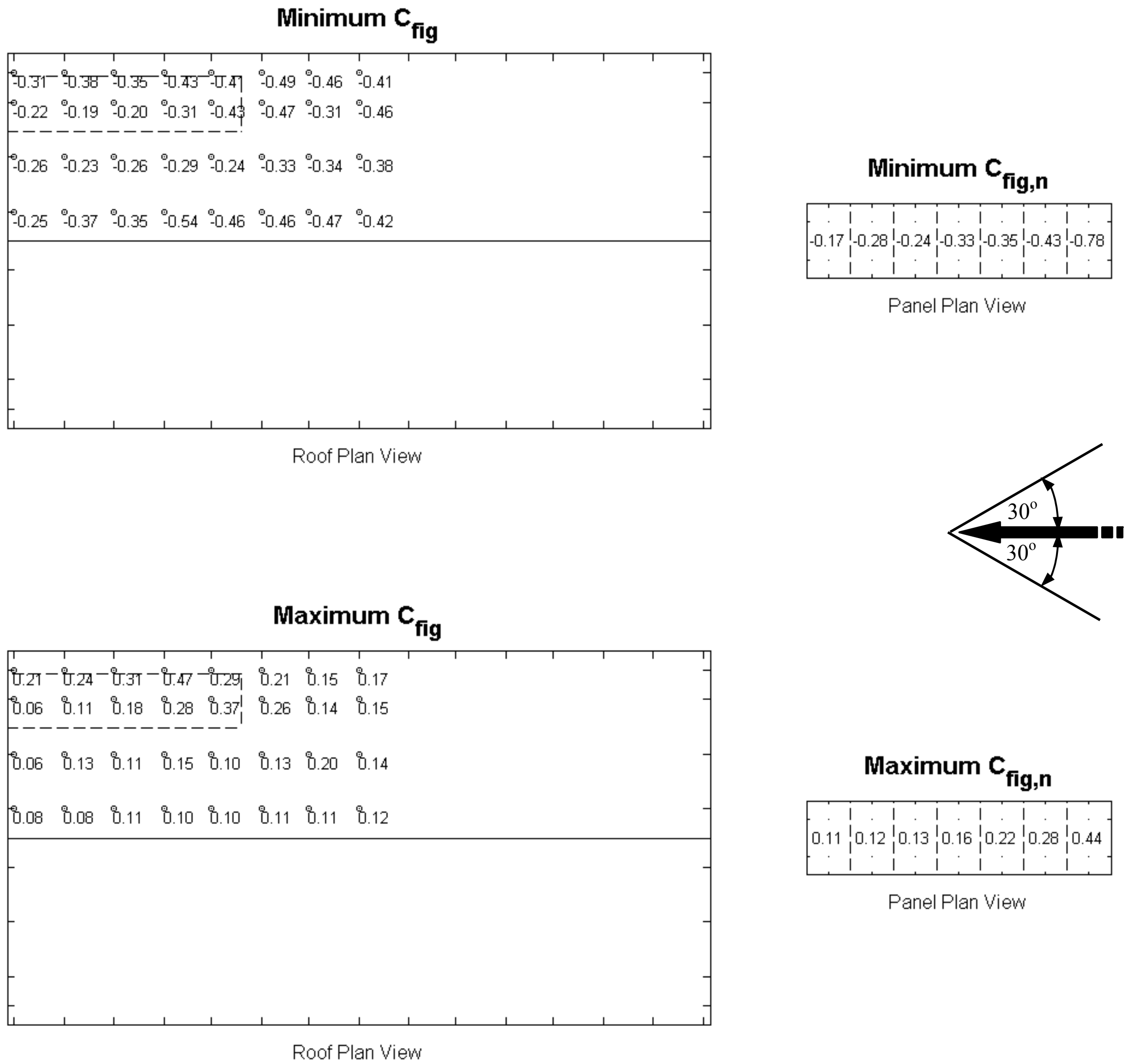


Figure A2-f. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 15°, Wind Direction 90° ± 30°

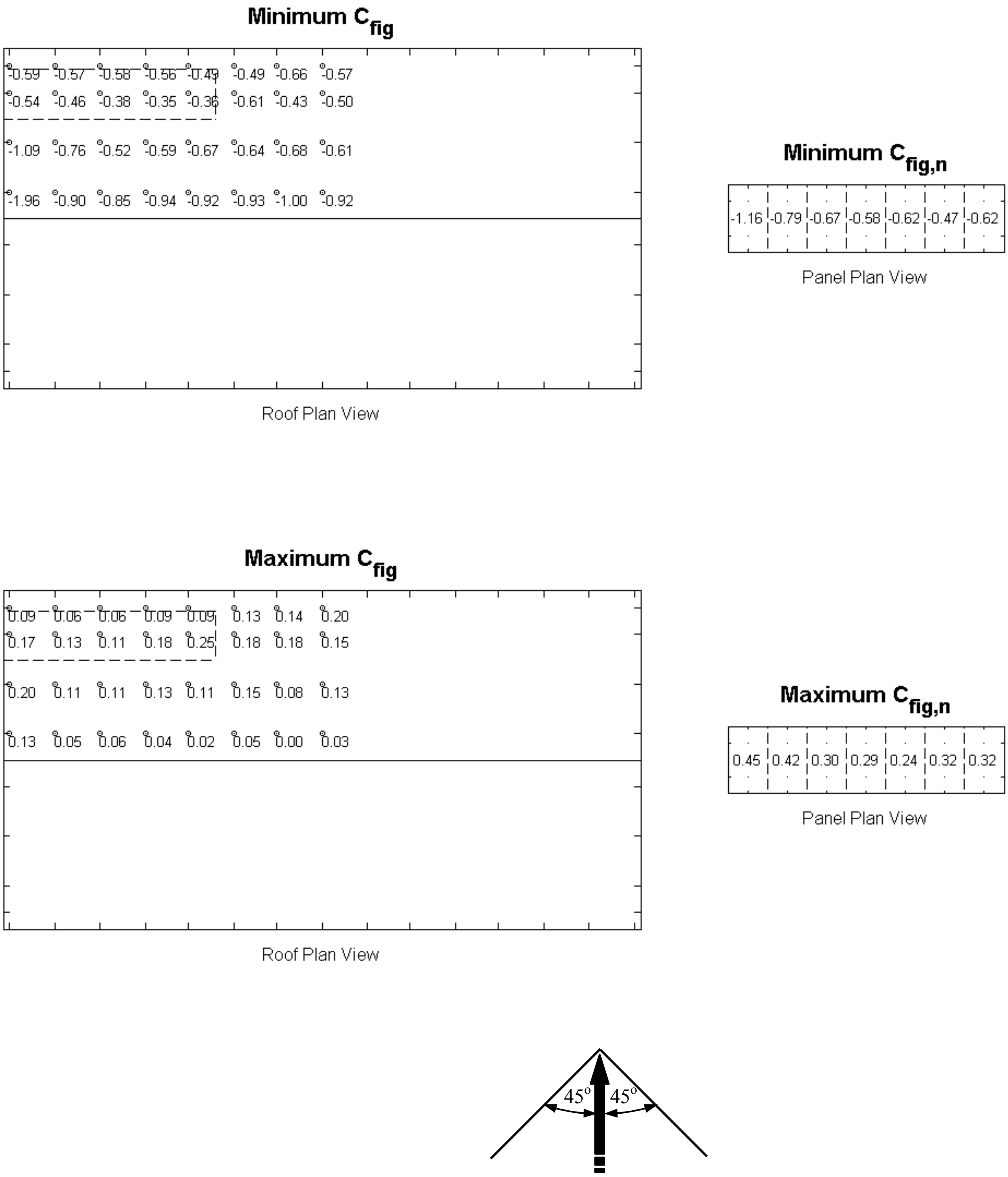
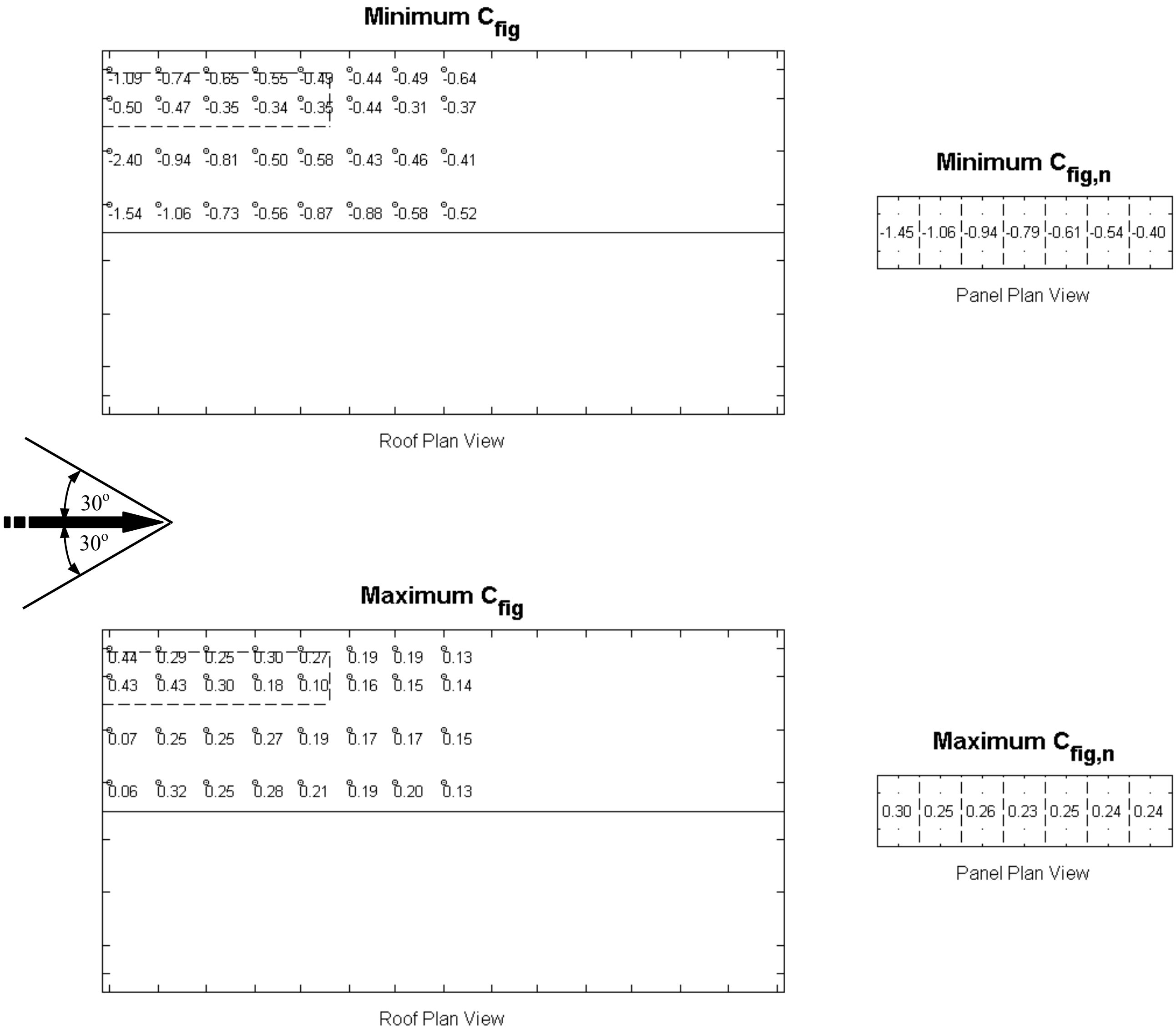


Figure A2-g. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 15°, Wind Direction 180° ± 45°



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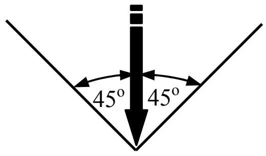
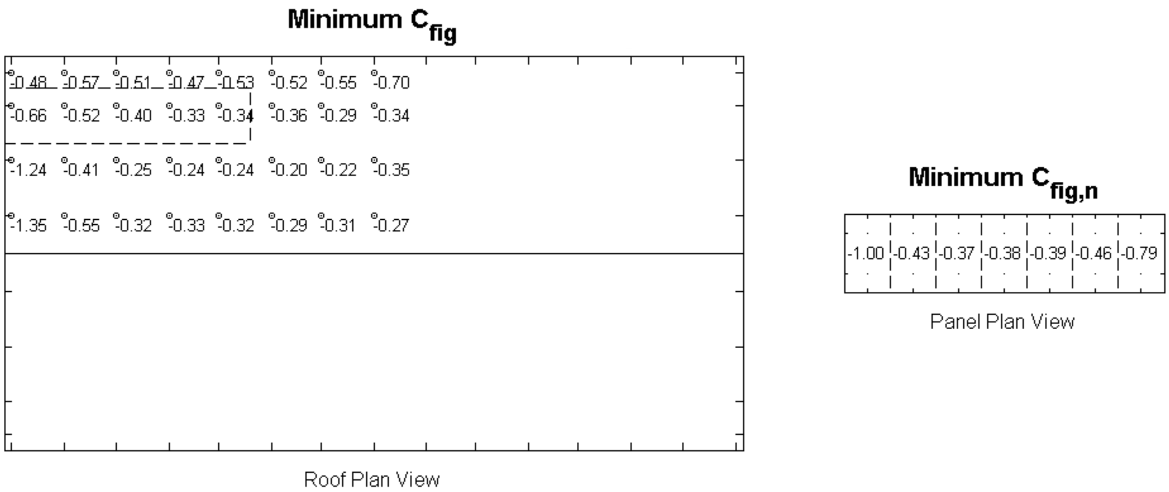




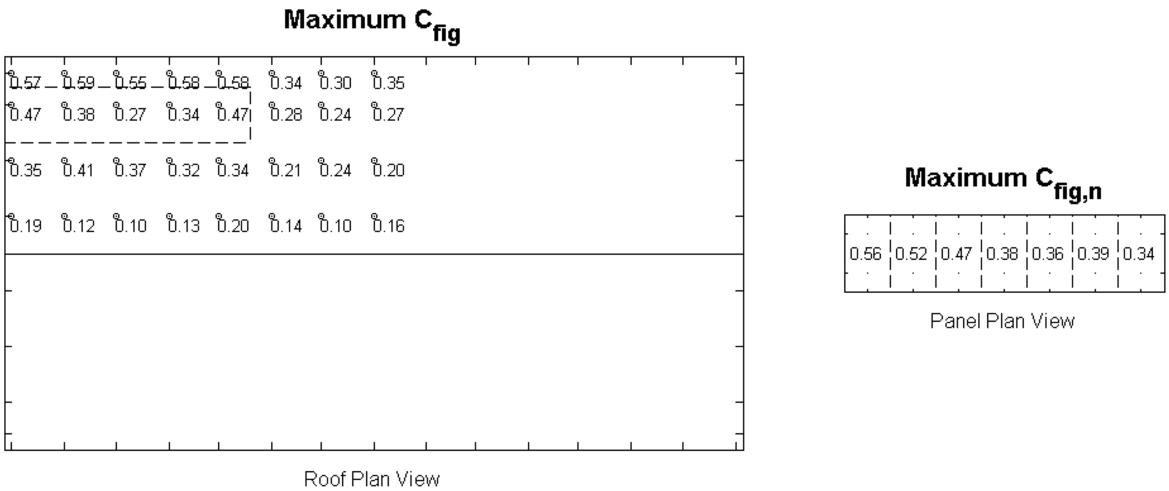
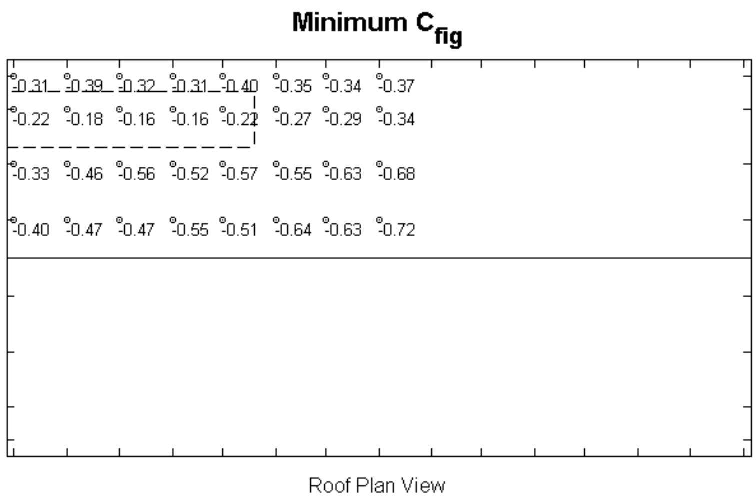
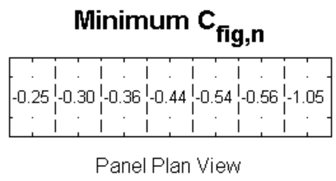
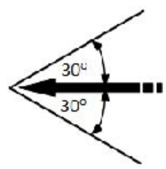
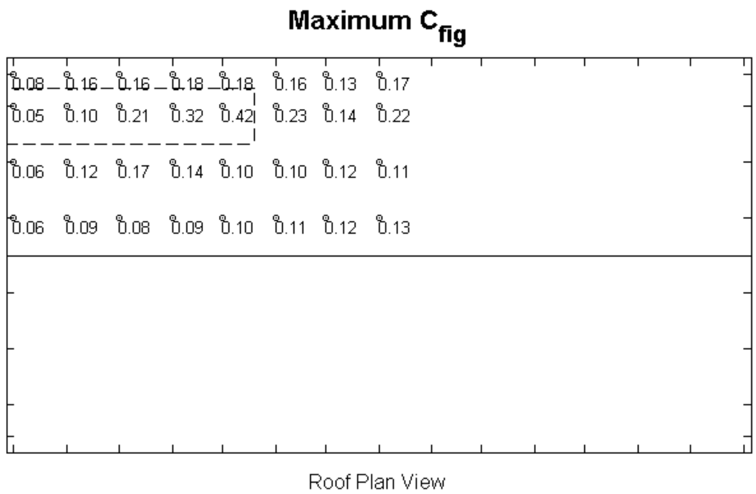


Figure A2-i C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 22.5°, Wind Direction 0° ± 45°









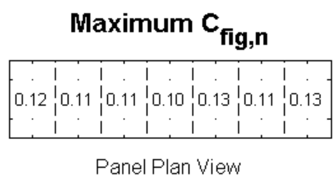


Figure A2-j. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 22.5°, Wind Direction 90° ± 30°

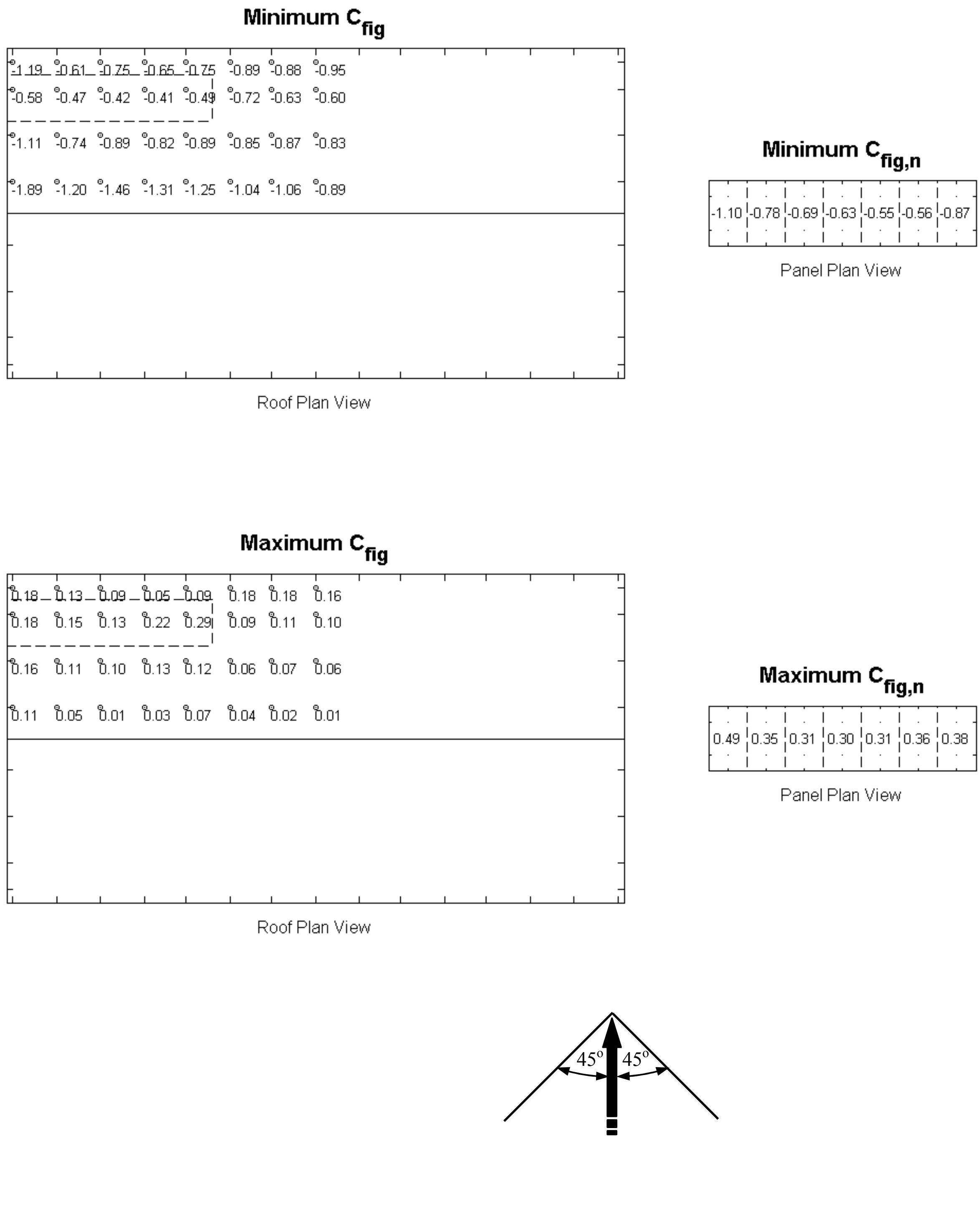


Figure A2-k. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 22.5°, Wind Direction 180° ± 45°

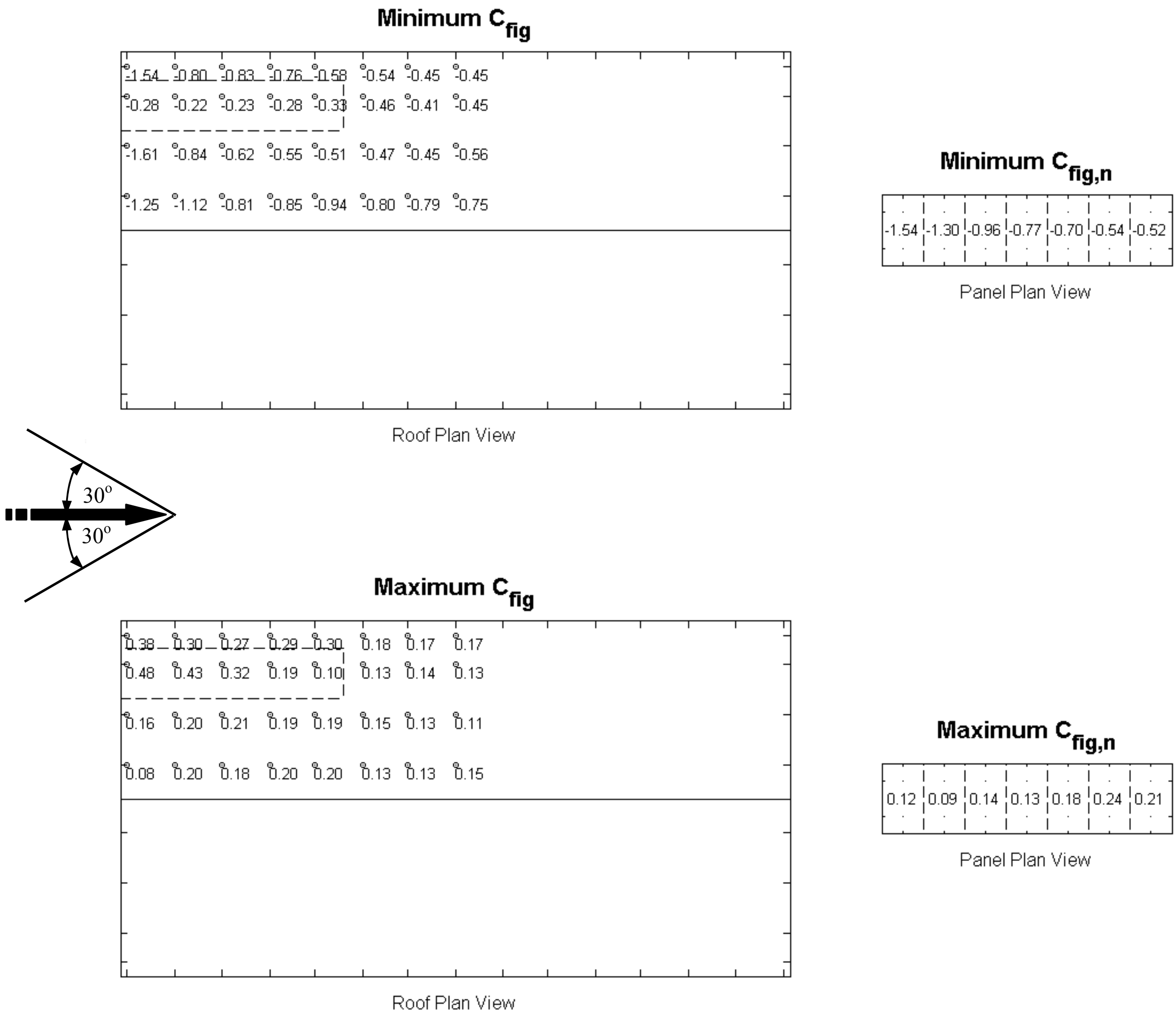
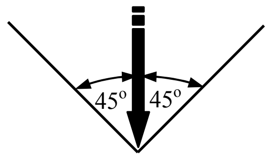
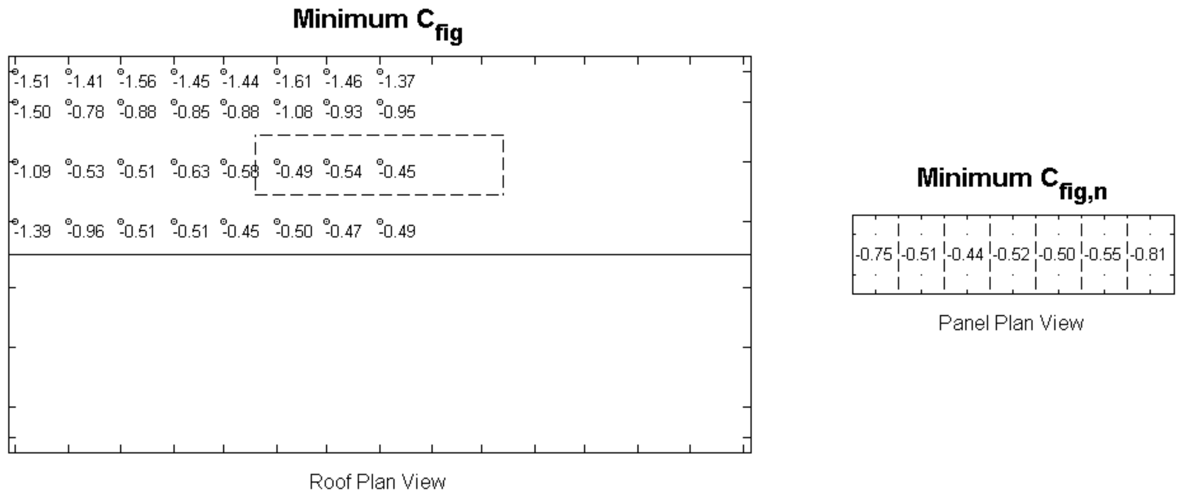


Figure A2-l. C_{fig} – Panel Position A, Gap 100mm - Roof Pitch 22.5°, Wind Direction 270° ± 30°





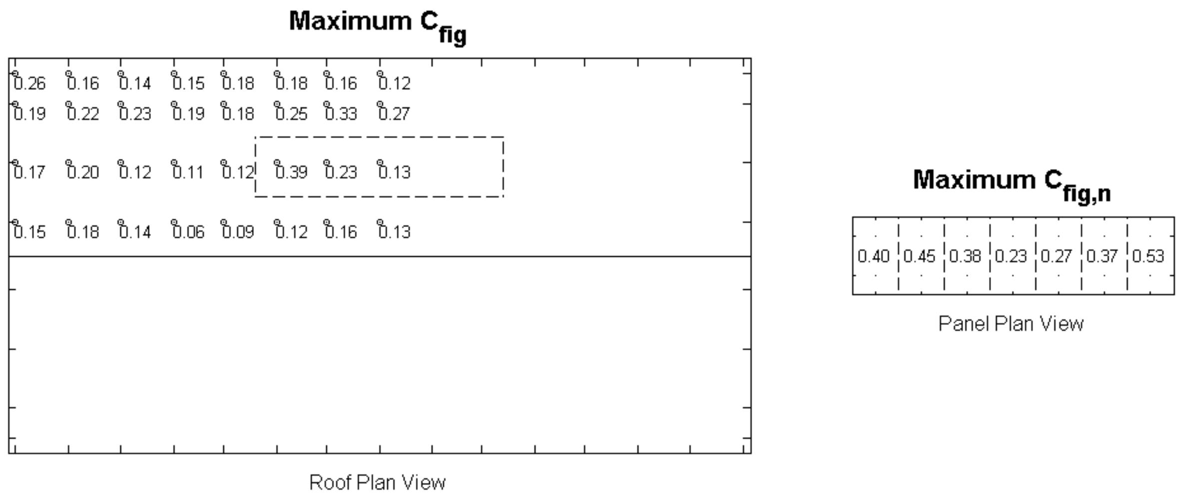


Figure A3-a. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 7.5°, Wind Direction 0° ± 45°

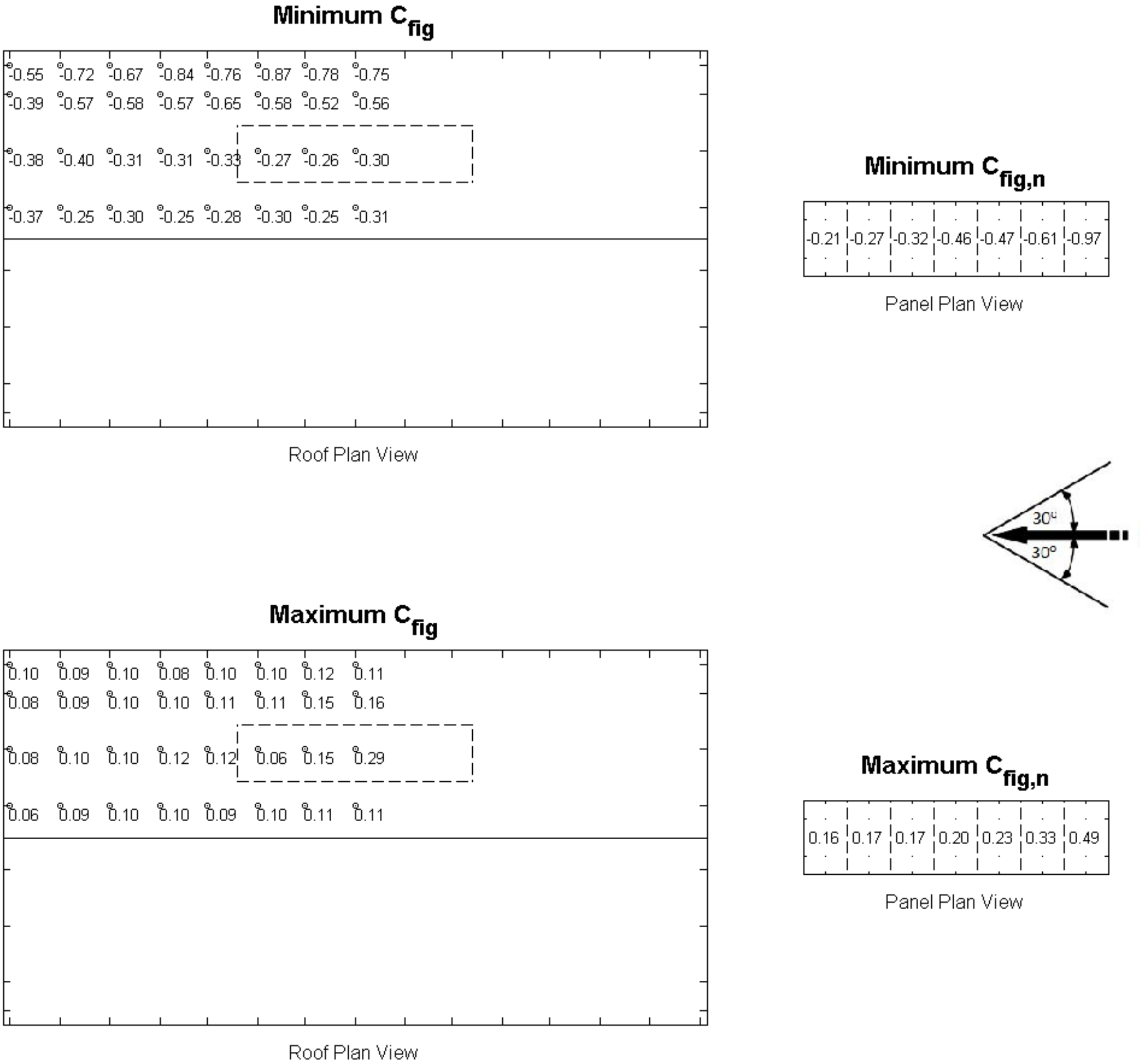


Figure A3-b.- C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 7.5^o, Wind Direction 90^o ± 30^o

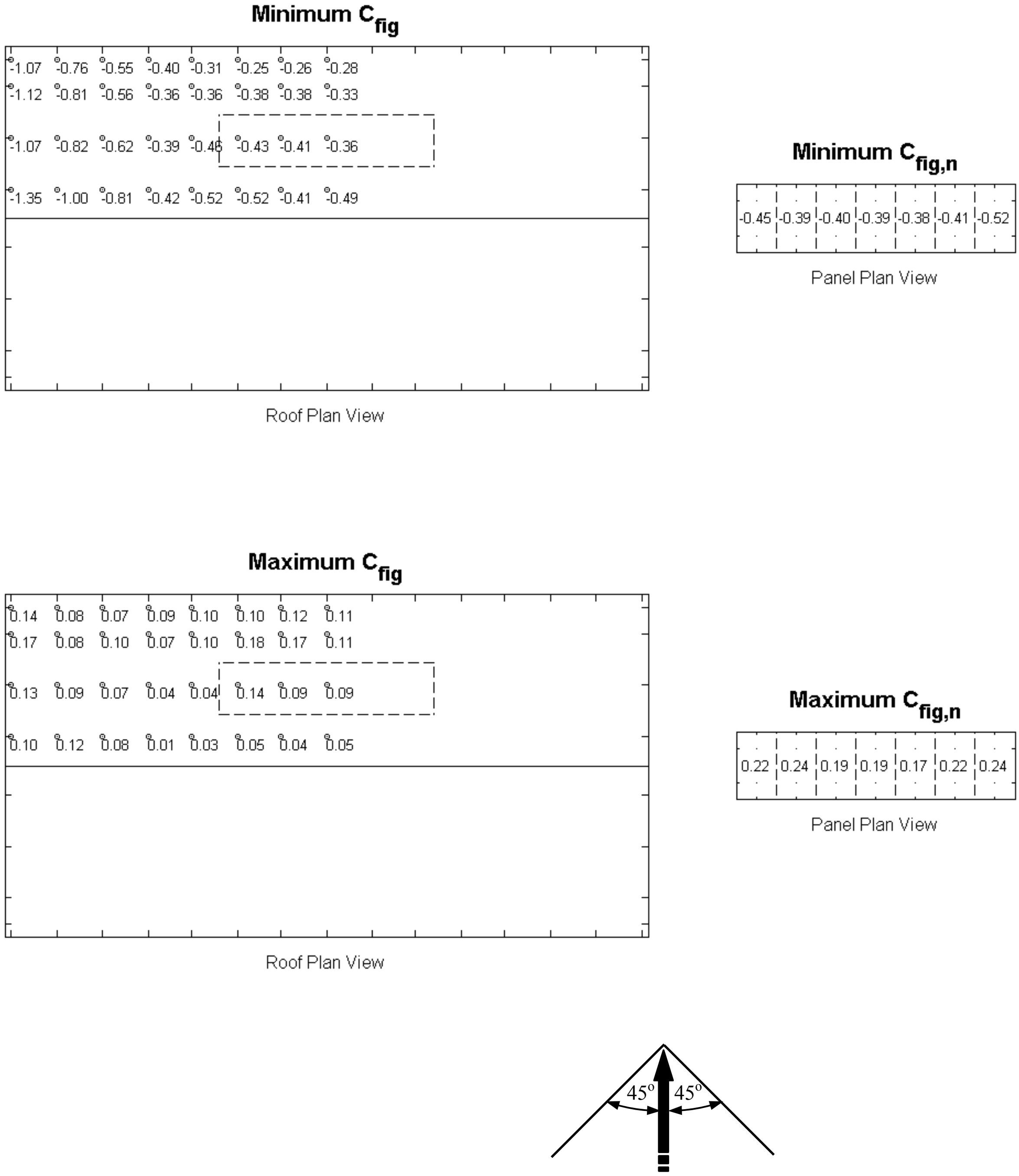


Figure A3-c. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 7.5°, Wind Direction 180° ± 45°

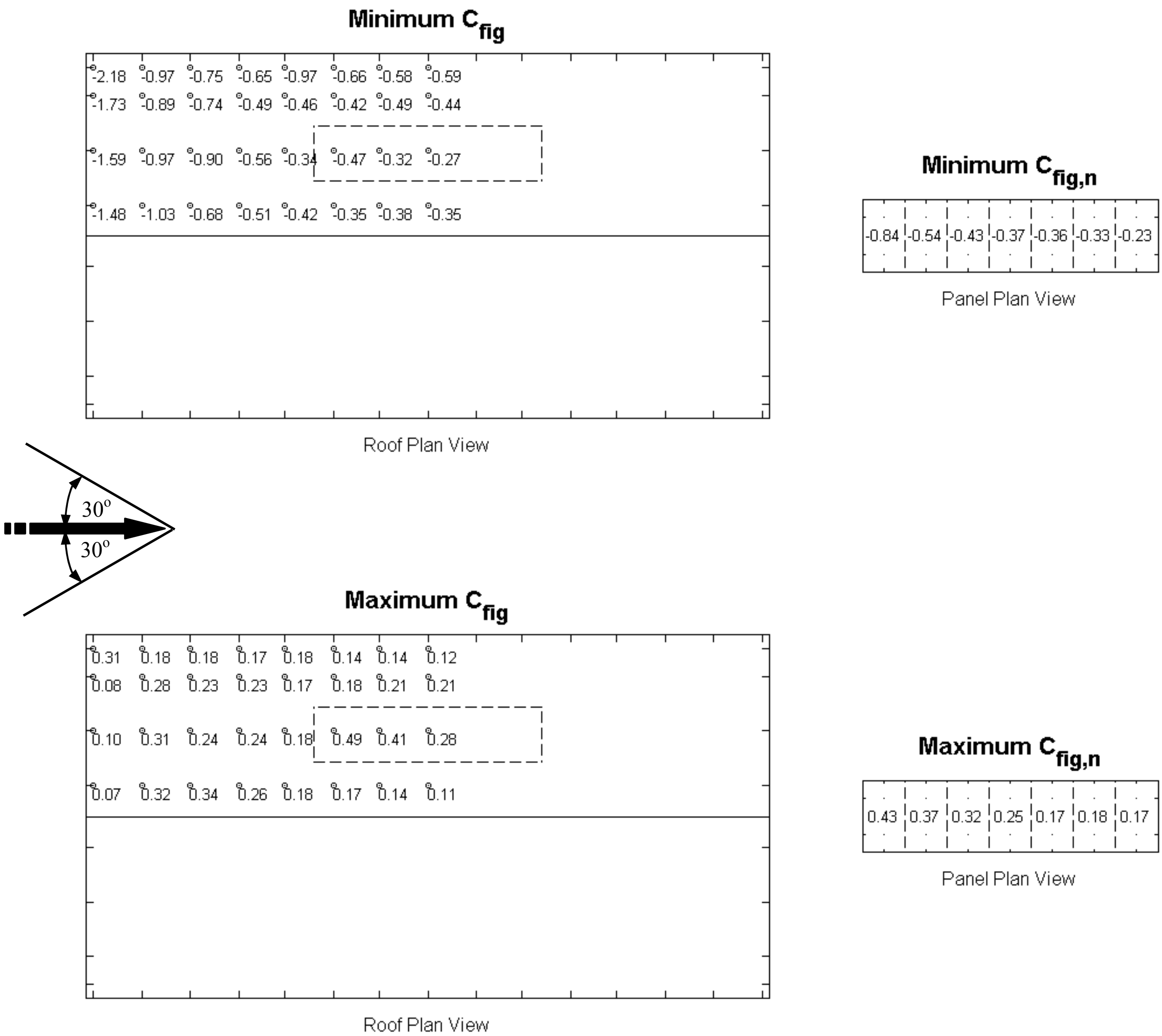


Figure A3-d. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 7.5°, Wind Direction 270° ± 30°

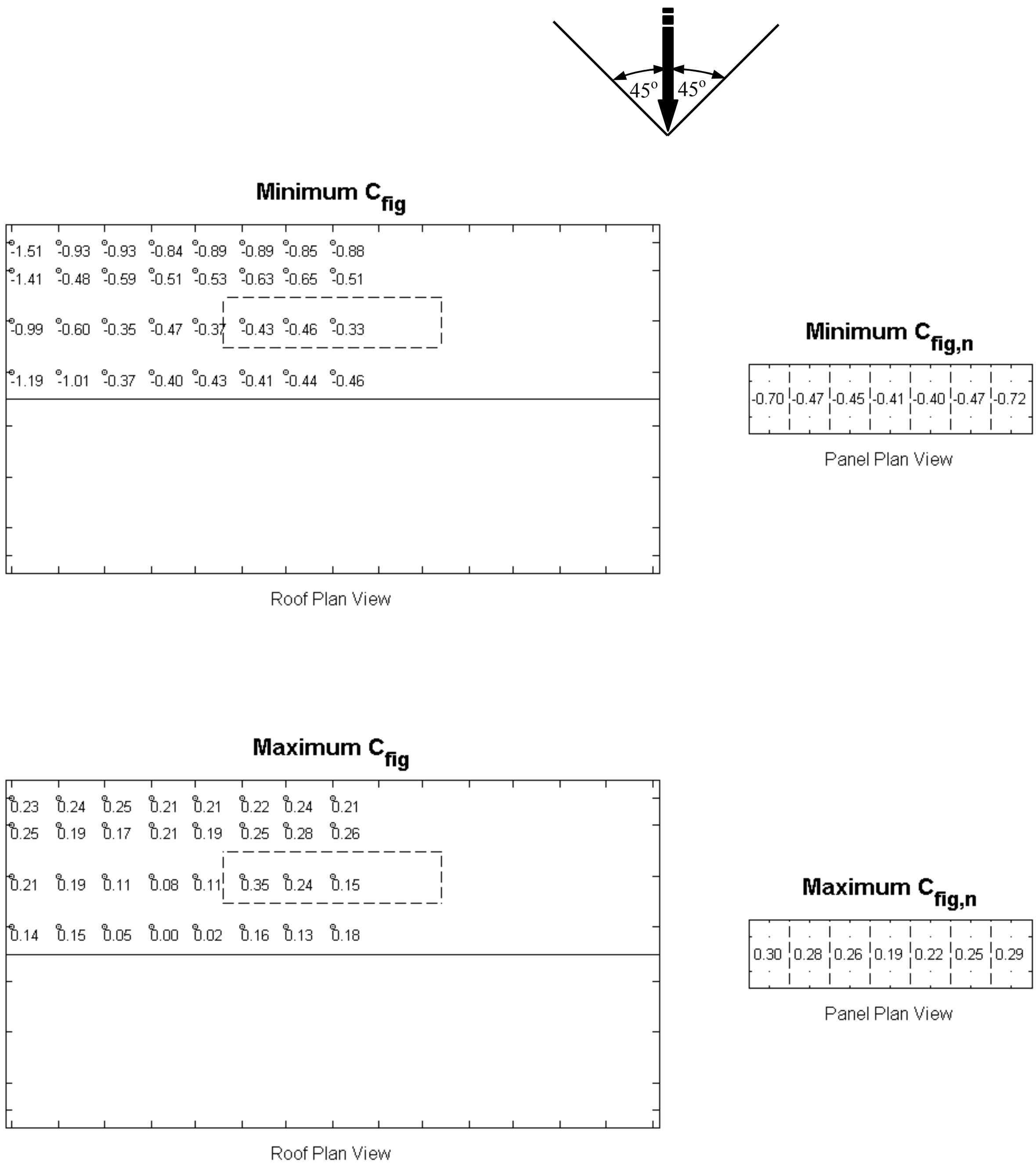


Figure A3-e. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 15°, Wind Direction 0° ± 45°

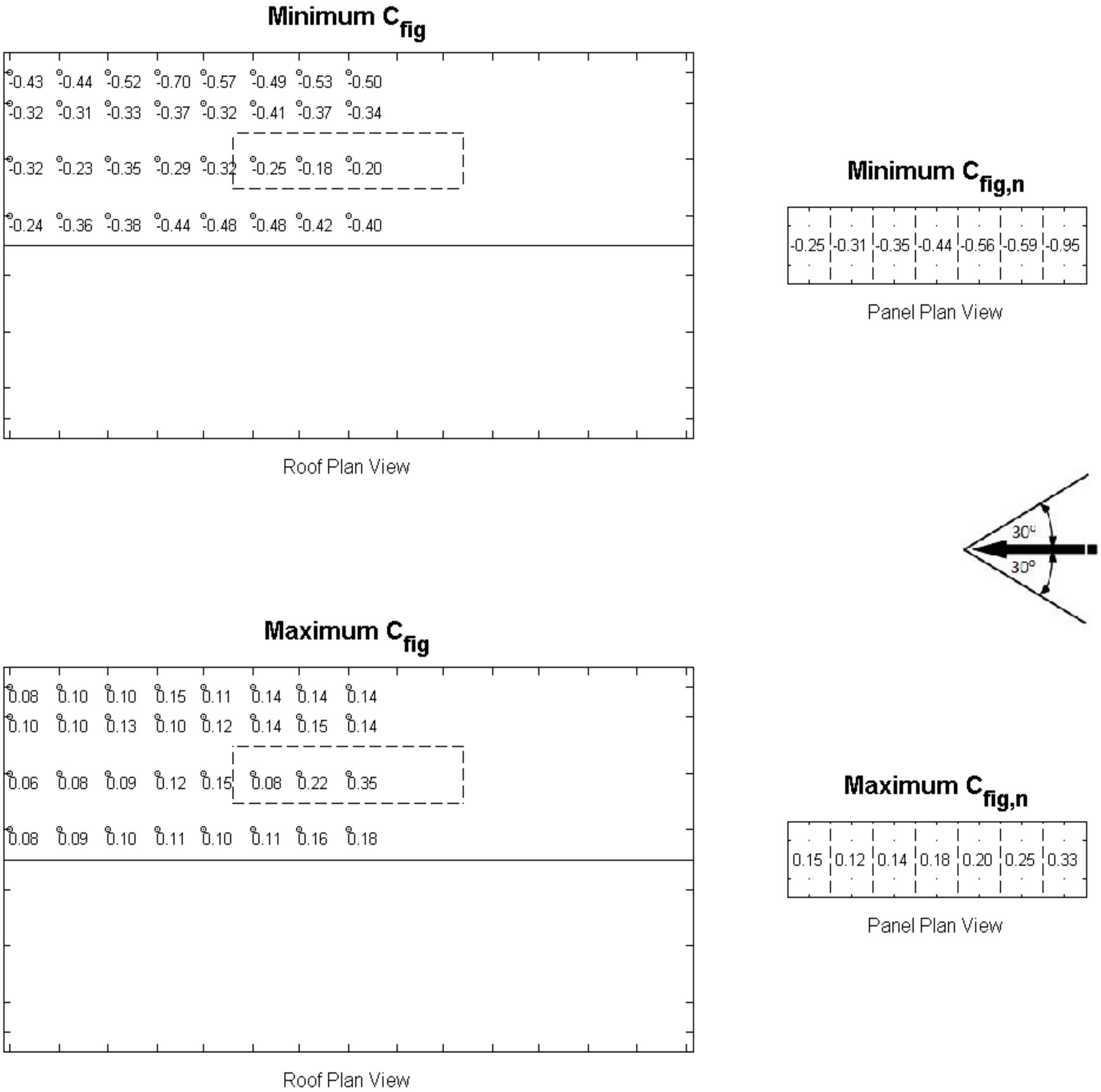
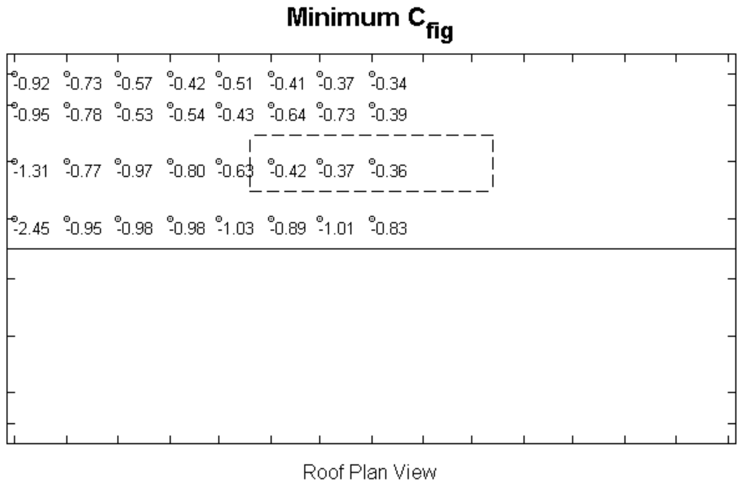
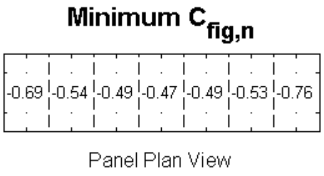
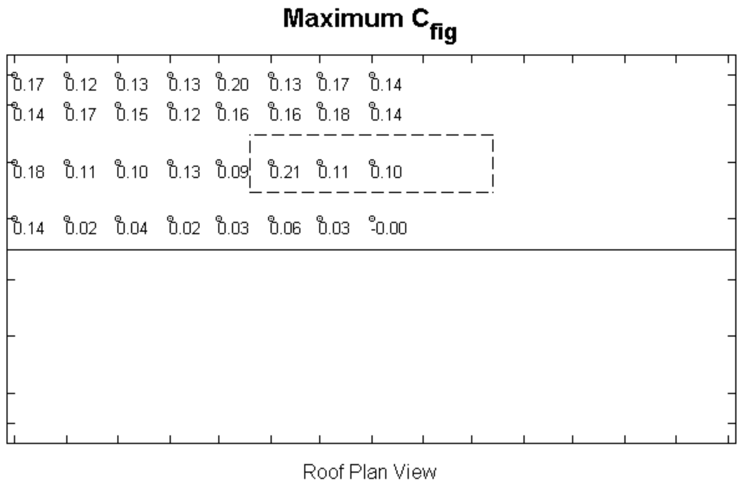
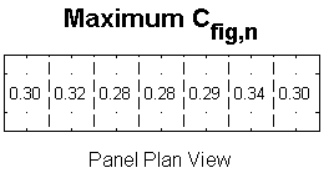


Figure A3-f. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 15°, Wind Direction 90° ± 30°









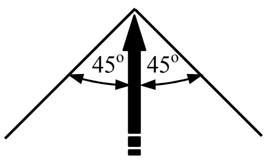


Figure A3-g. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 15°, Wind Direction 180° ± 45°

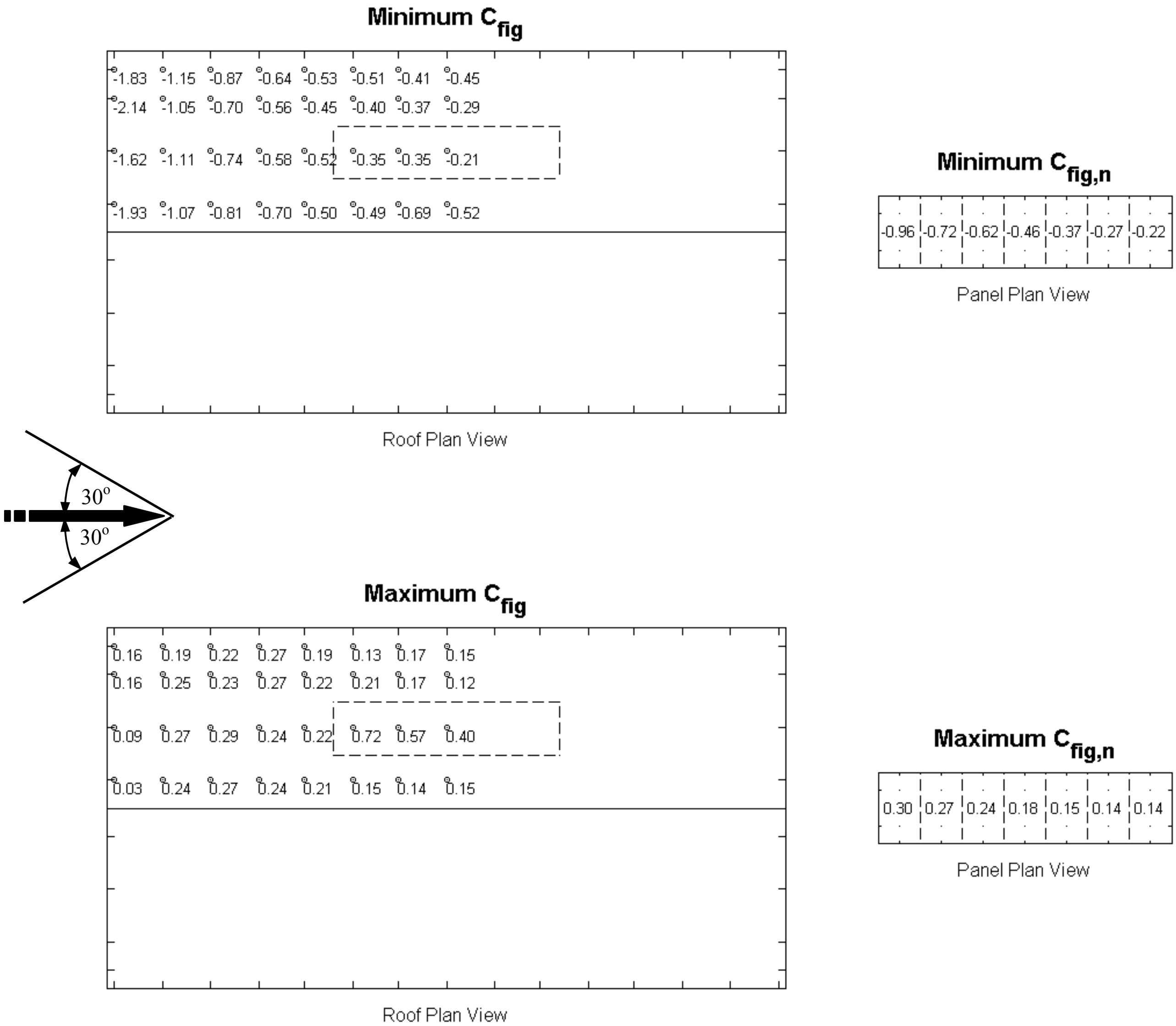


Figure A3-h. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 15^o, Wind Direction 270^o ± 30^o

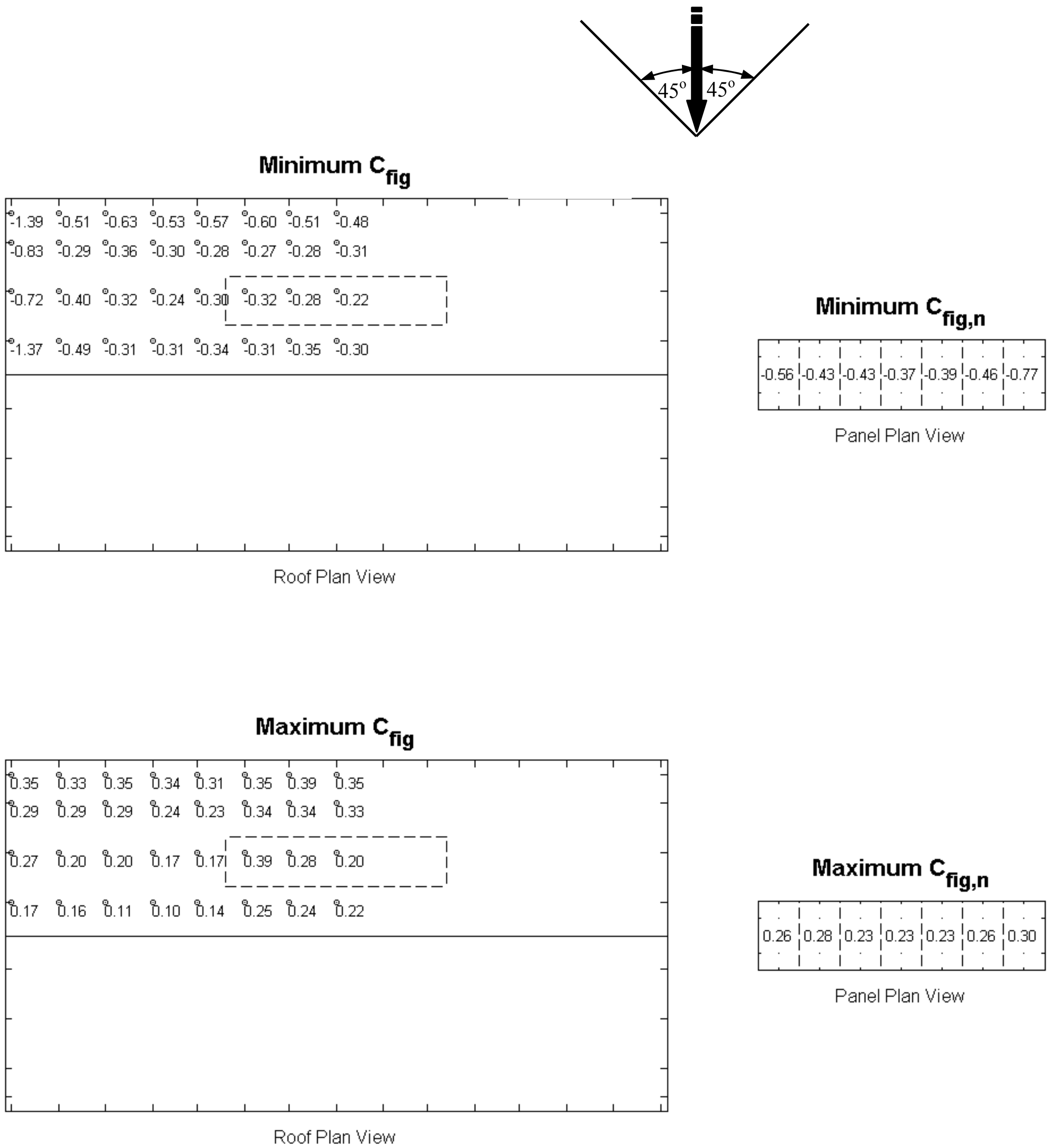


Figure A3-i. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 22.5°, Wind Direction 0° ± 45°

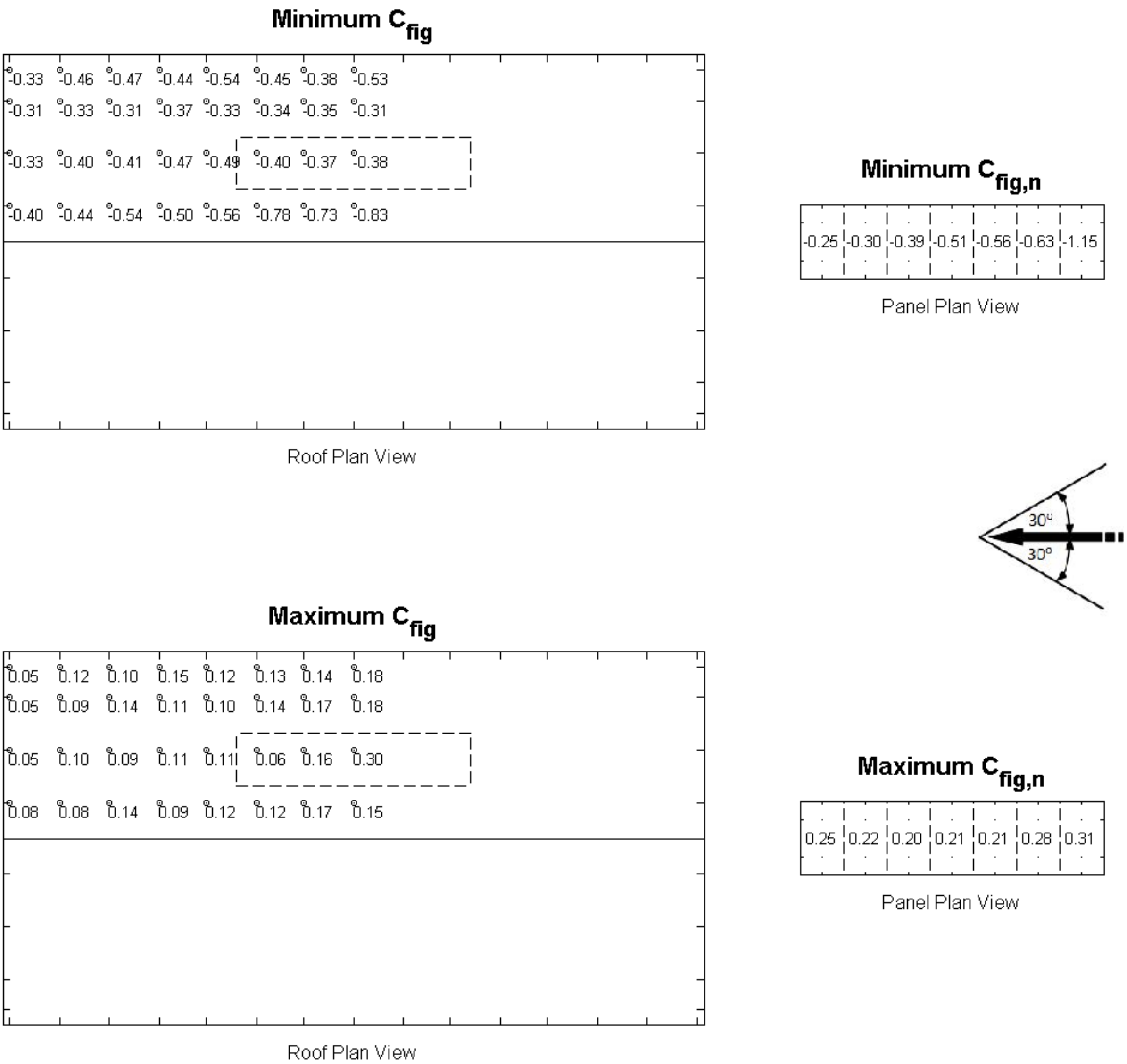
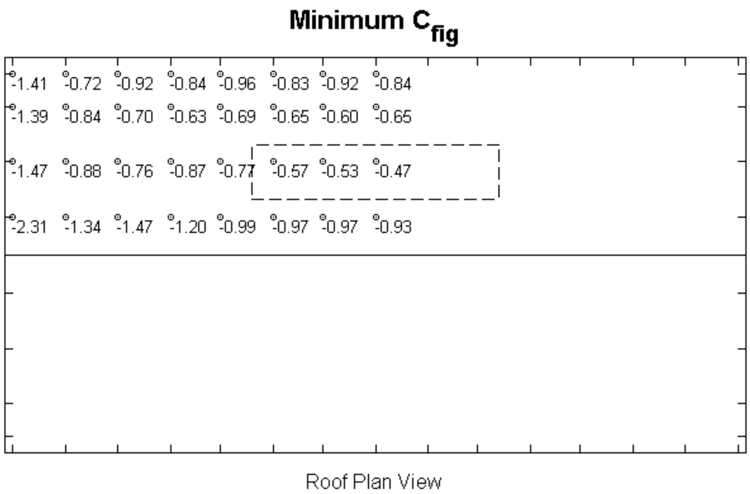
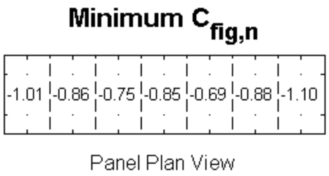
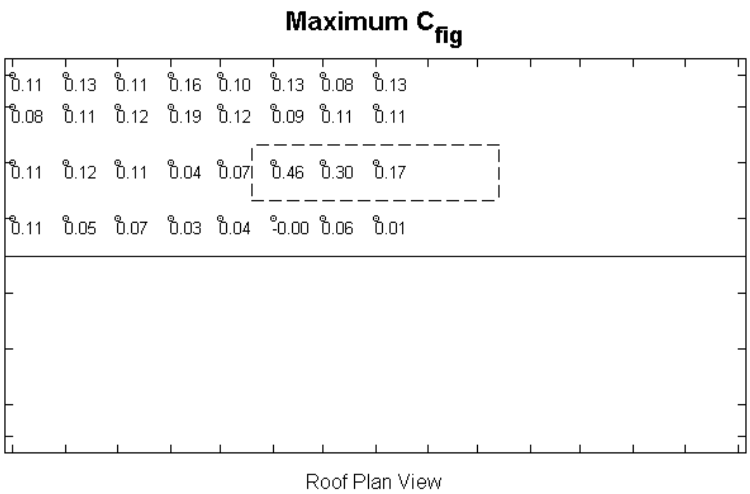
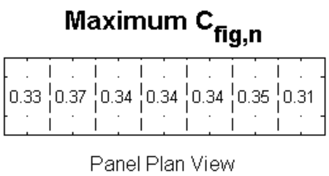


Figure A3-j.- C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 22.5^o, Wind Direction 90^o ± 30^o









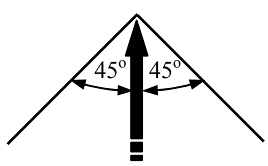


Figure A3-k. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 22.5°, Wind Direction 180° ± 45°

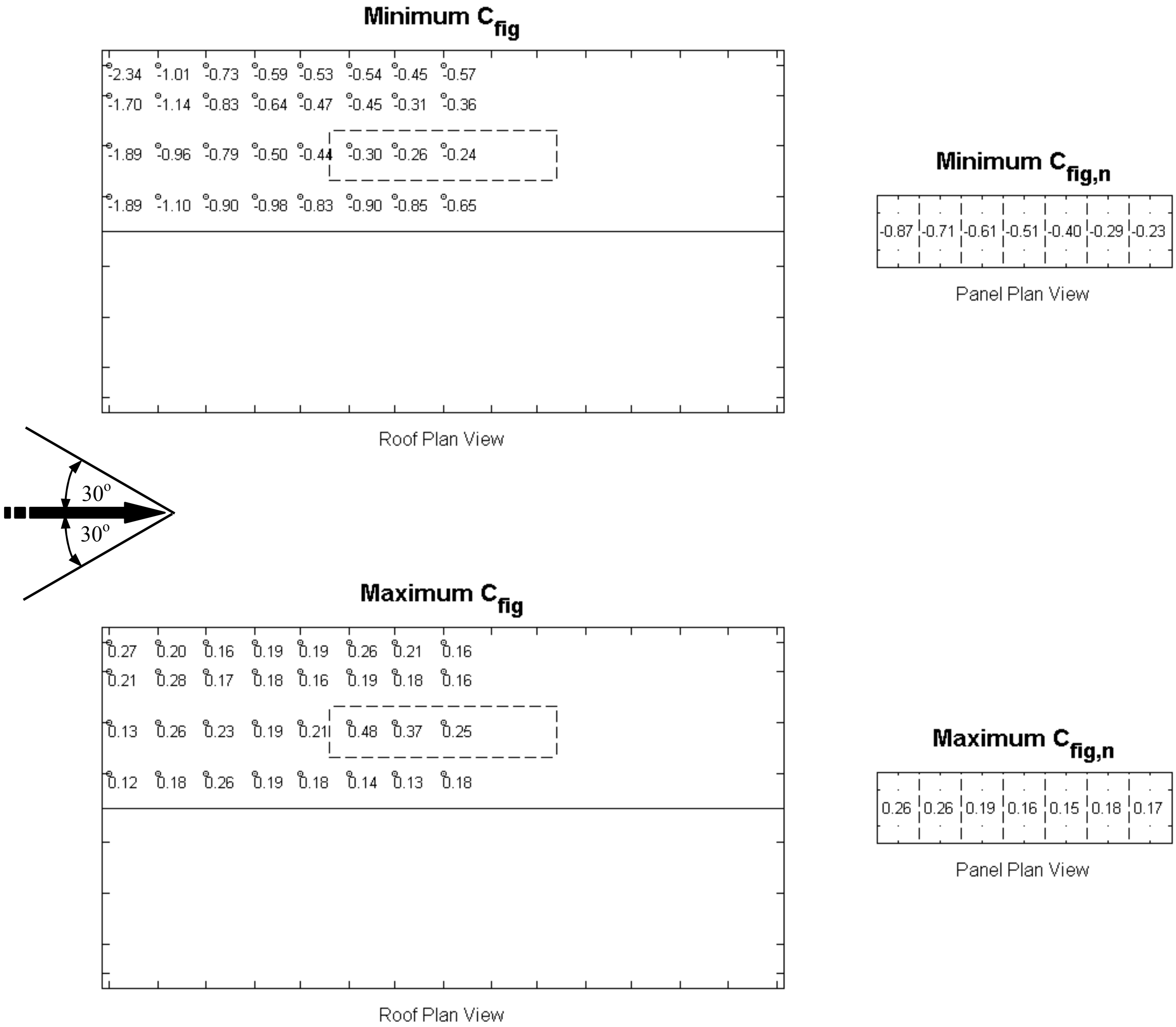


Figure A3-l. C_{fig} – Panel Position B, Gap 100mm - Roof Pitch 22.5°, Wind Direction 270° ± 30°

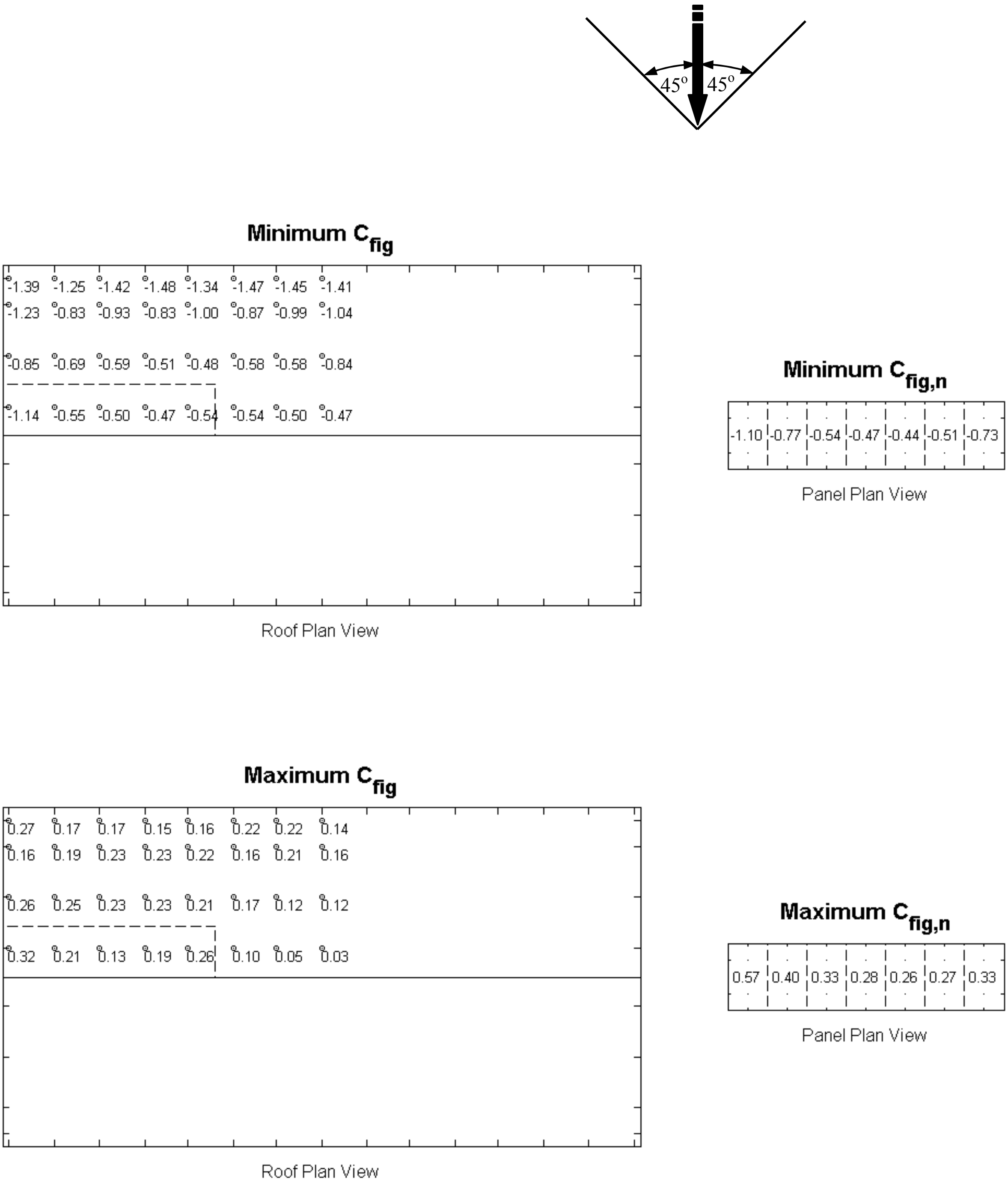


Figure A4-a. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 7.5°, Wind Direction 0° ± 45°

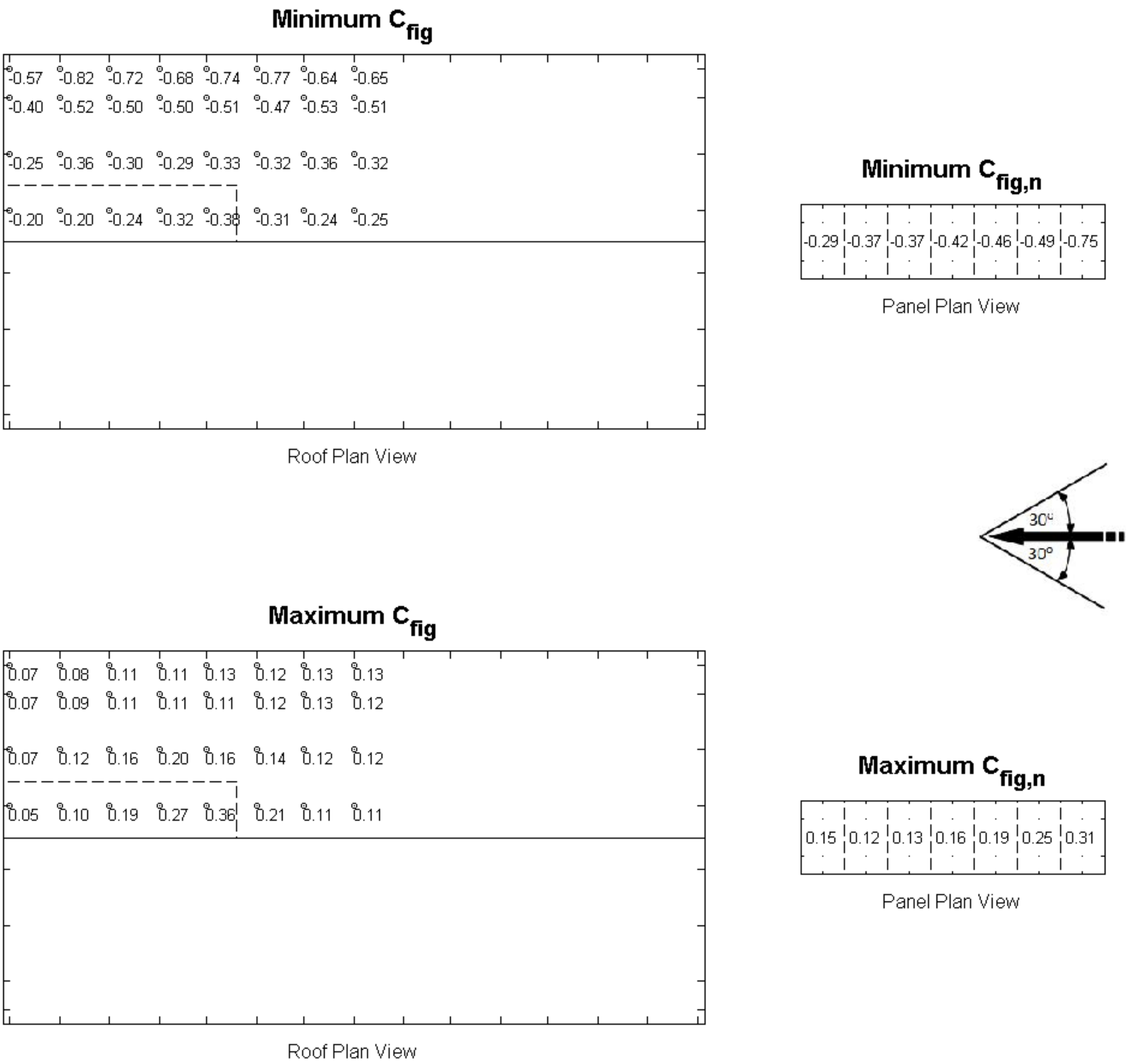


Figure A4-b. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 7.5^o, Wind Direction 90^o ± 30^o

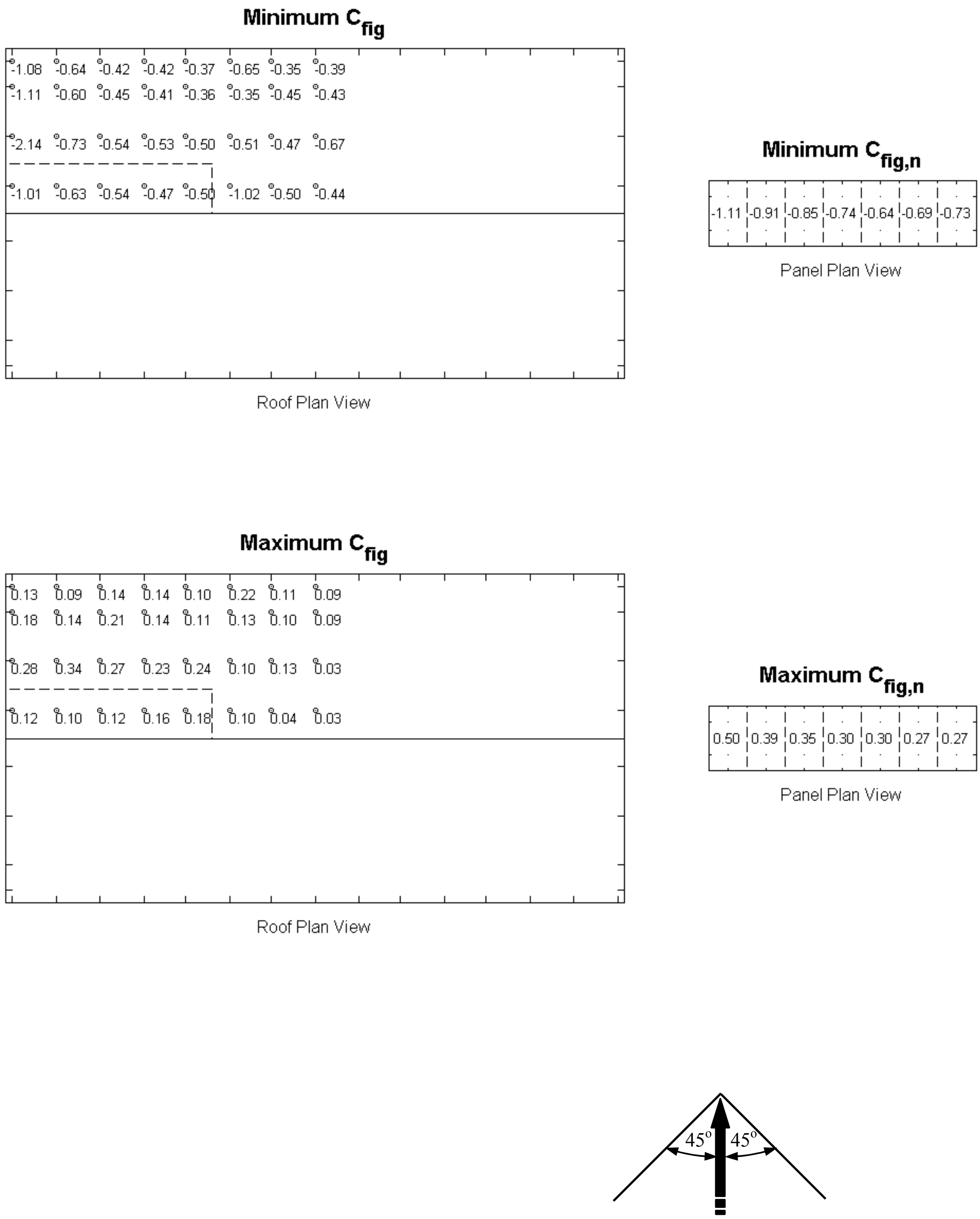


Figure A4-c. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 7.5°, Wind Direction 180° ± 45°

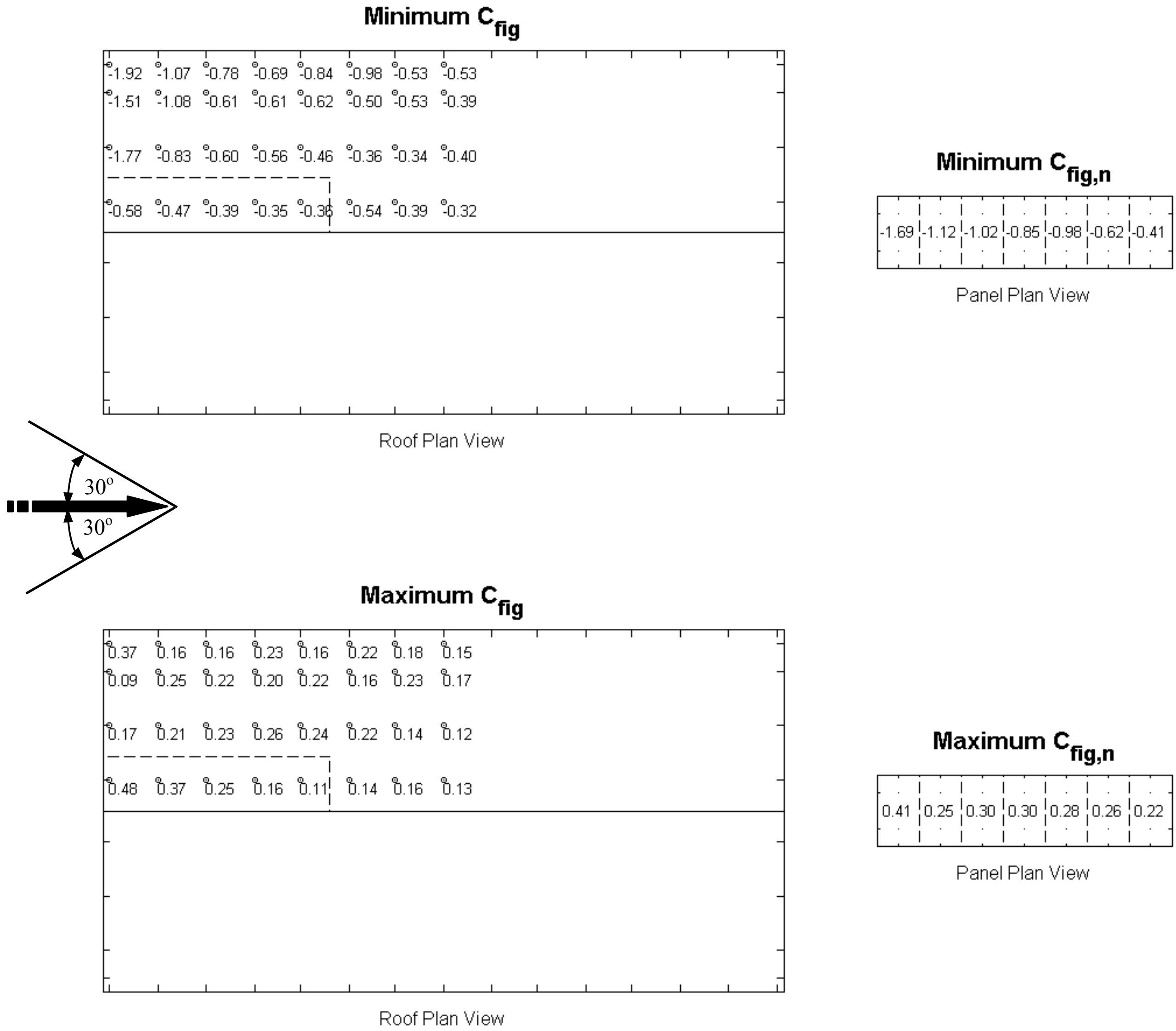


Figure A4-d. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 7.5^o, Wind Direction 270^o ± 30^o

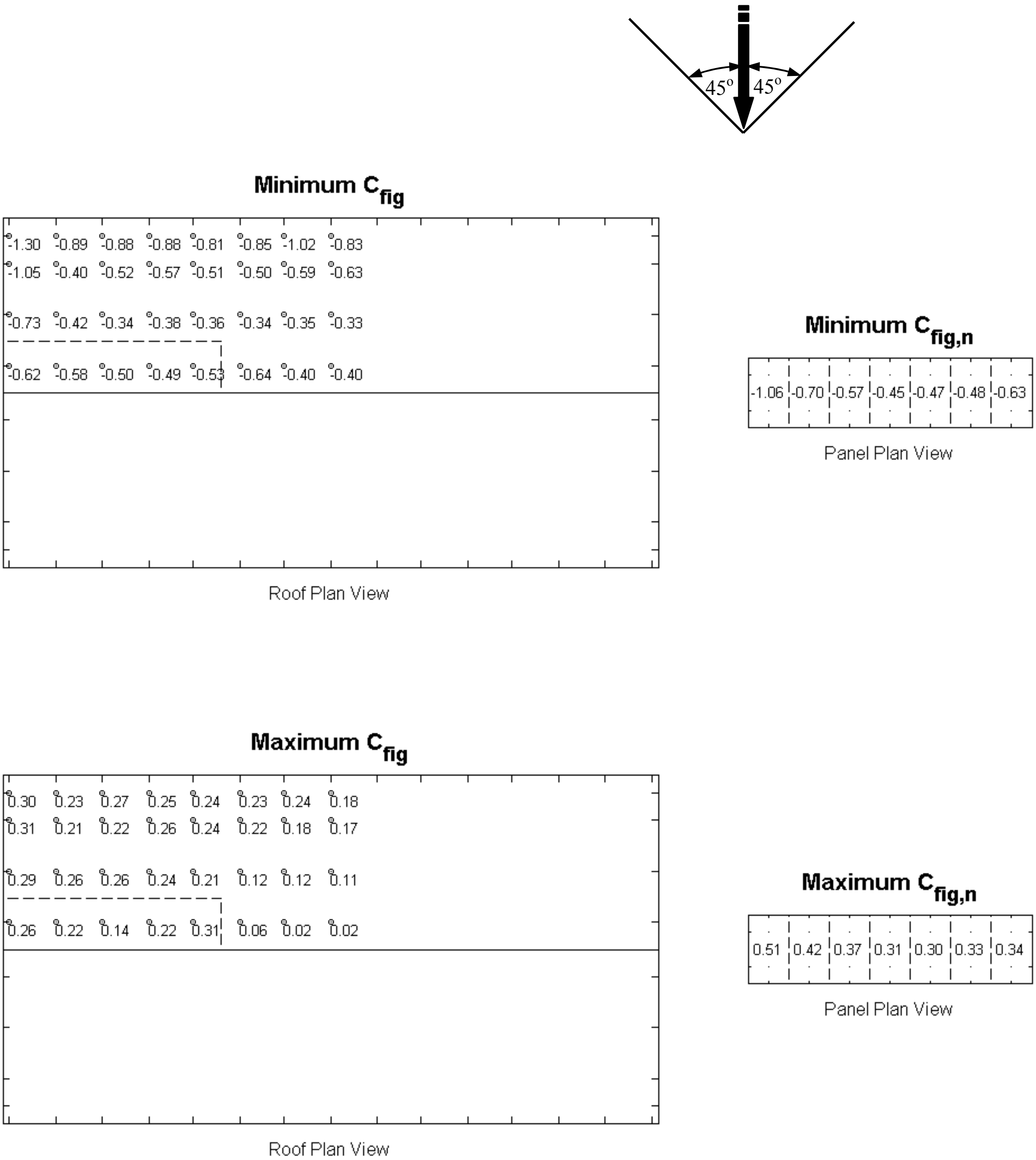


Figure A4-e. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 15^o, Wind Direction 0^o ± 45^o

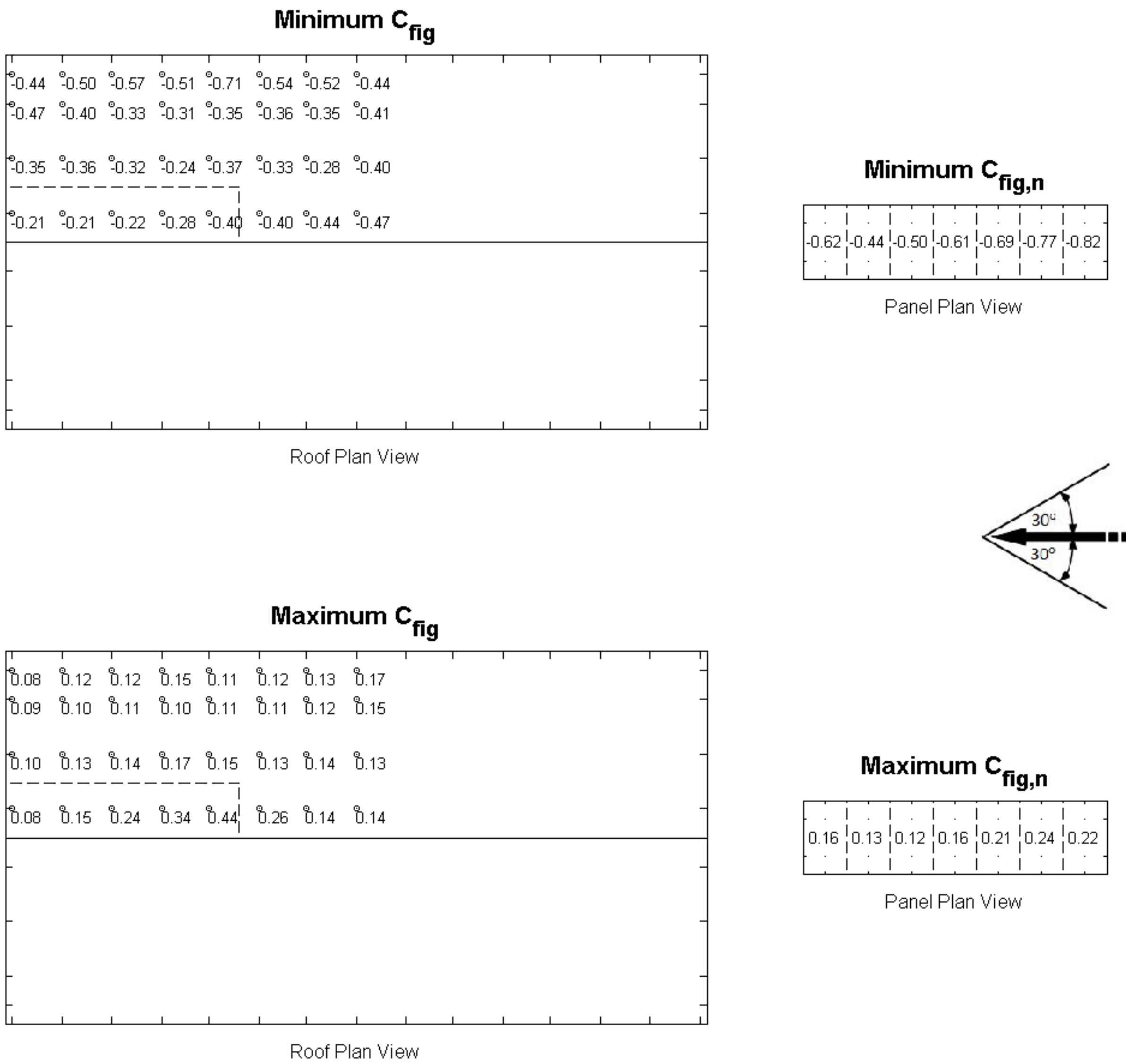


Figure A4-f. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 15°, Wind Direction 90° ± 30°

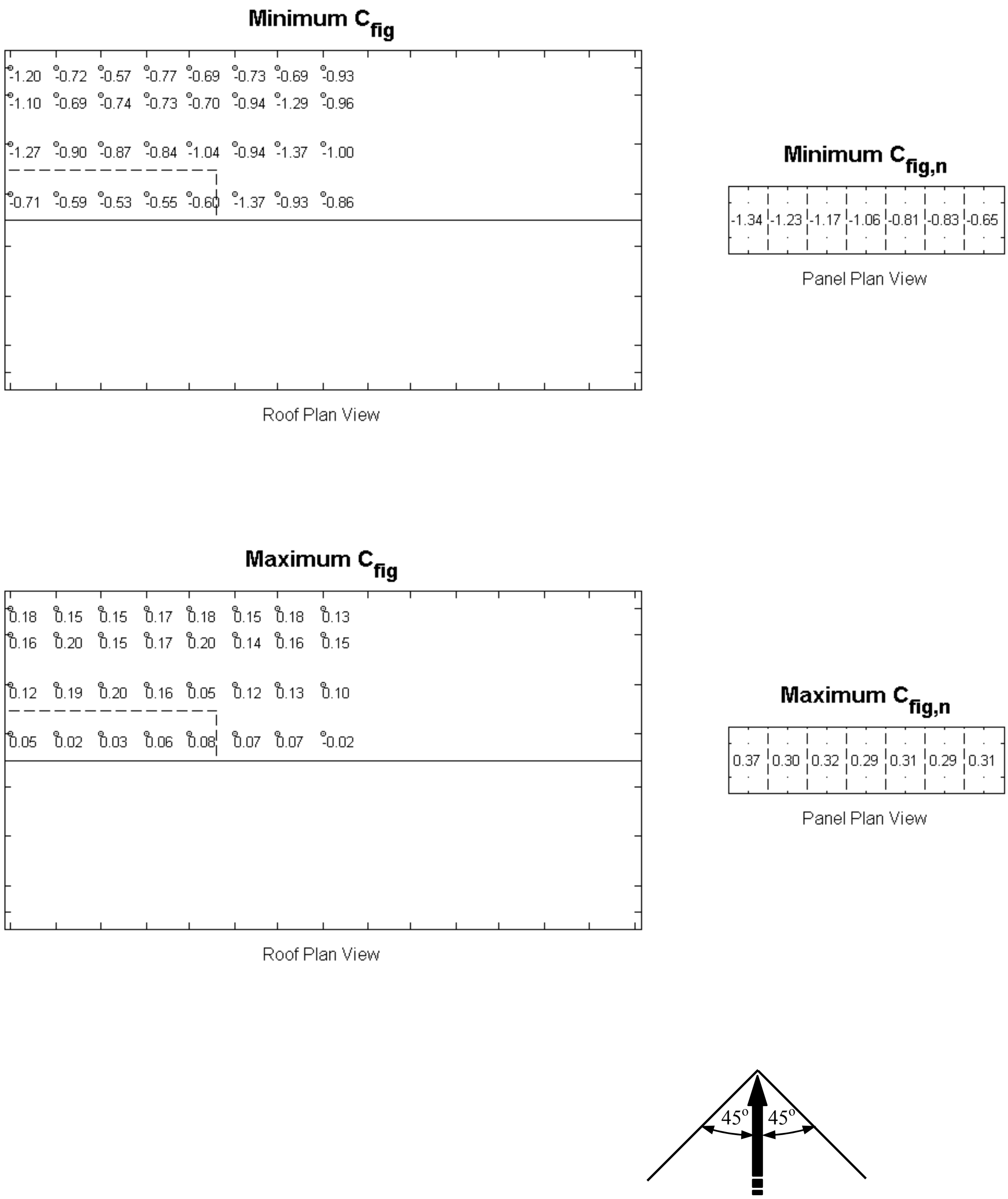


Figure A4-g. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 15°, Wind Direction 180° ± 45°

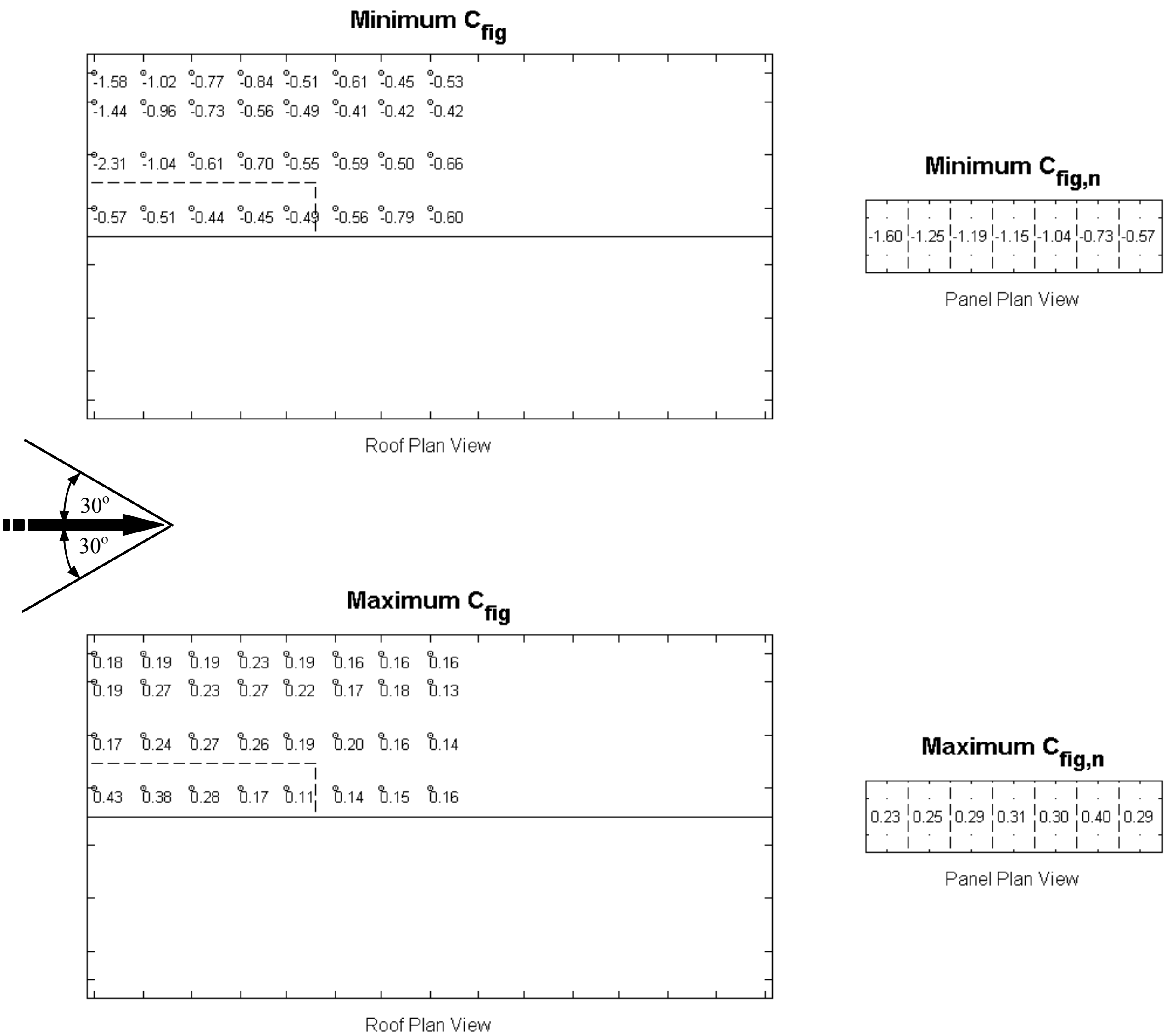


Figure A4-h. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 15^o, Wind Direction 270^o ± 30^o

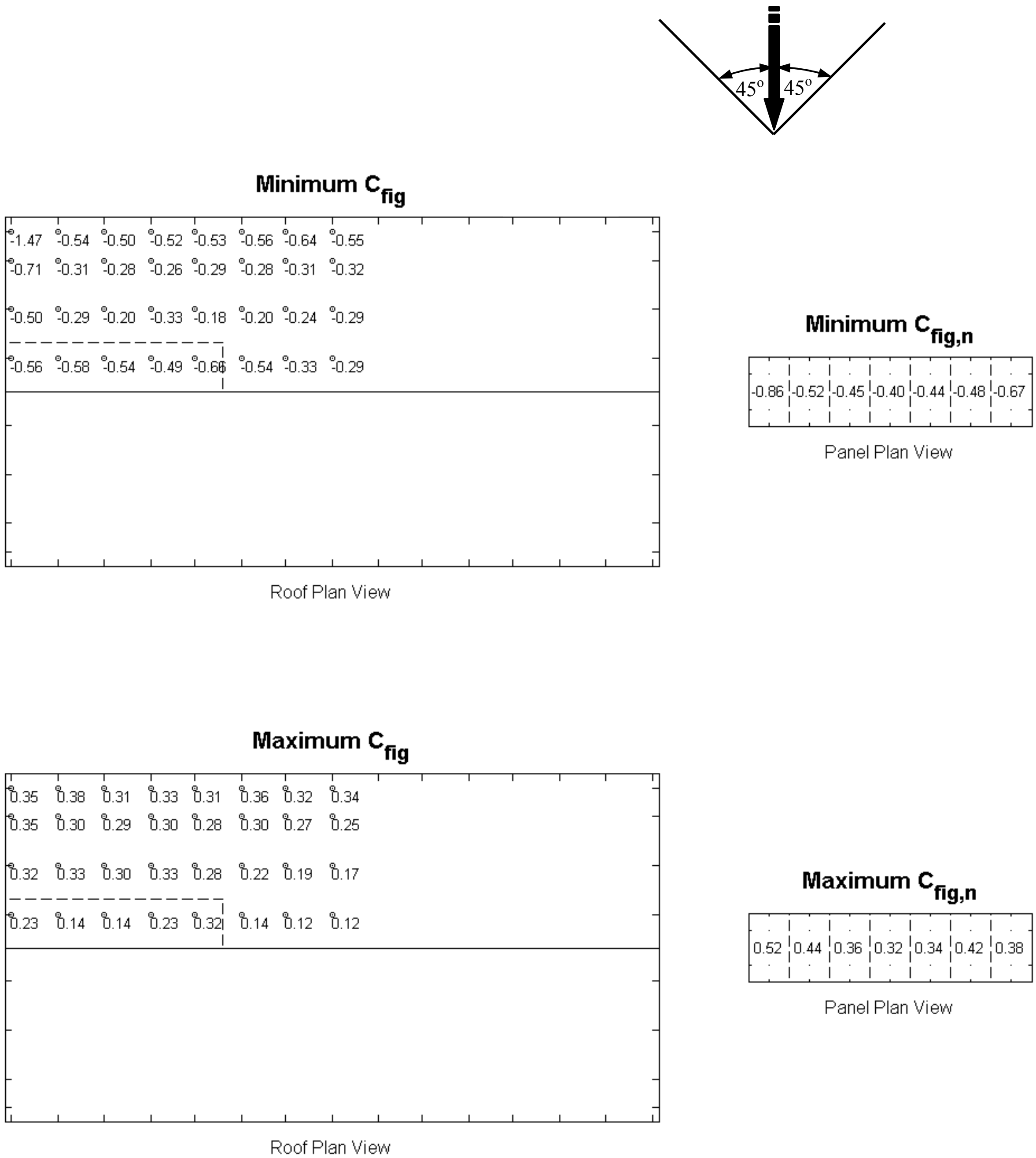


Figure A4-i. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 22.5°, Wind Direction 0° ± 45°

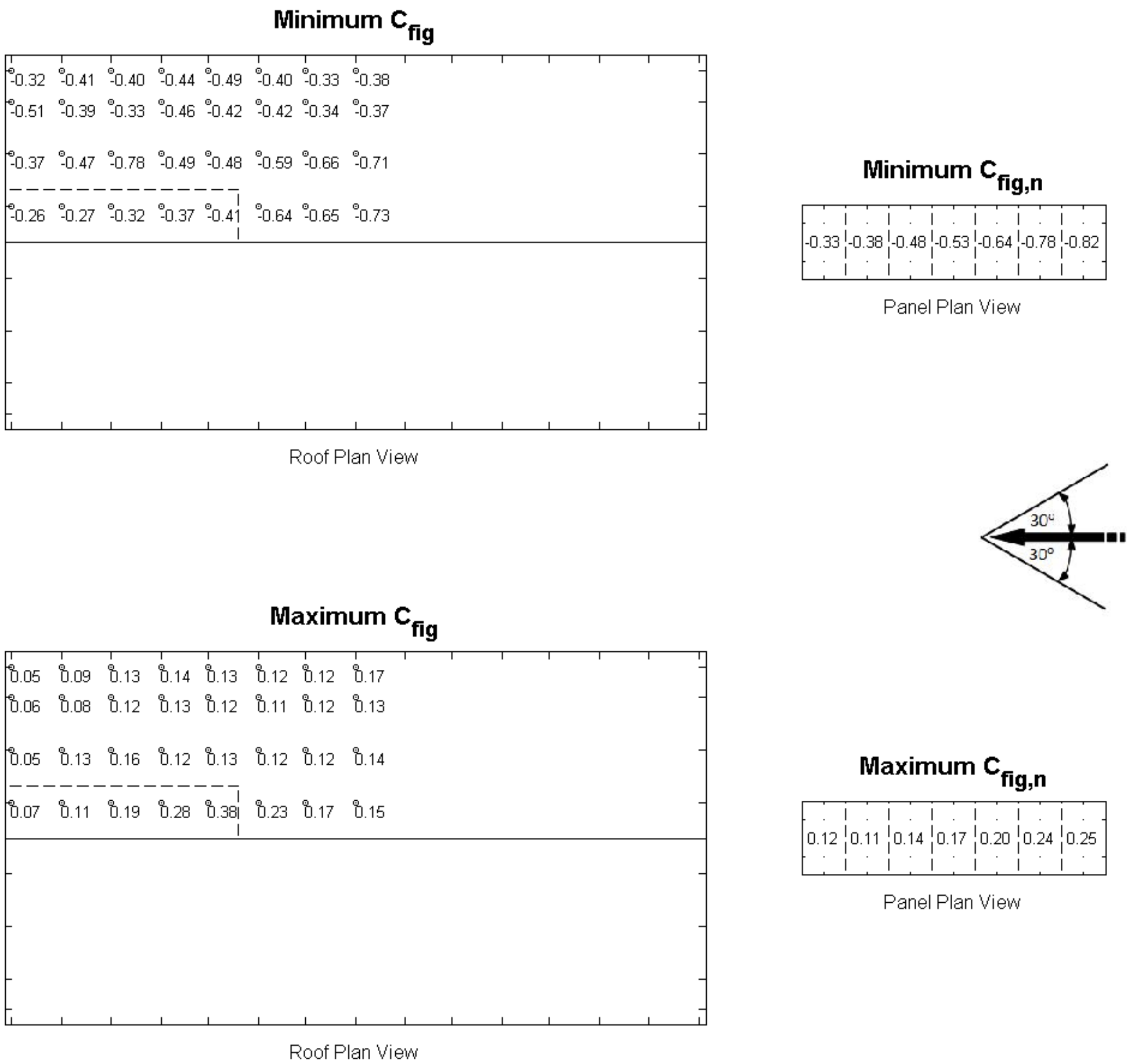
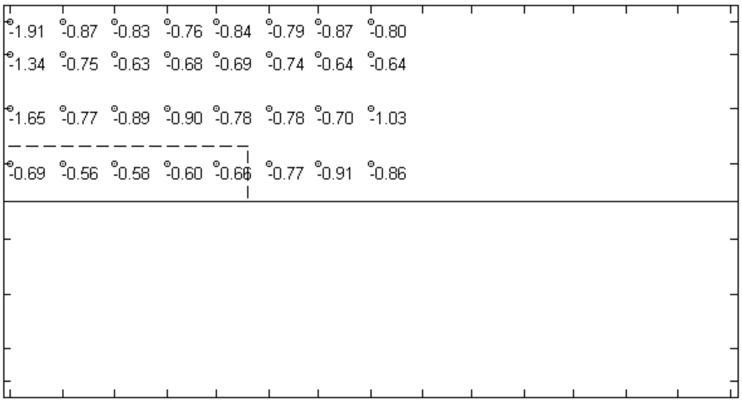


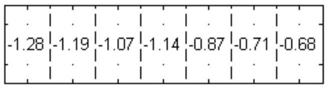
Figure A4-j. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 22.5^o, Wind Direction 90^o ± 30^o

Minimum C_{fig}



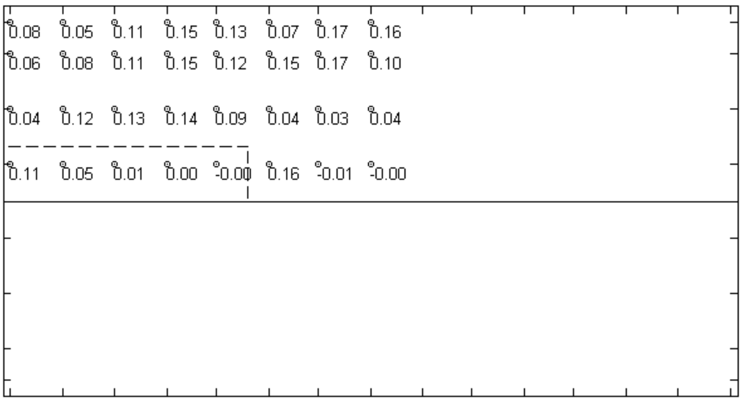
Roof Plan View

Minimum $C_{fig,n}$



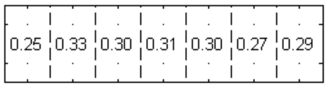
Panel Plan View

Maximum C_{fig}



Roof Plan View

Maximum $C_{fig,n}$



Panel Plan View

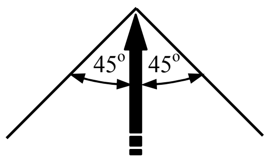


Figure A4-k. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 22.5°, Wind Direction 180° ± 45°

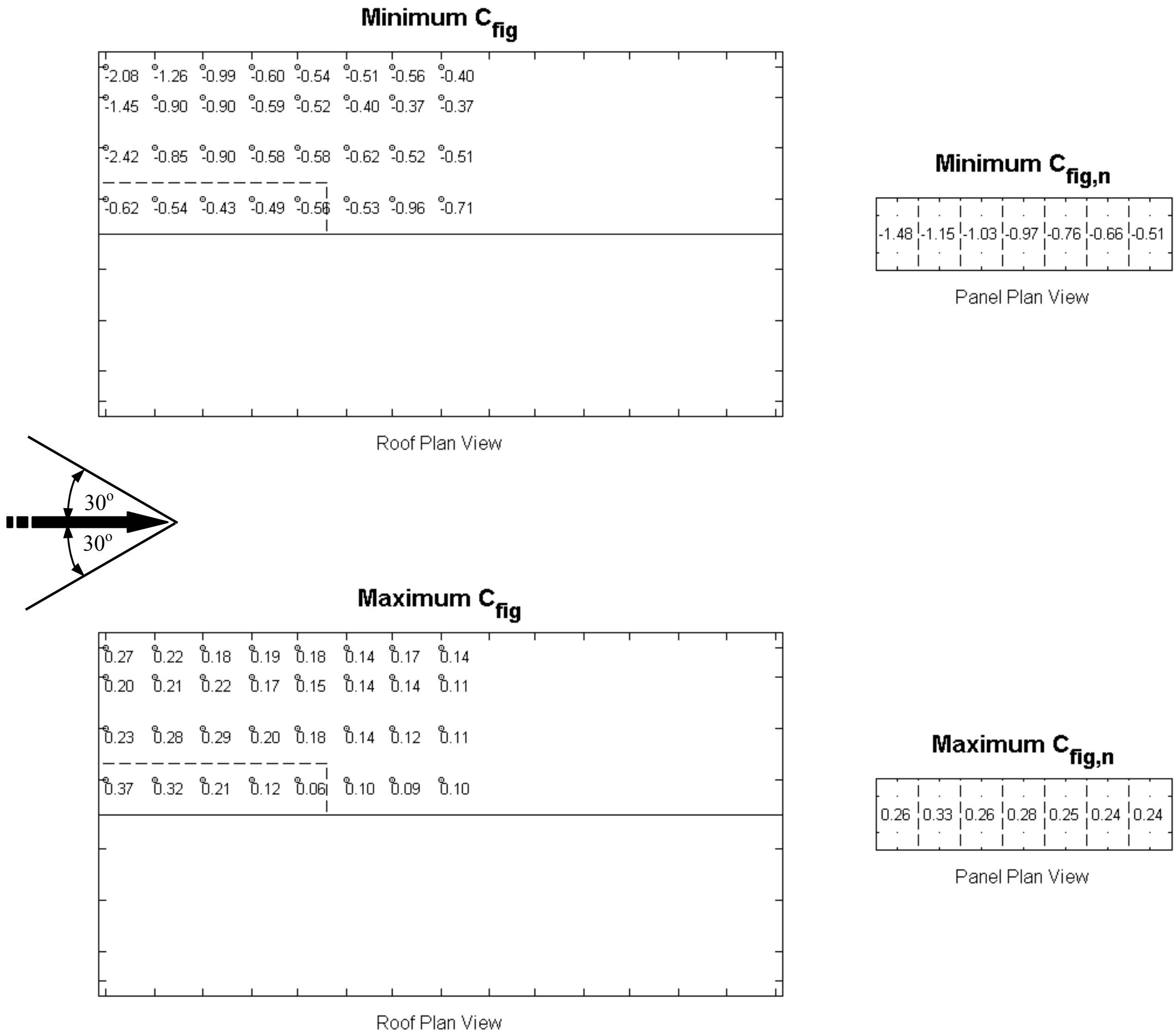


Figure A4-l. C_{fig} – Panel Position C, Gap 100mm - Roof Pitch 22.5°, Wind Direction 270° ± 30°

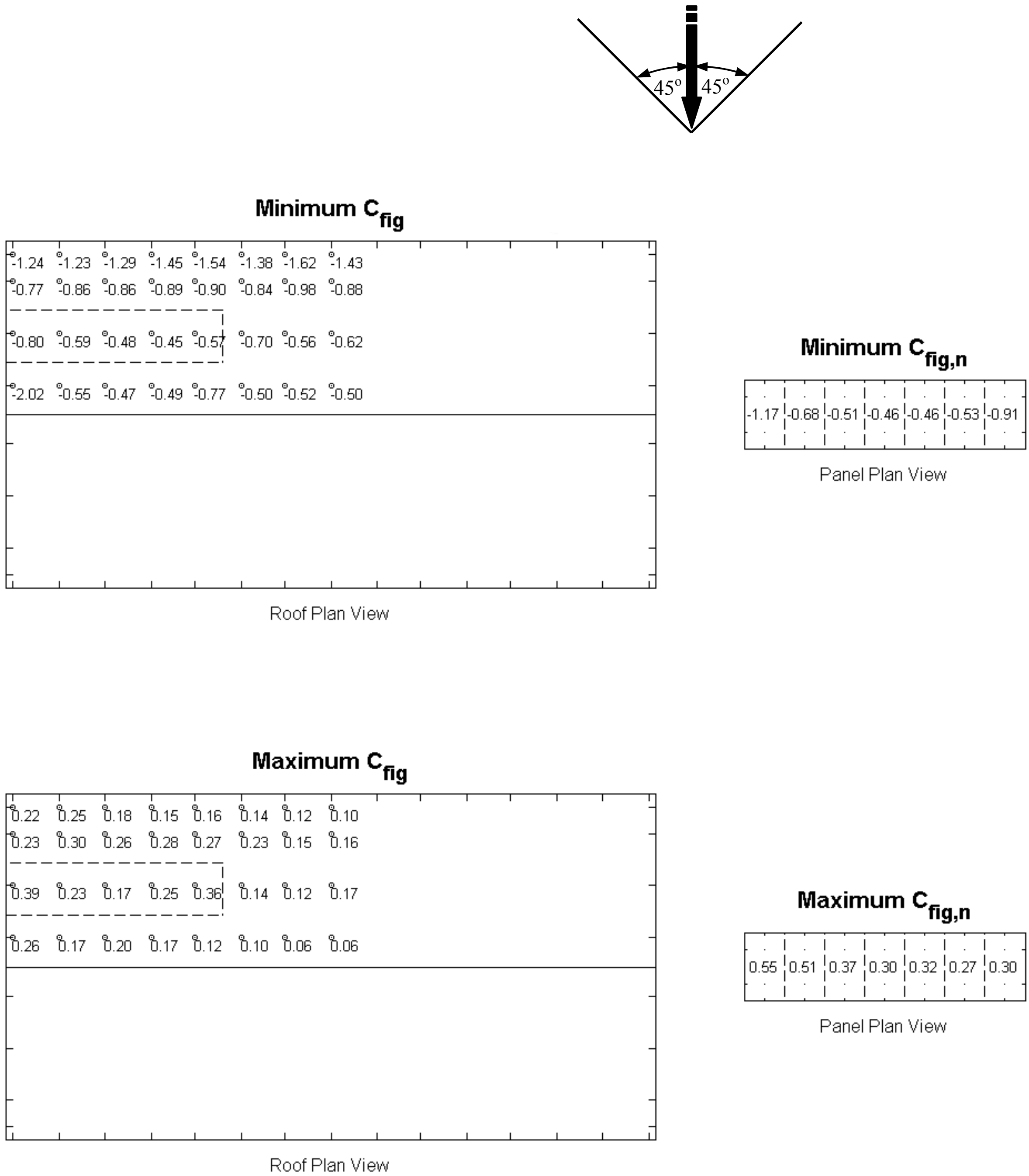


Figure A5-a. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 7.5°, Wind Direction 0° ± 45°

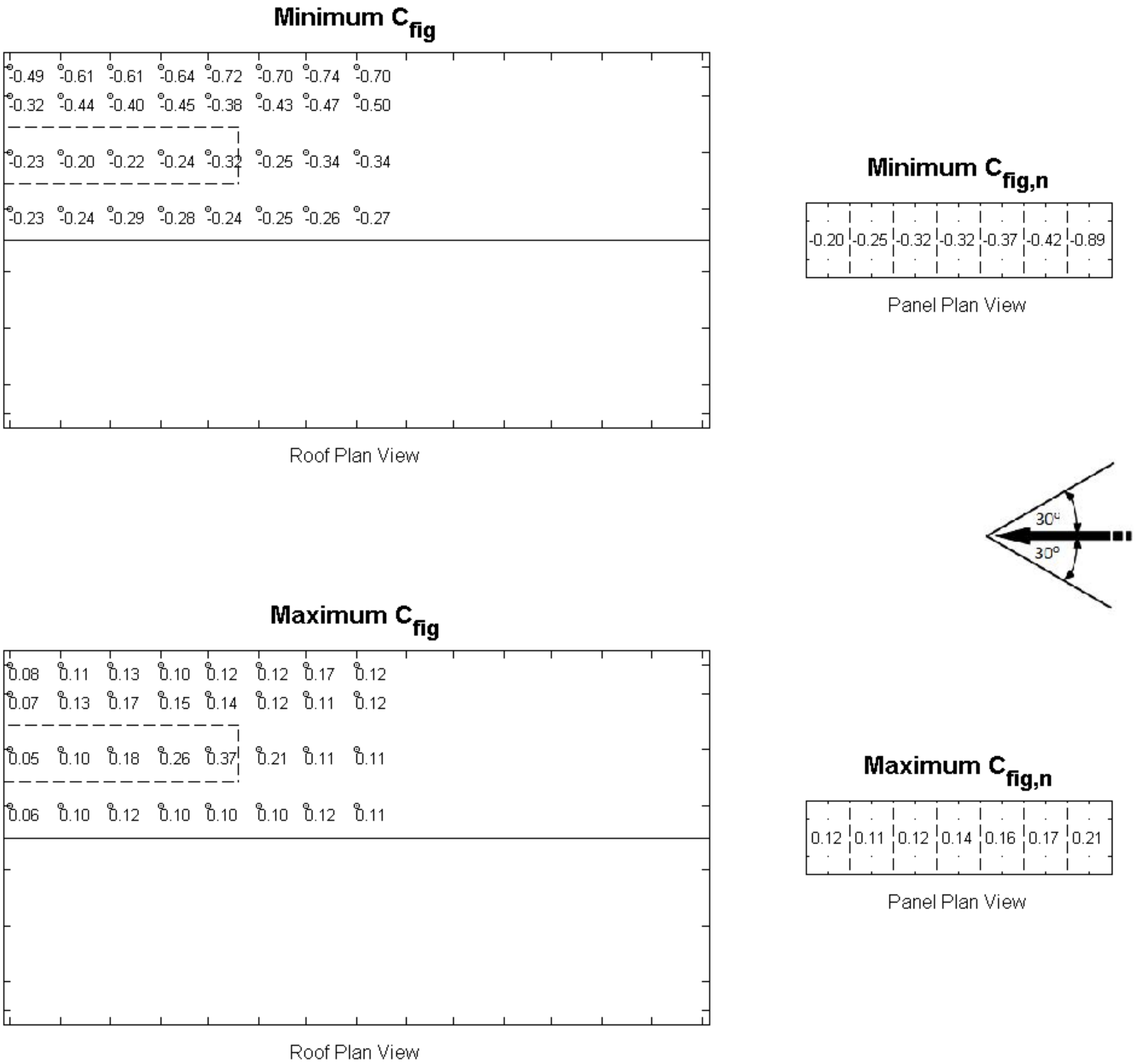
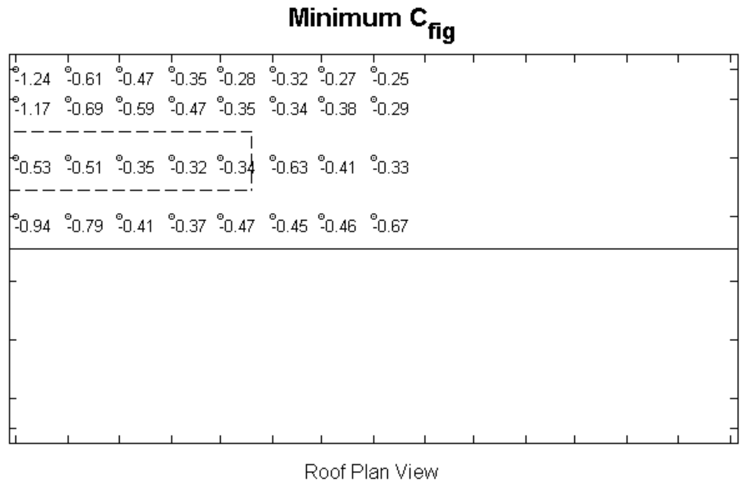
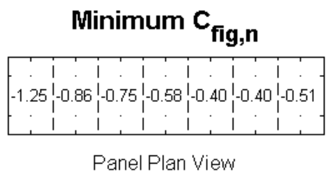
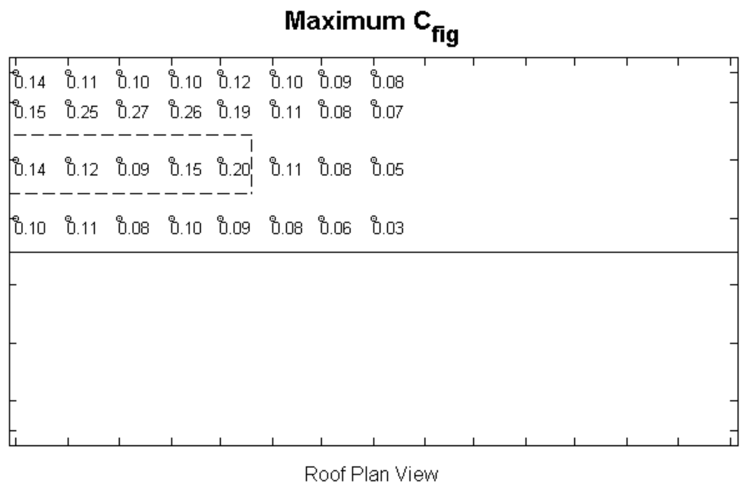
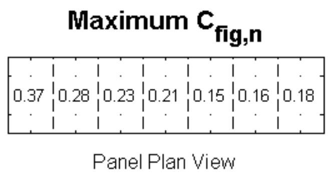


Figure A5-b. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 7.5^o, Wind Direction 90^o ± 30^o









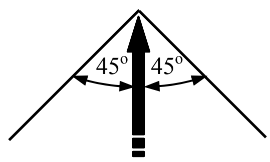


Figure A5-c. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 7.5°, Wind Direction 180° ± 45°

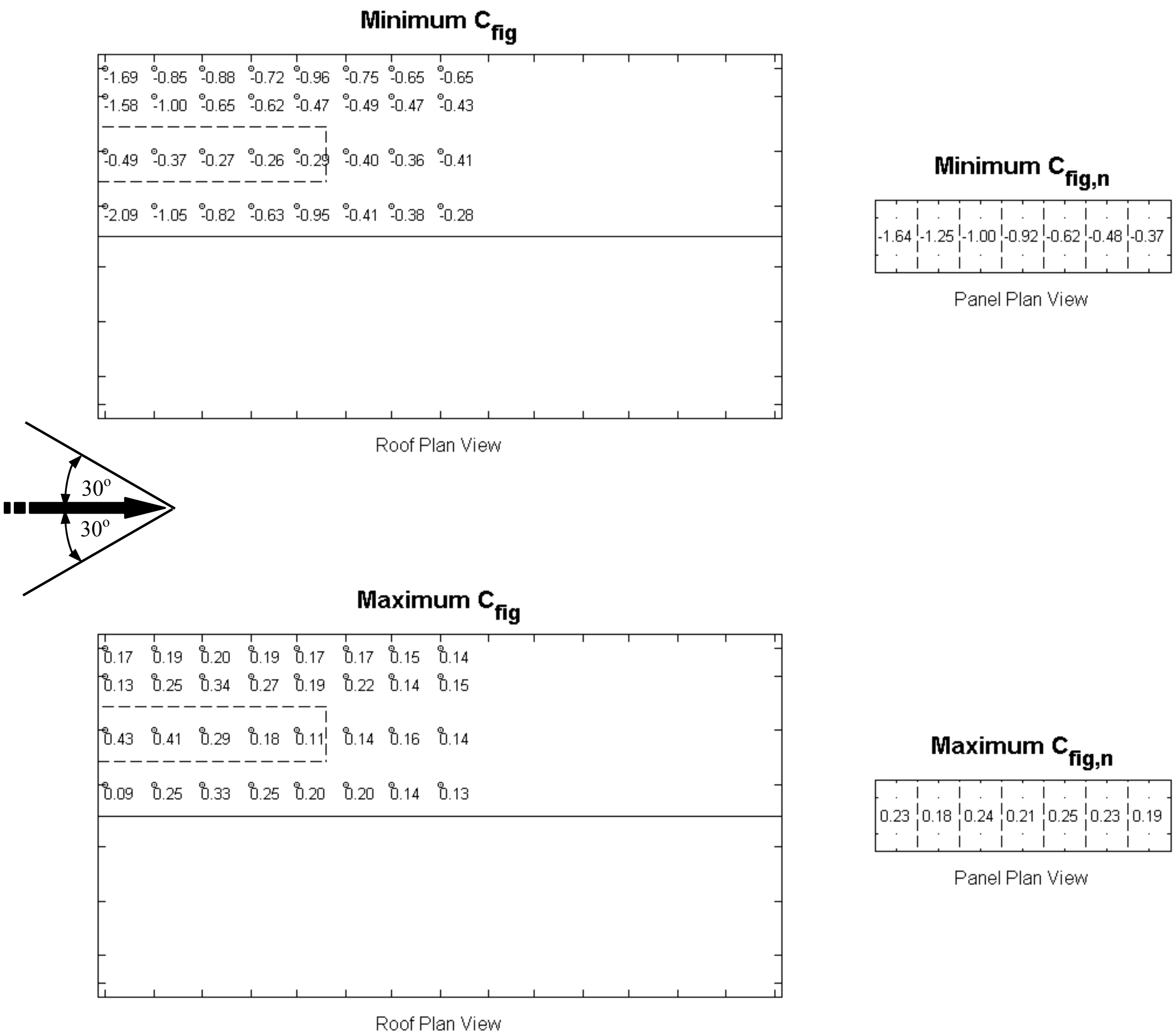
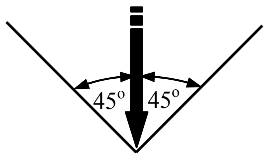
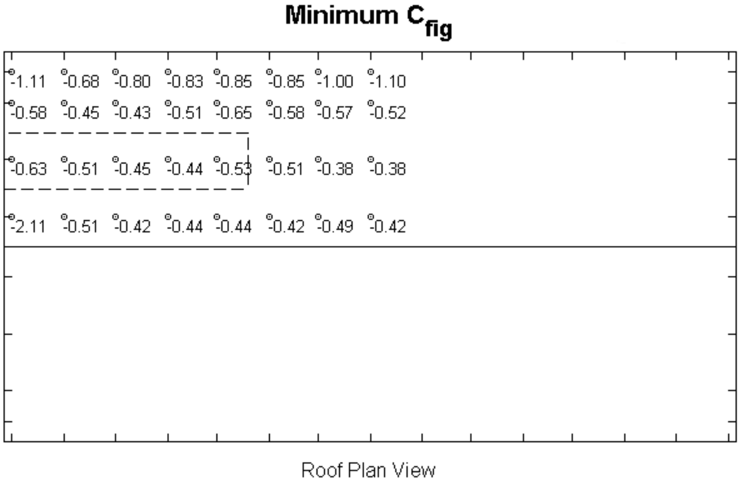
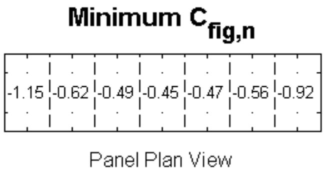
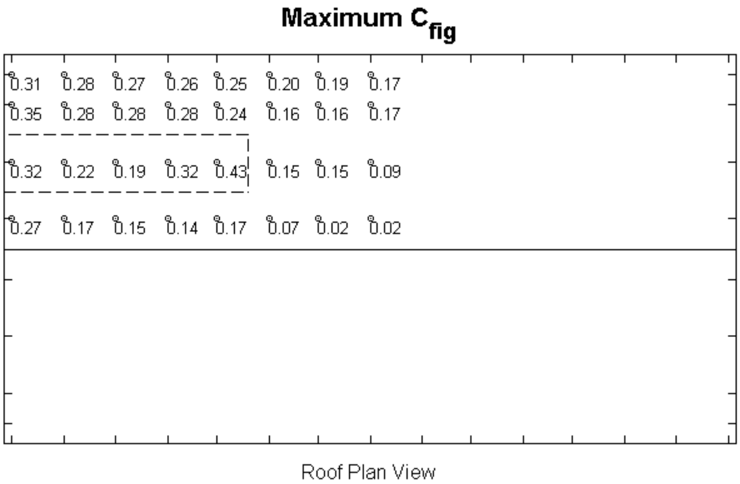


Figure 11d - C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 7.5°, Wind Direction 270° ± 30°









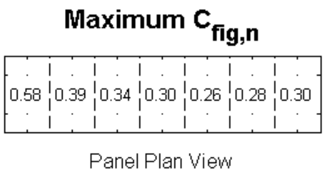


Figure A5-e. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 15°, Wind Direction 0° ± 45°

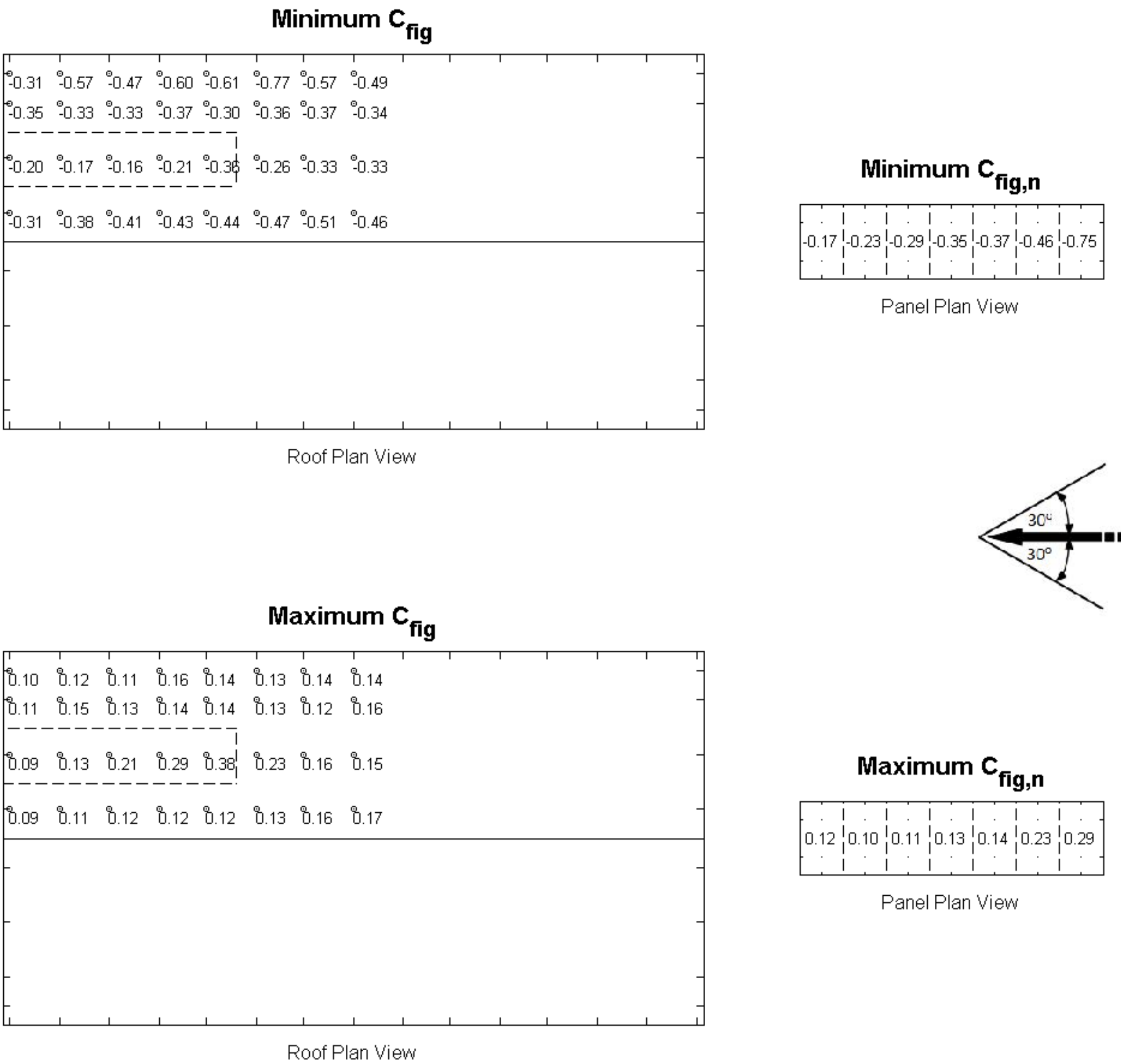


Figure A5-f. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 15°, Wind Direction 90° ± 30°

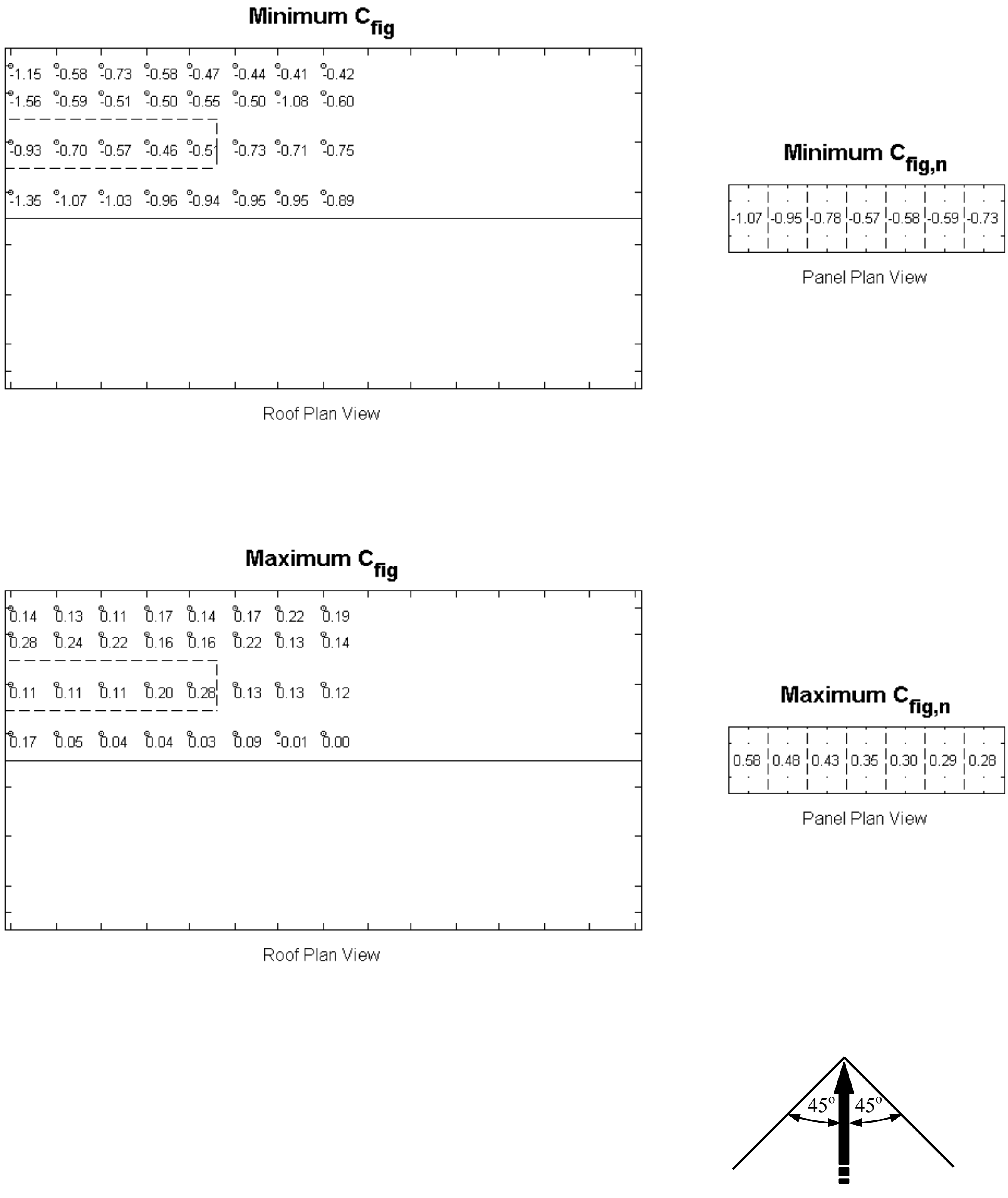


Figure A5-g. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 15^o, Wind Direction 180^o ± 45^o

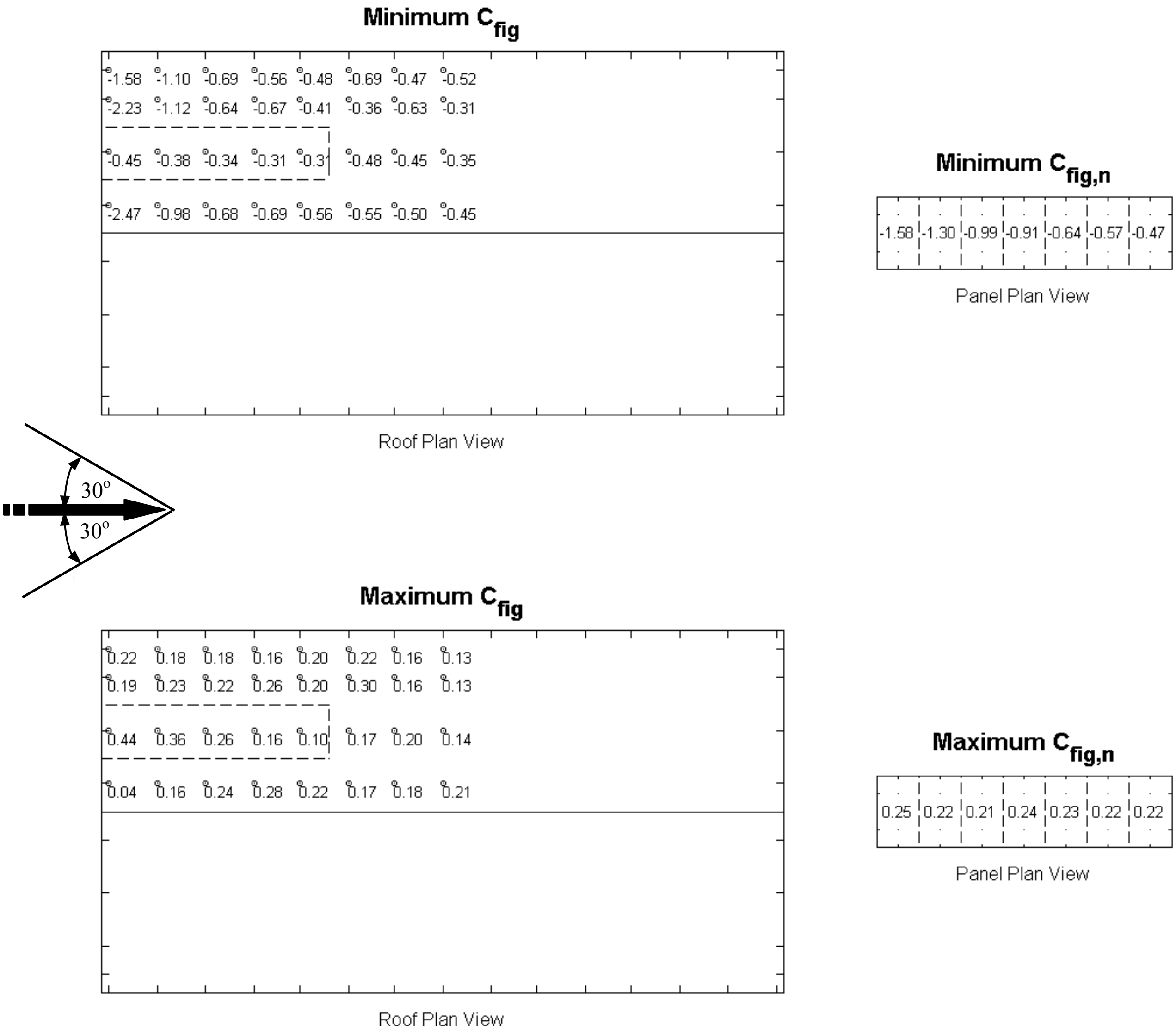


Figure 11h - C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 15°, Wind Direction 270° ± 30°

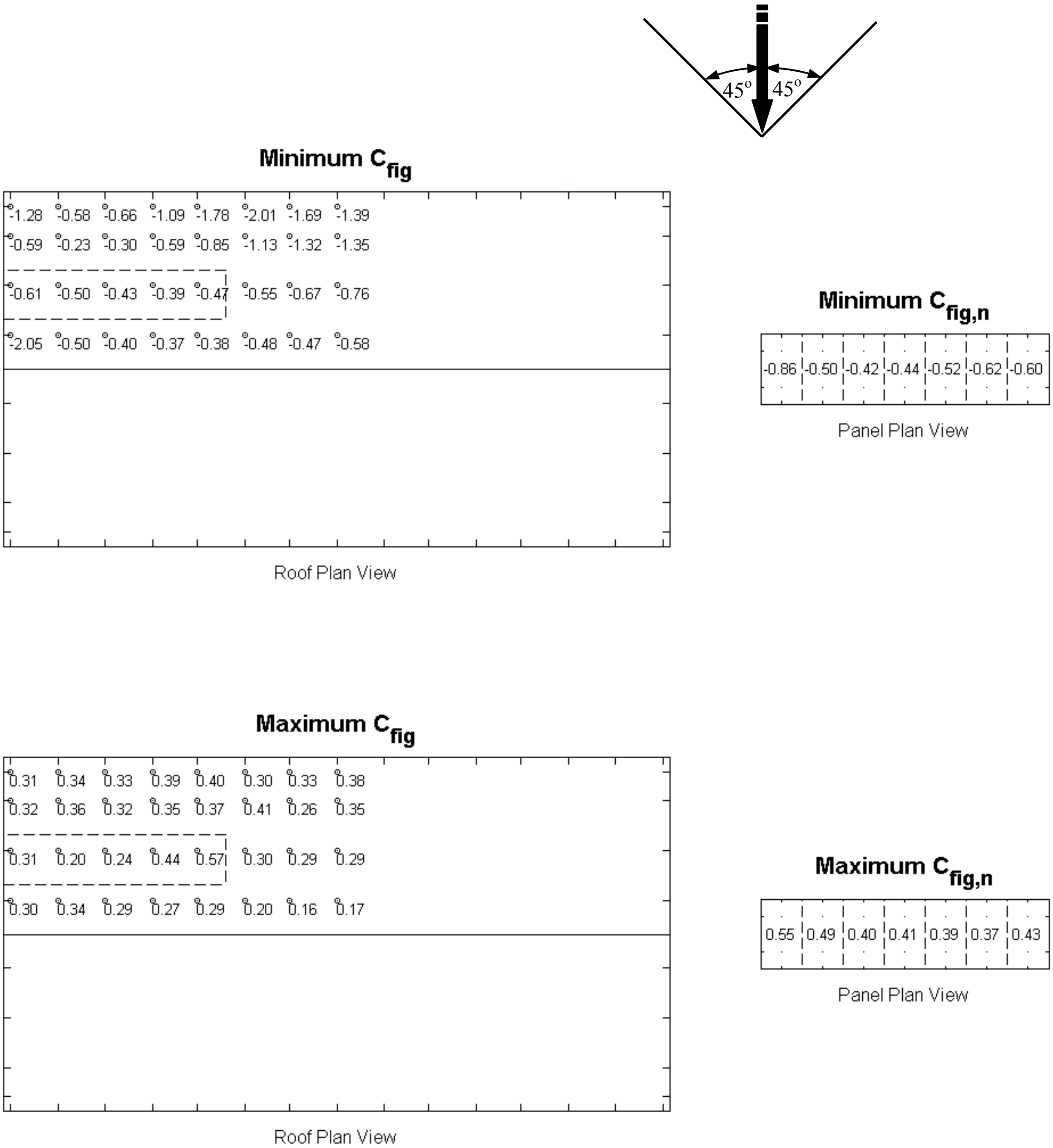


Figure A5-i. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 22.5°, Wind Direction 0° ± 45°

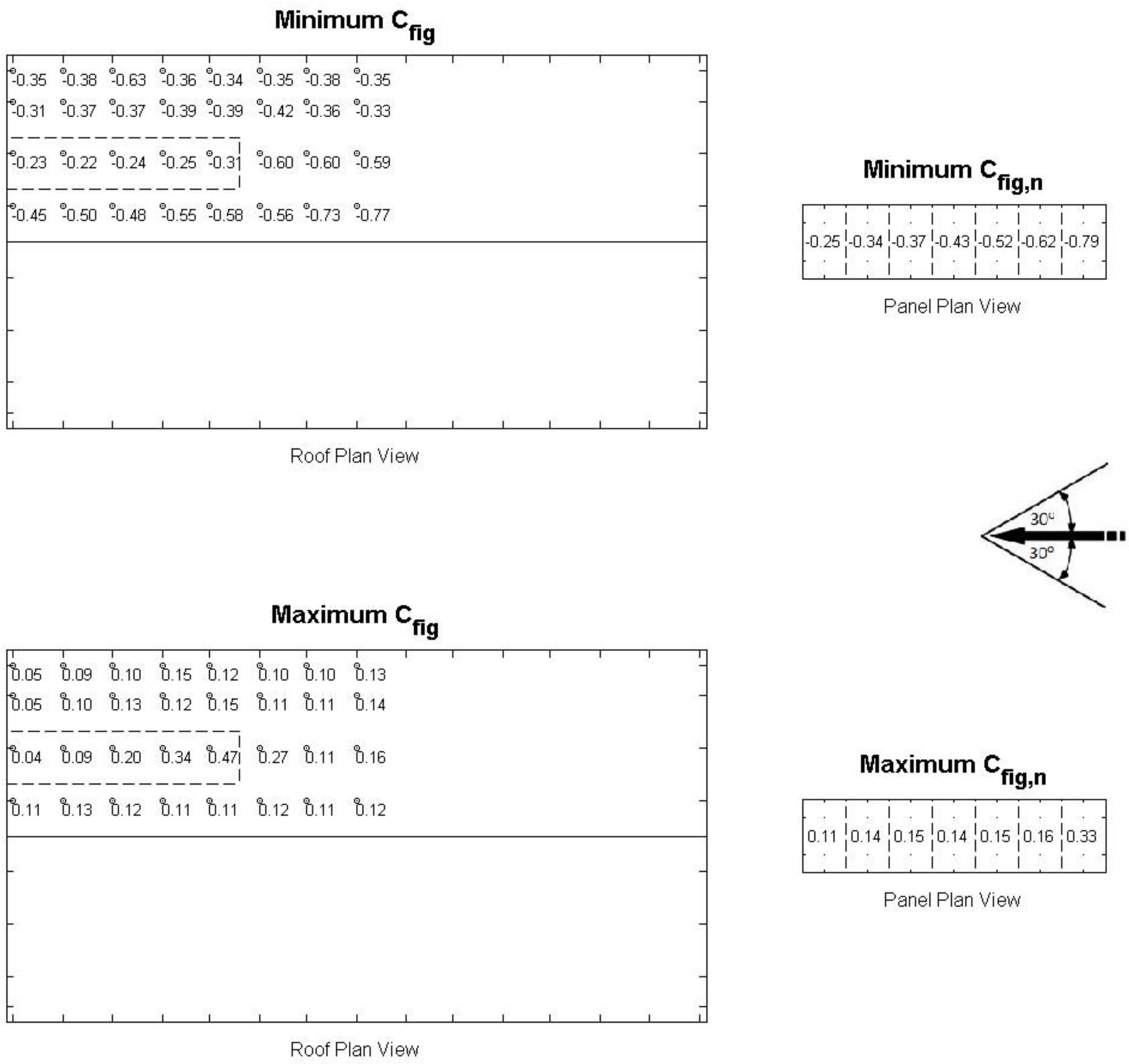


Figure A5-j. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 22.5°, Wind Direction 90° ± 30°

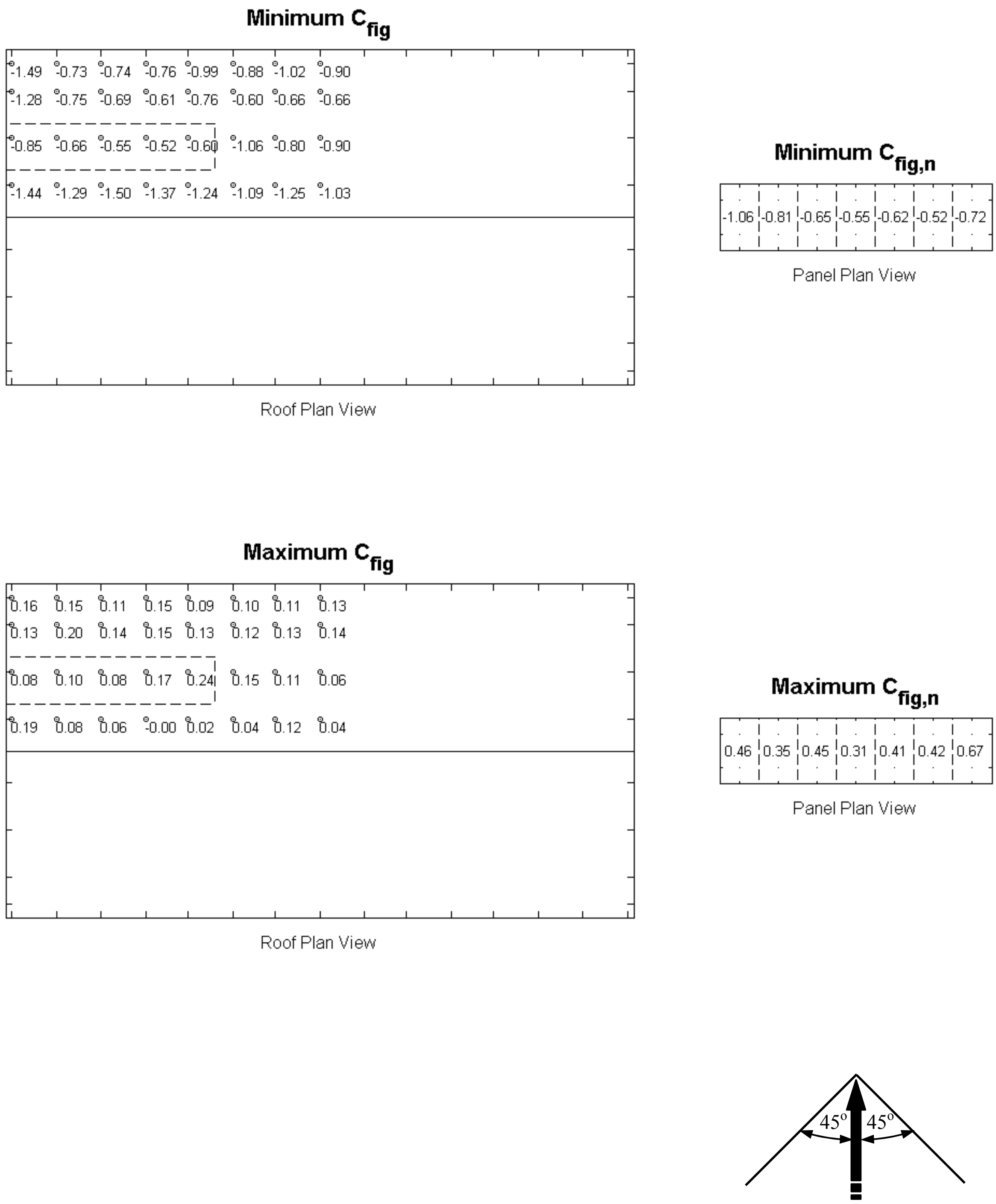


Figure A5-k. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 22.5°, Wind Direction 180° ± 45°

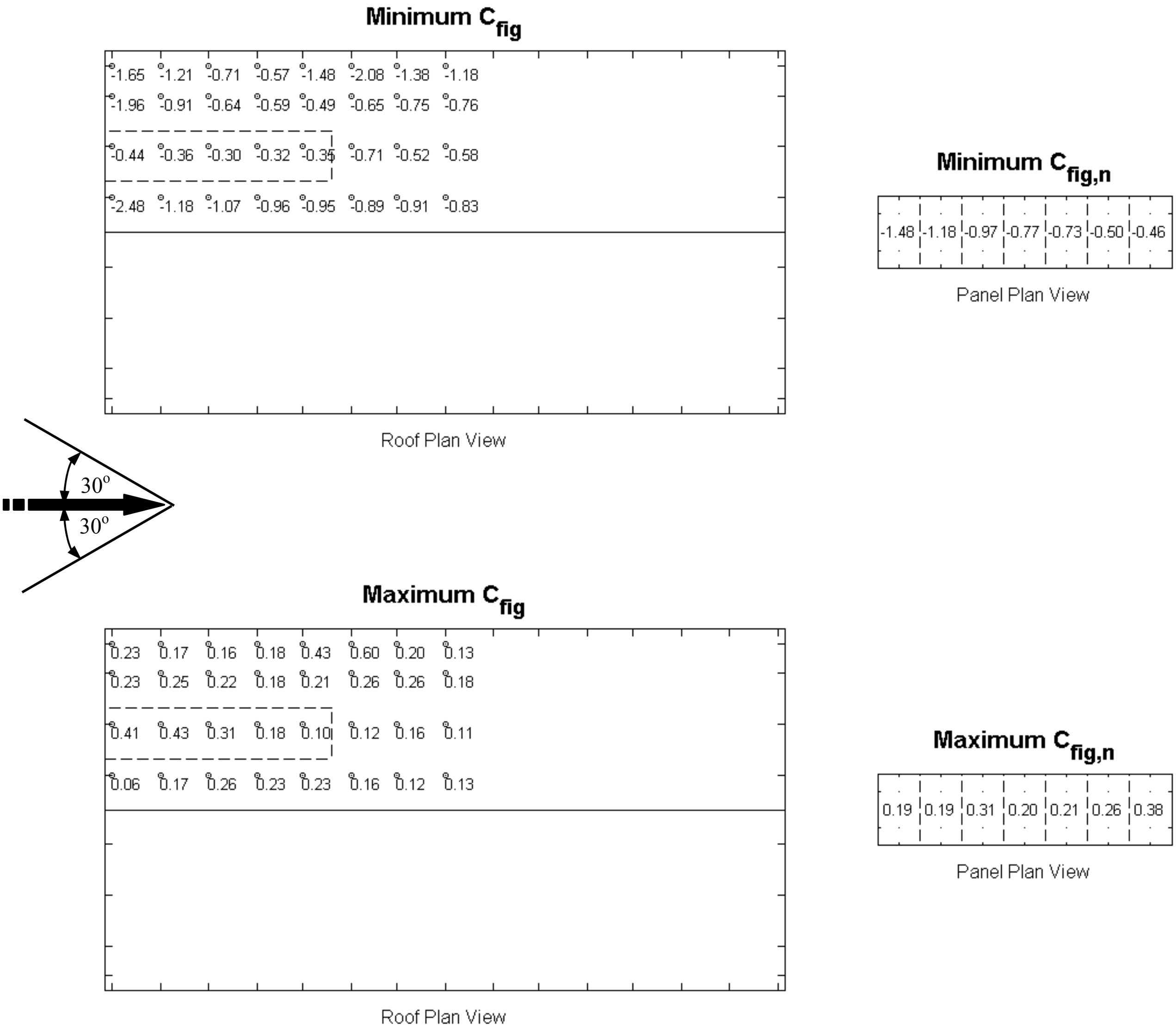


Figure A5-l. C_{fig} – Panel Position D, Gap 100mm - Roof Pitch 22.5°, Wind Direction 270° ± 30°

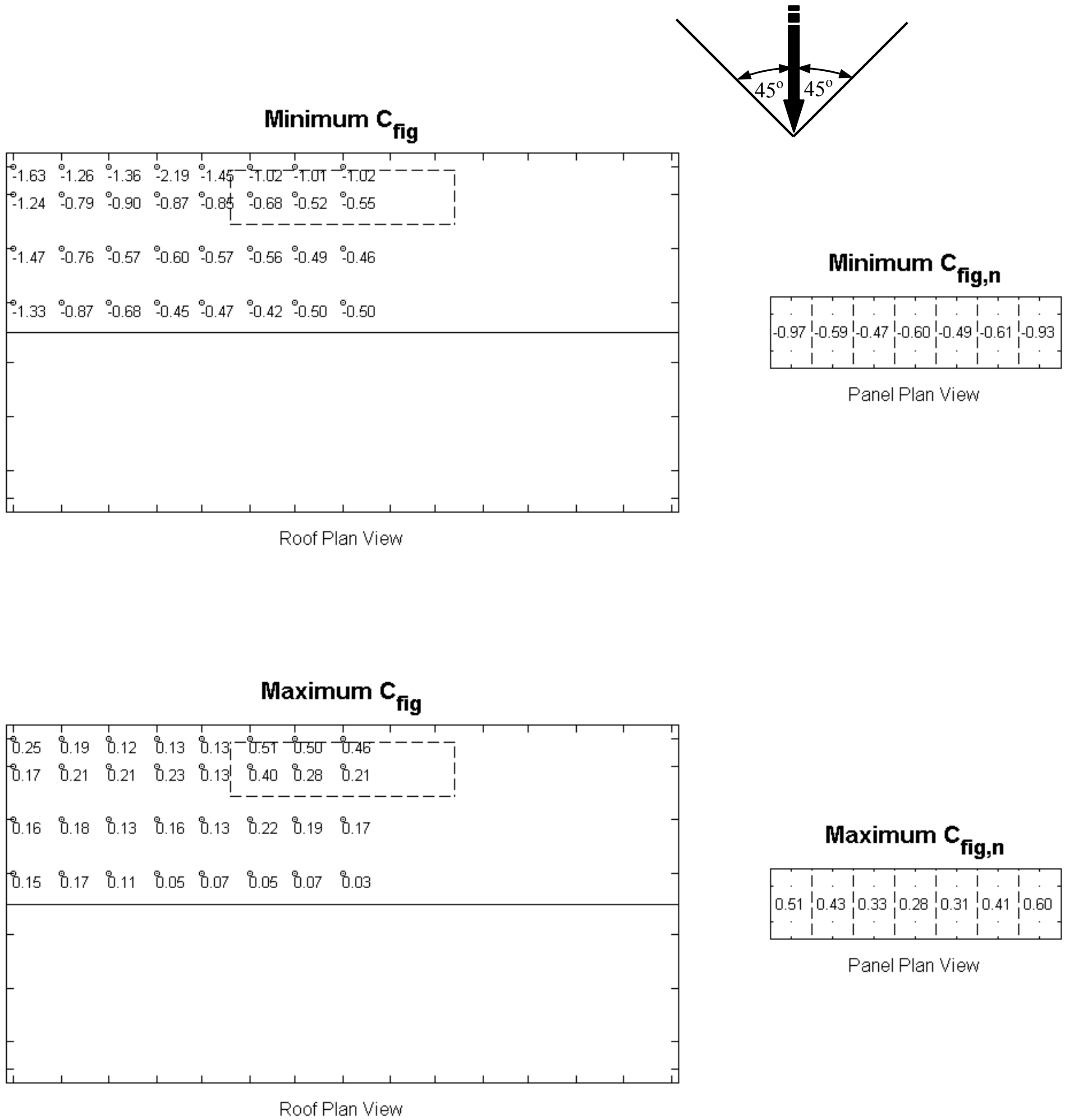


Figure A6-a. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 7.5°, Wind Direction 0° ± 45°

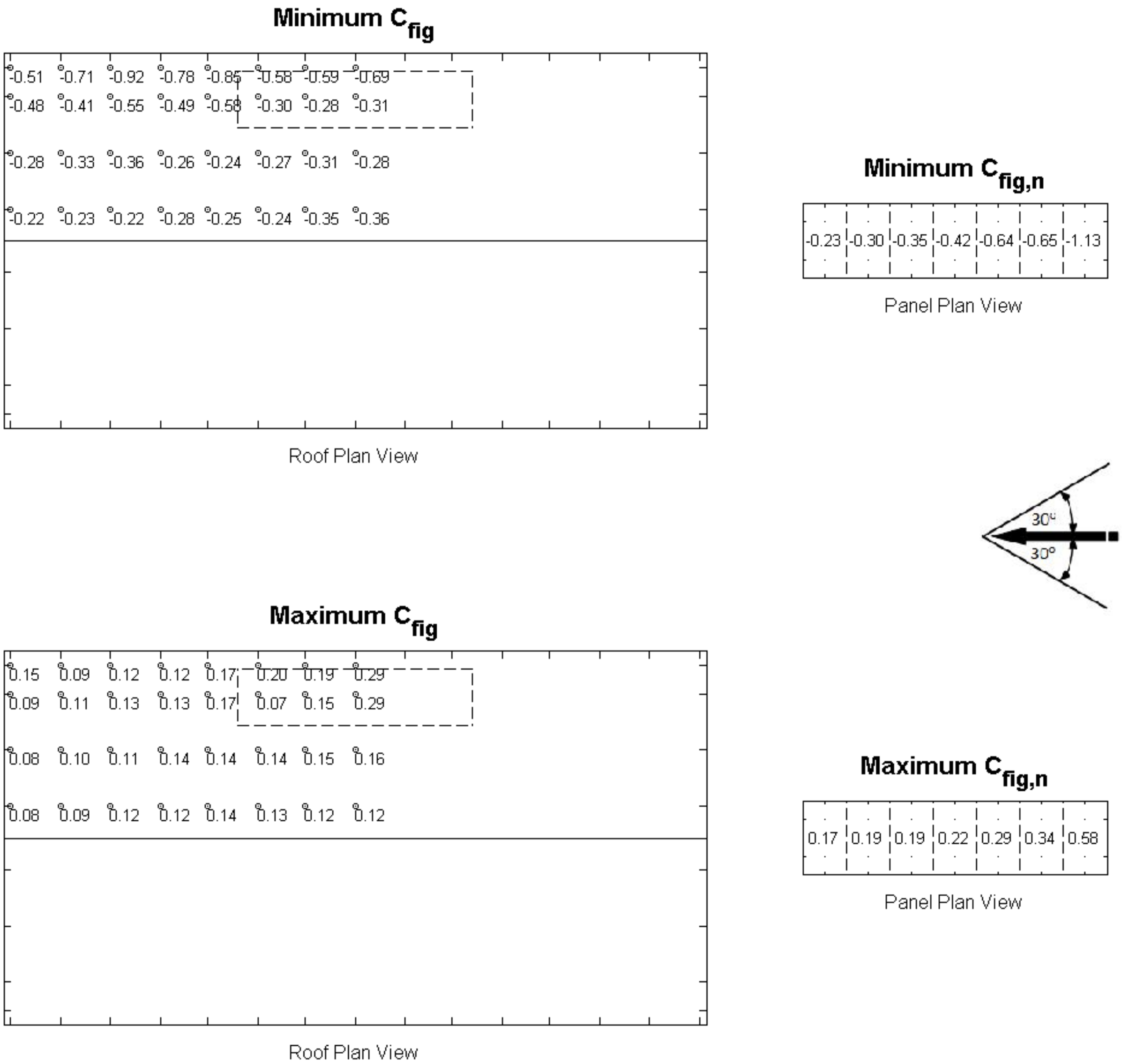


Figure A6-b. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 7.5^o, Wind Direction 90^o ± 30^o

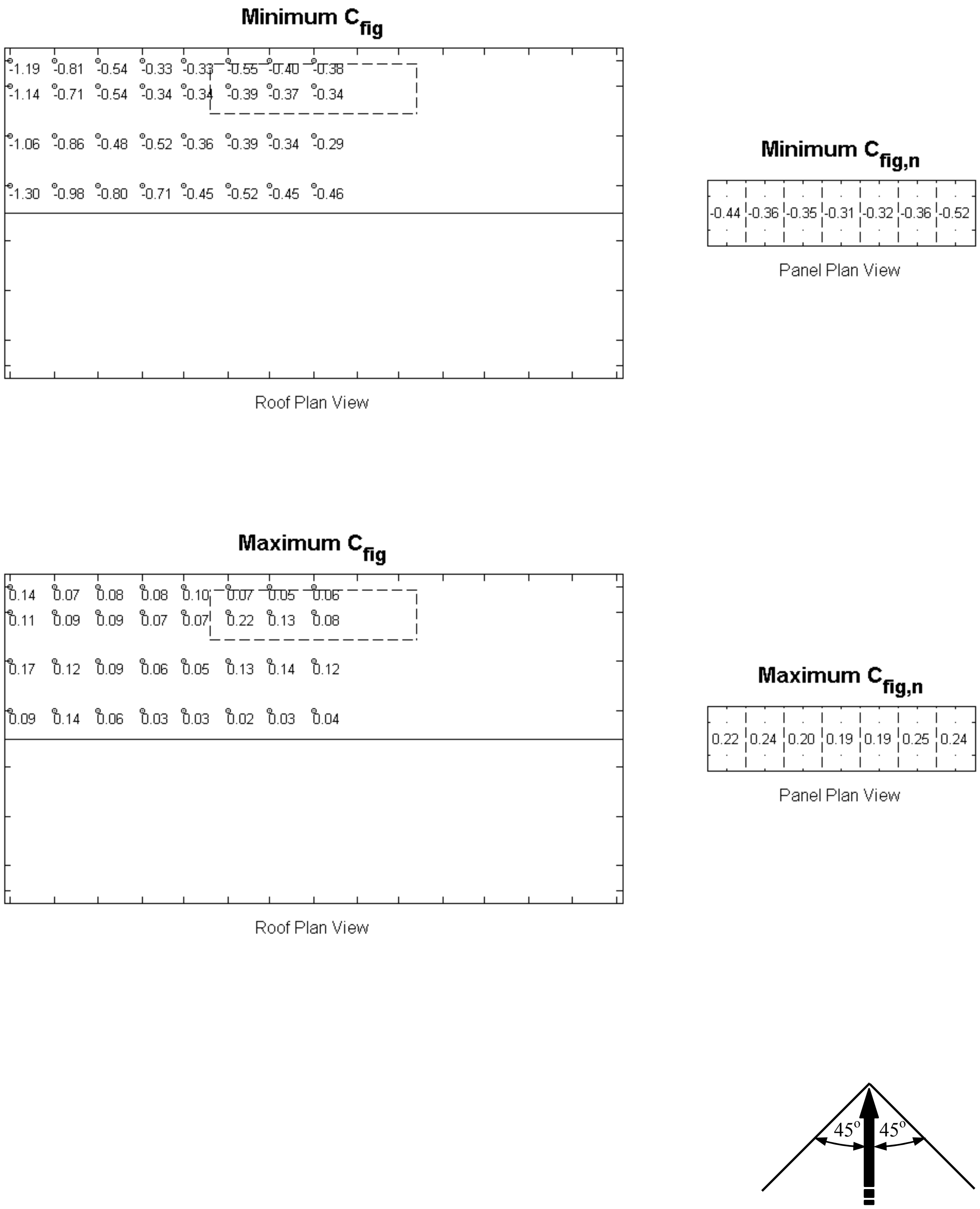


Figure A6-c. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 7.5°, Wind Direction 180° ± 45°

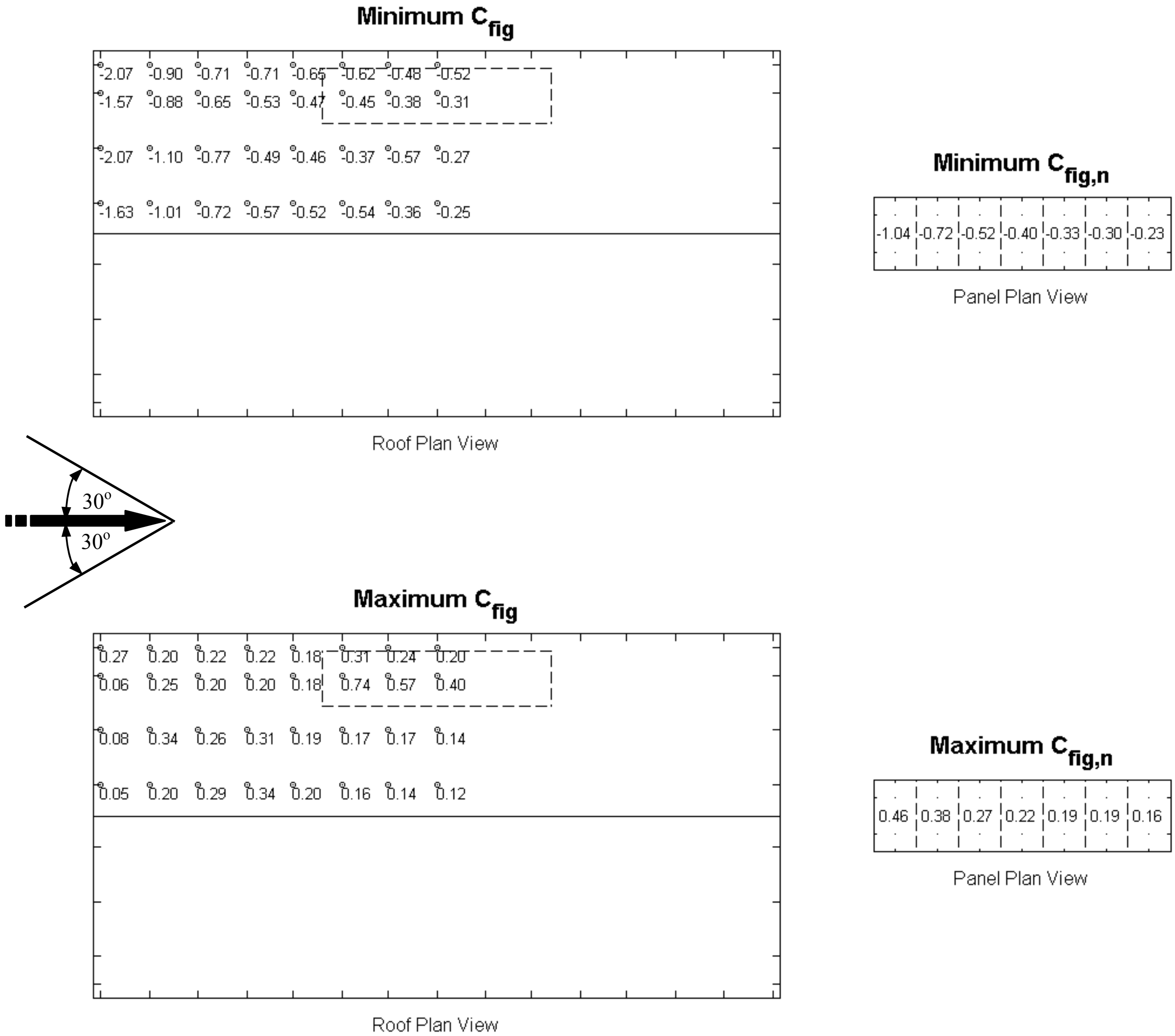


Figure A6-d- C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 7.5°, Wind Direction 270° ± 30°

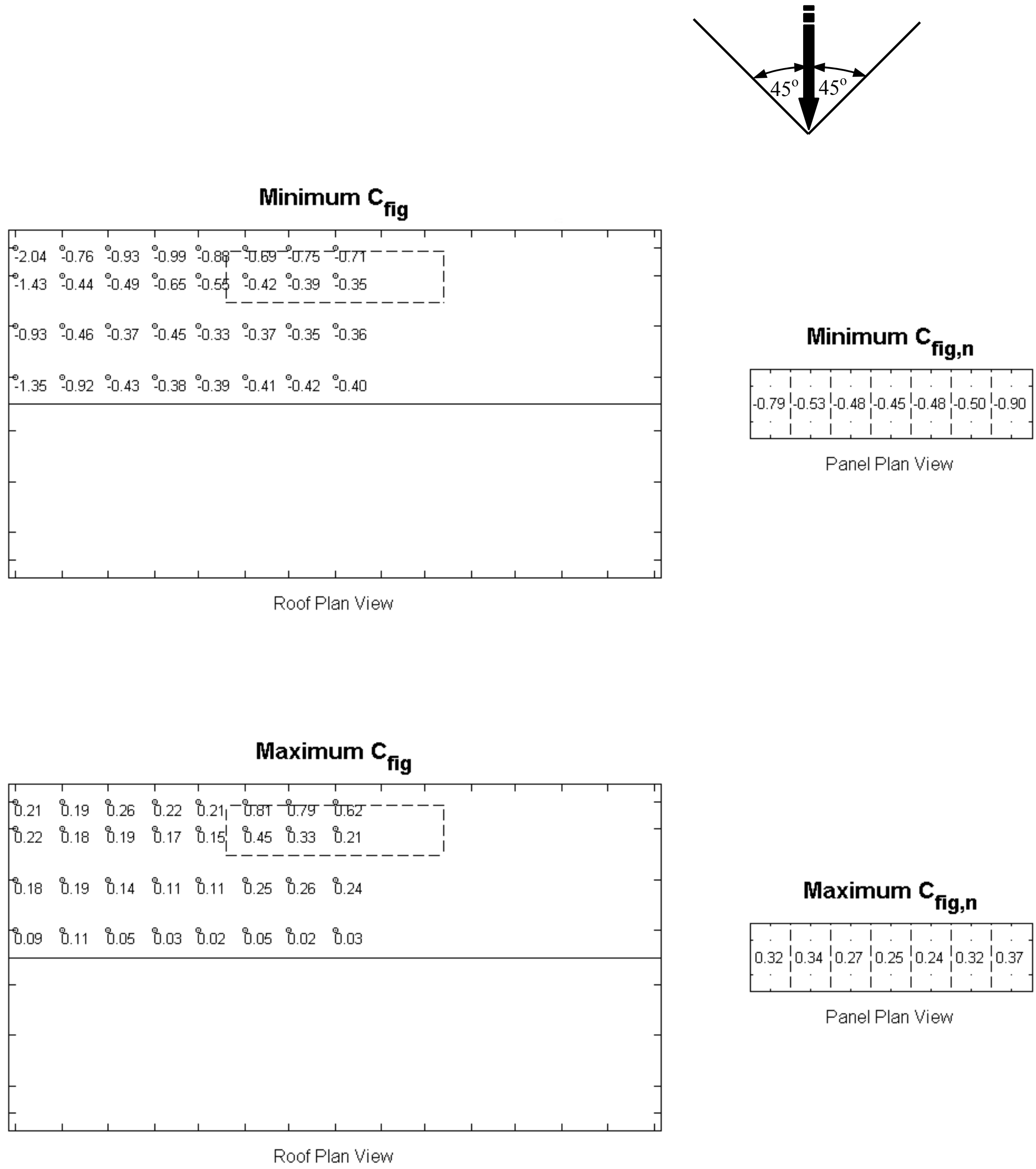


Figure A6-e. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 15°, Wind Direction 0° ± 45°

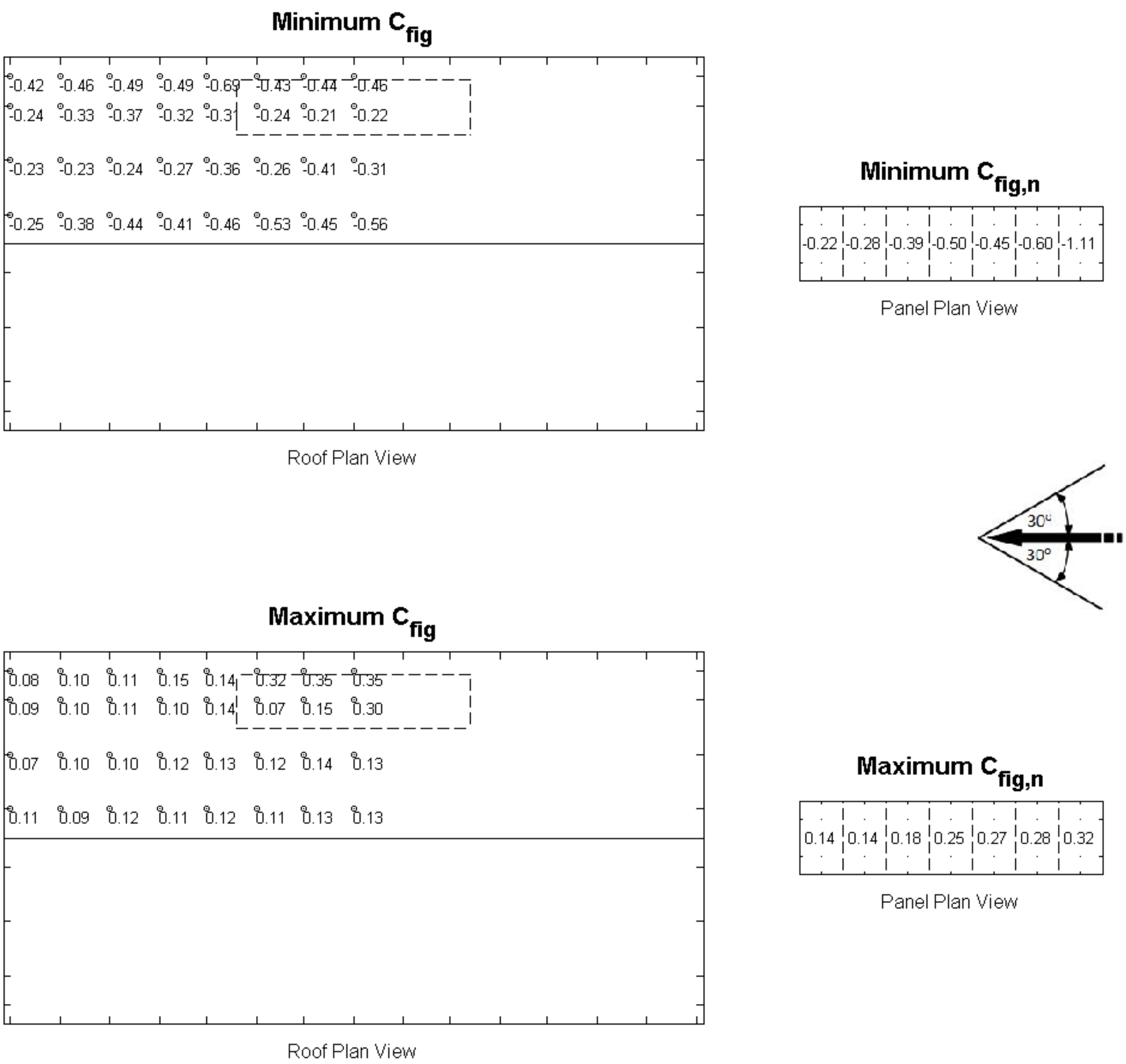


Figure A6-f.- C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 15°, Wind Direction 90° ± 30°

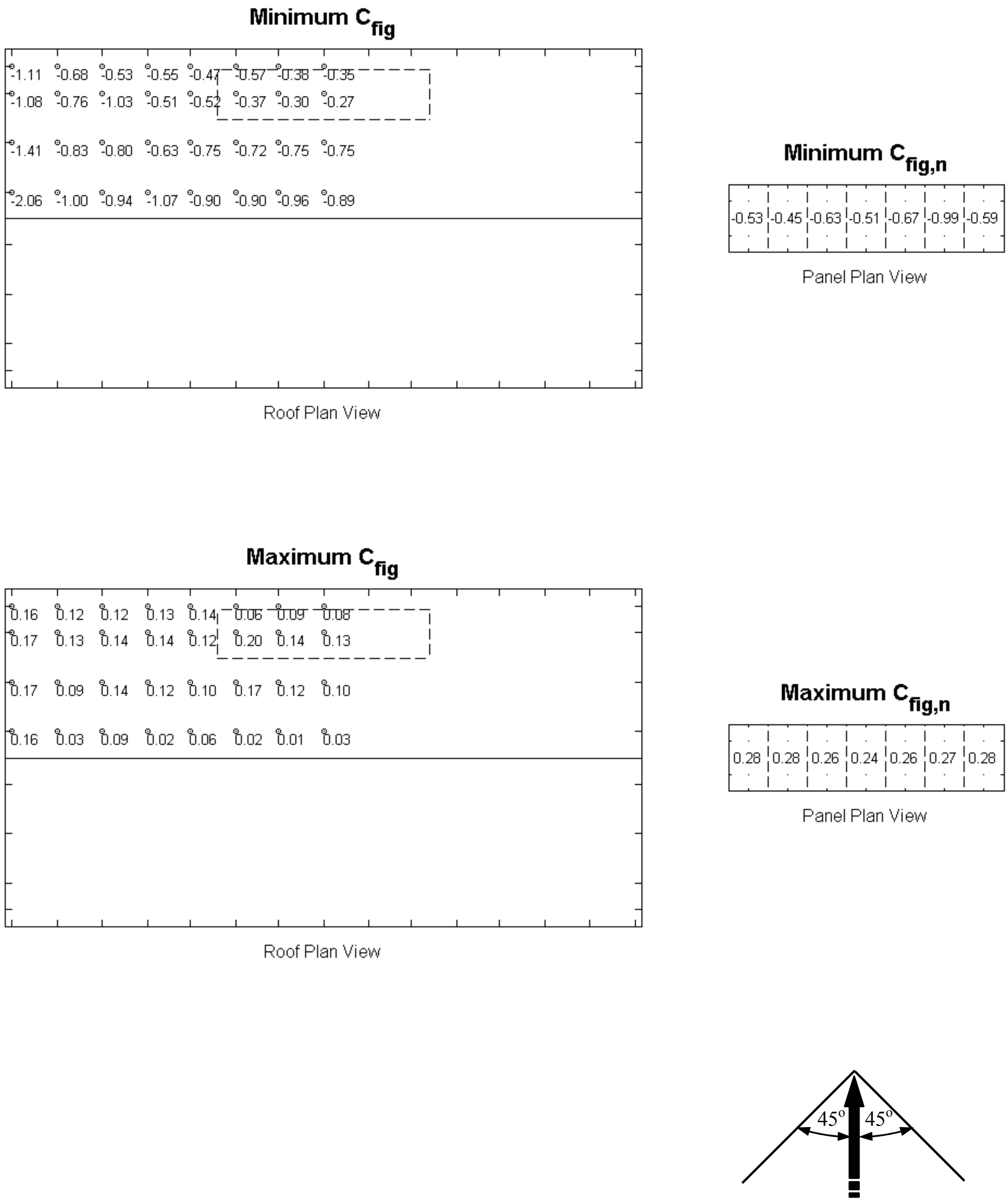


Figure A6-g. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 15°, Wind Direction 180° ± 45°

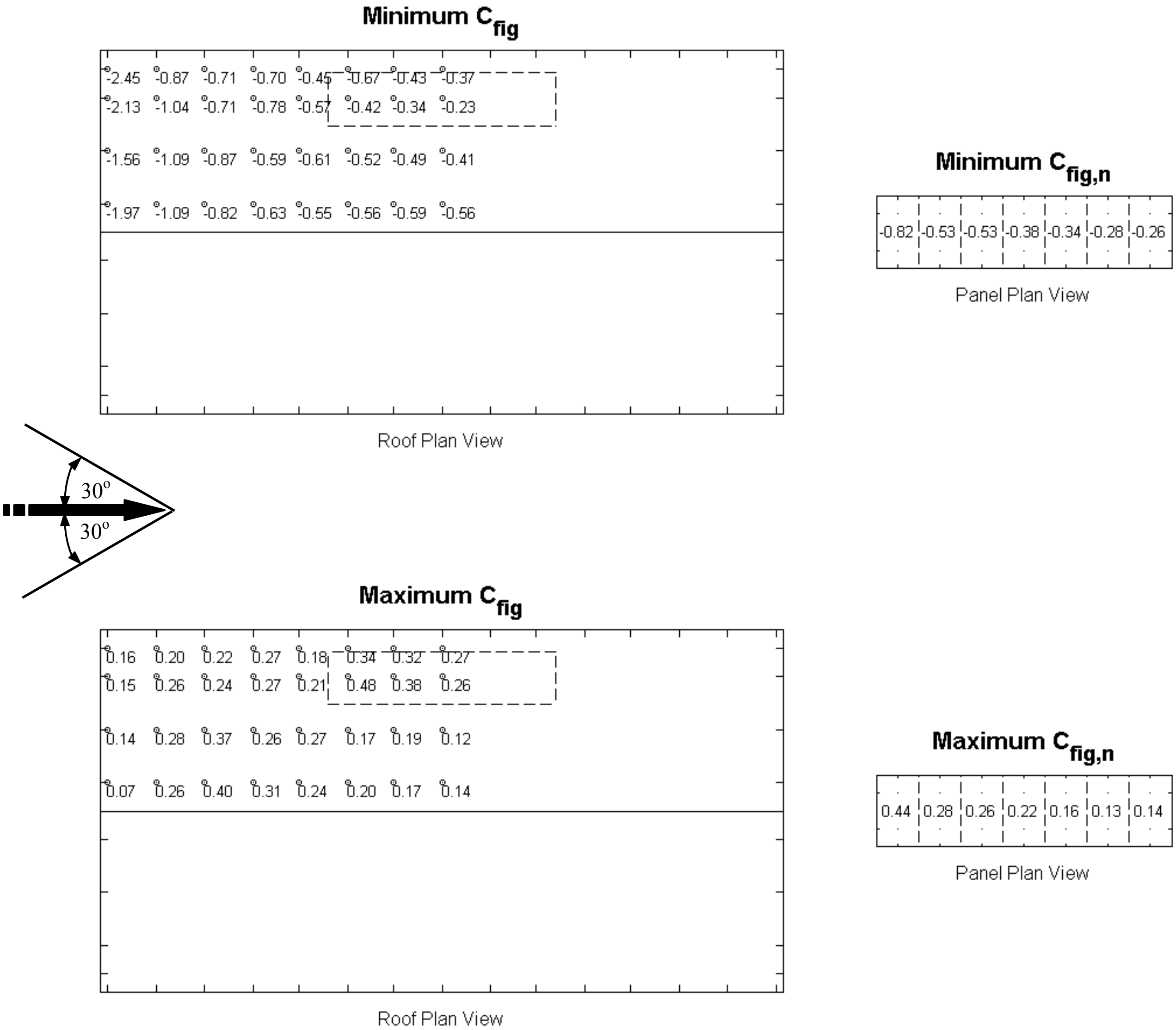


Figure A6-h. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 15°, Wind Direction 270° ± 30°

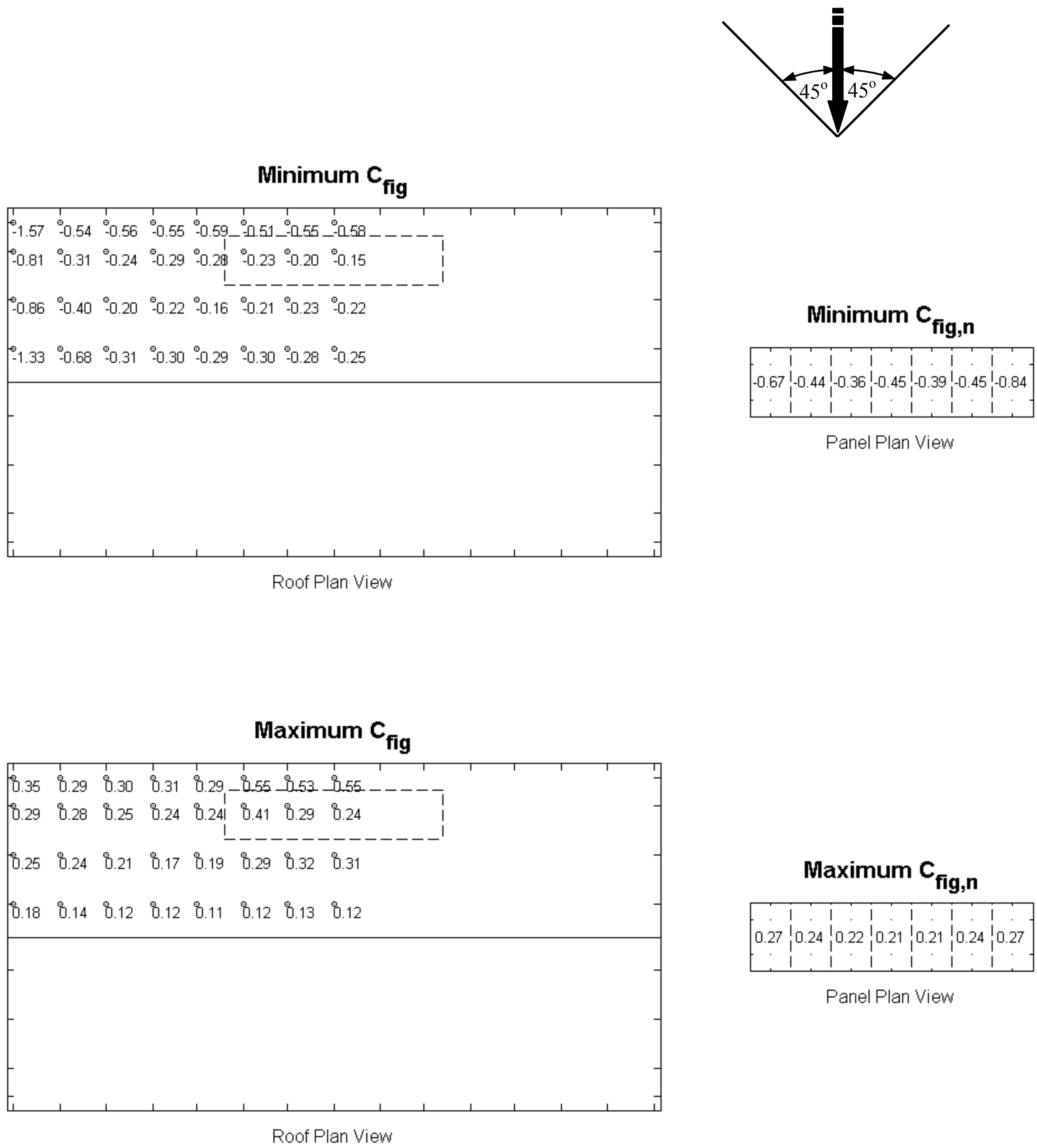


Figure A6-i. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 22.5°, Wind Direction 0° ± 45°

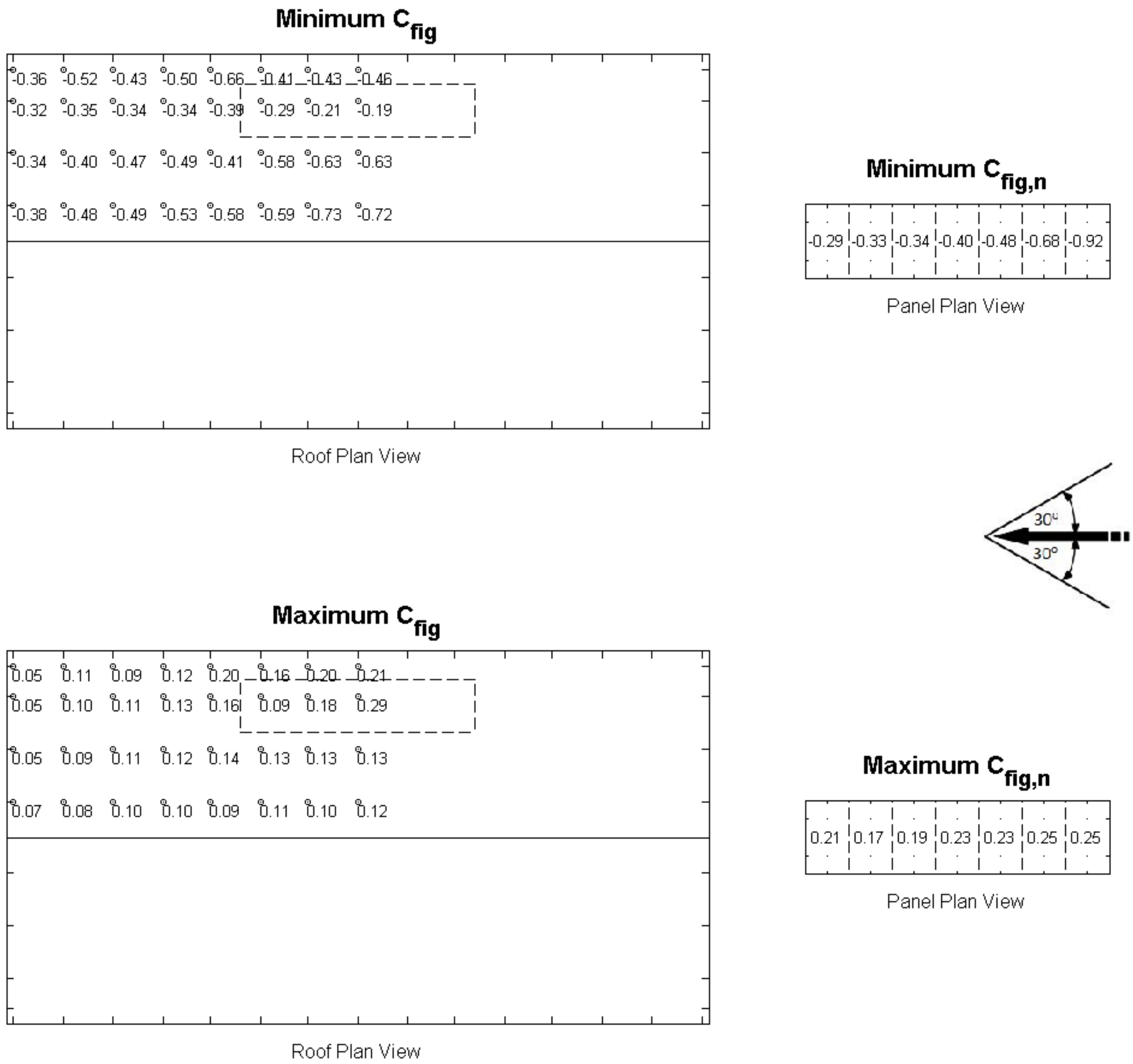
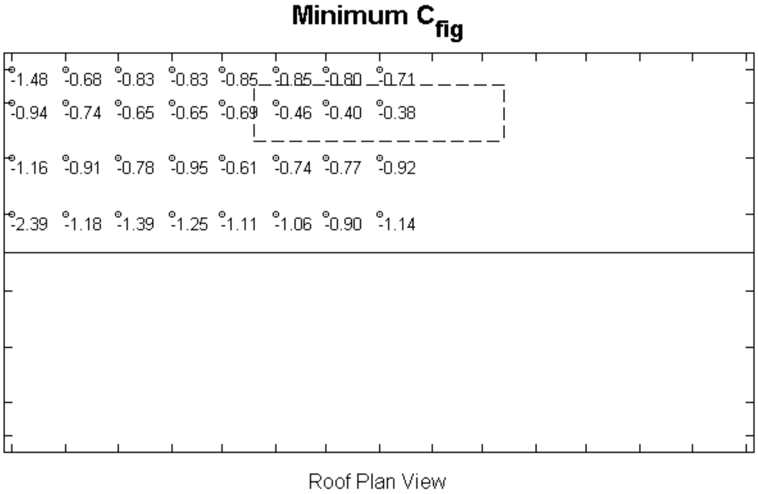
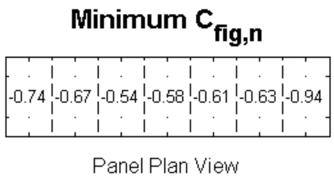
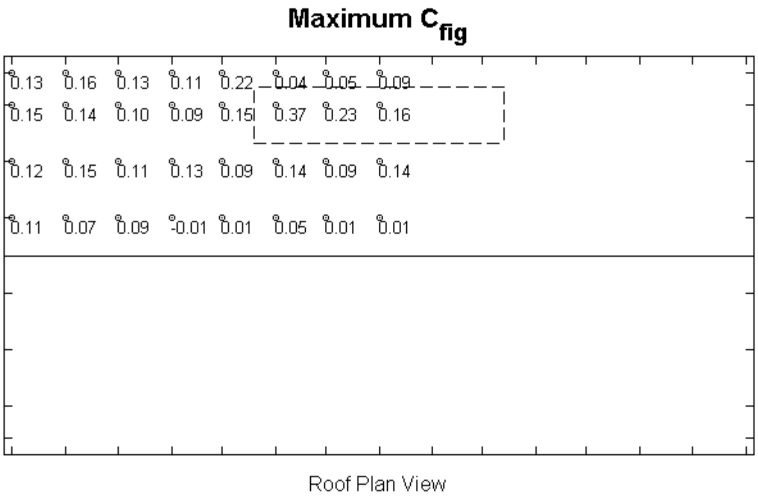
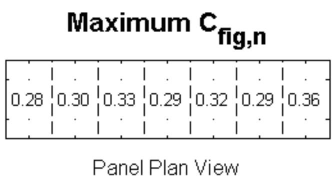


Figure A6-j. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 22.5°, Wind Direction 90° ± 30°









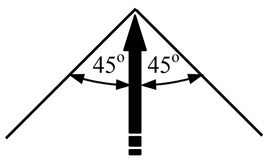


Figure A6-k. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 22.5°, Wind Direction 180° ± 45°

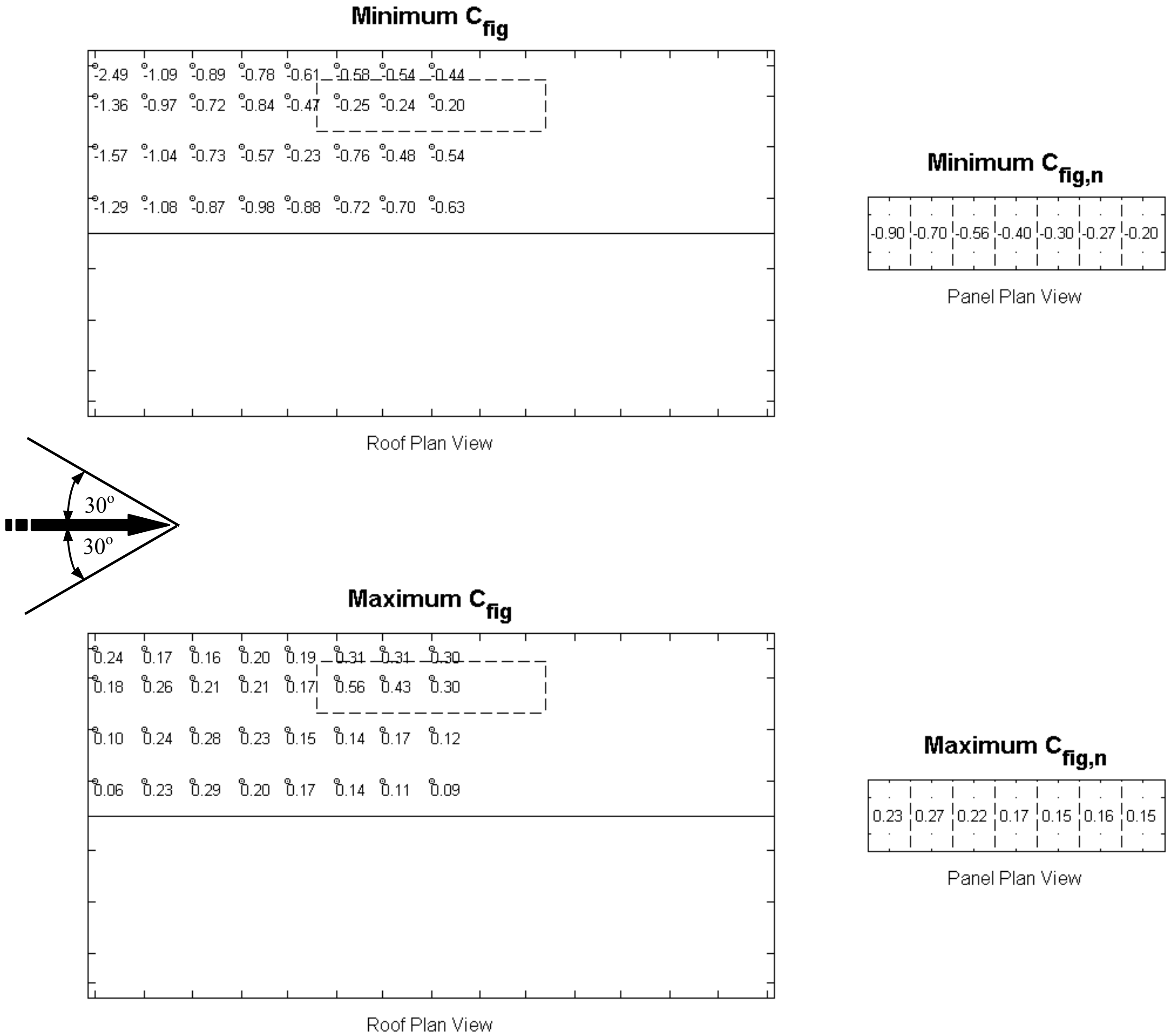


Figure A6-l. C_{fig} – Panel Position E, Gap 100mm - Roof Pitch 22.5°, Wind Direction 270° ± 30°

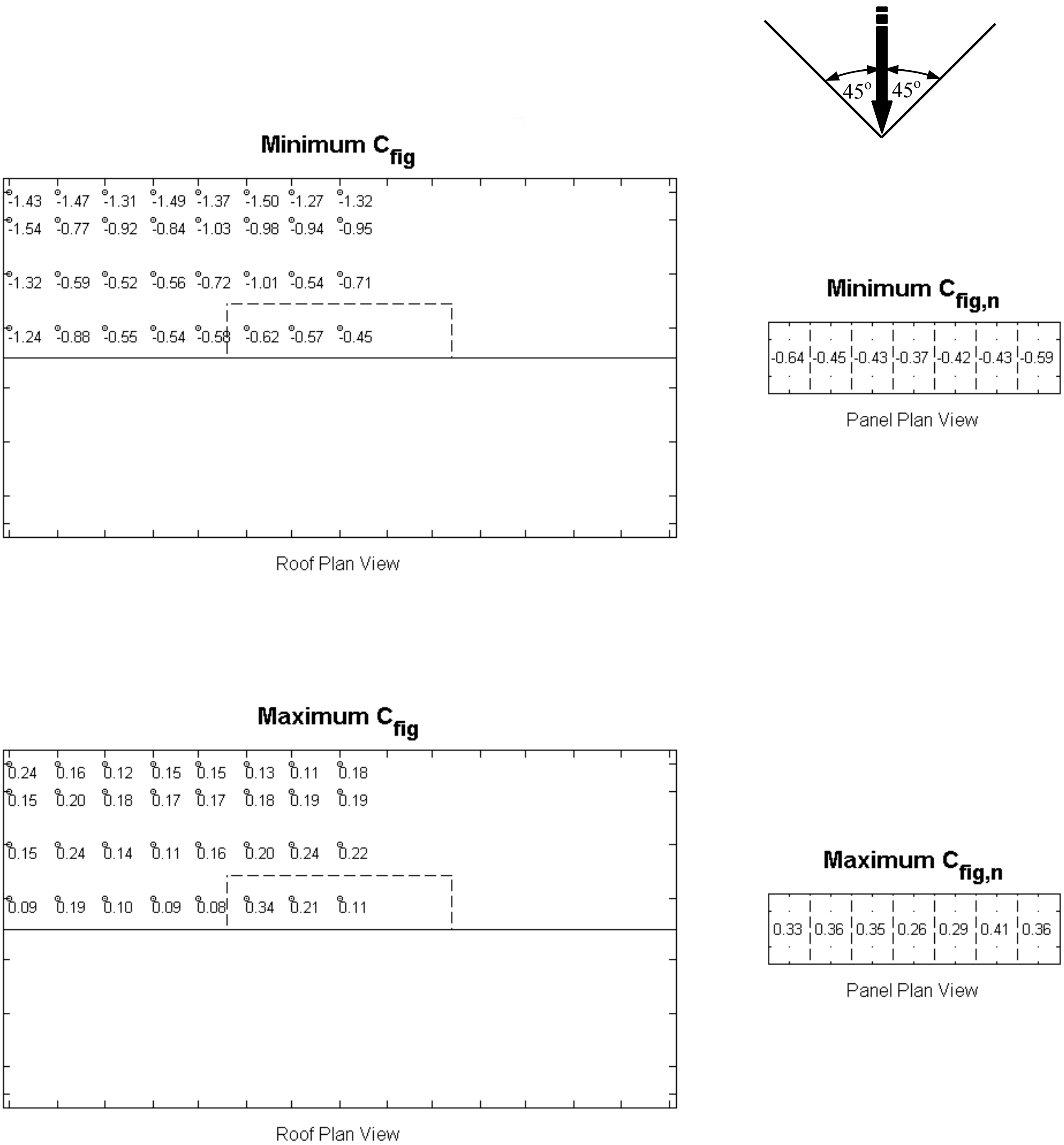


Figure A7-a. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 7.5°, Wind Direction 0° ± 45°

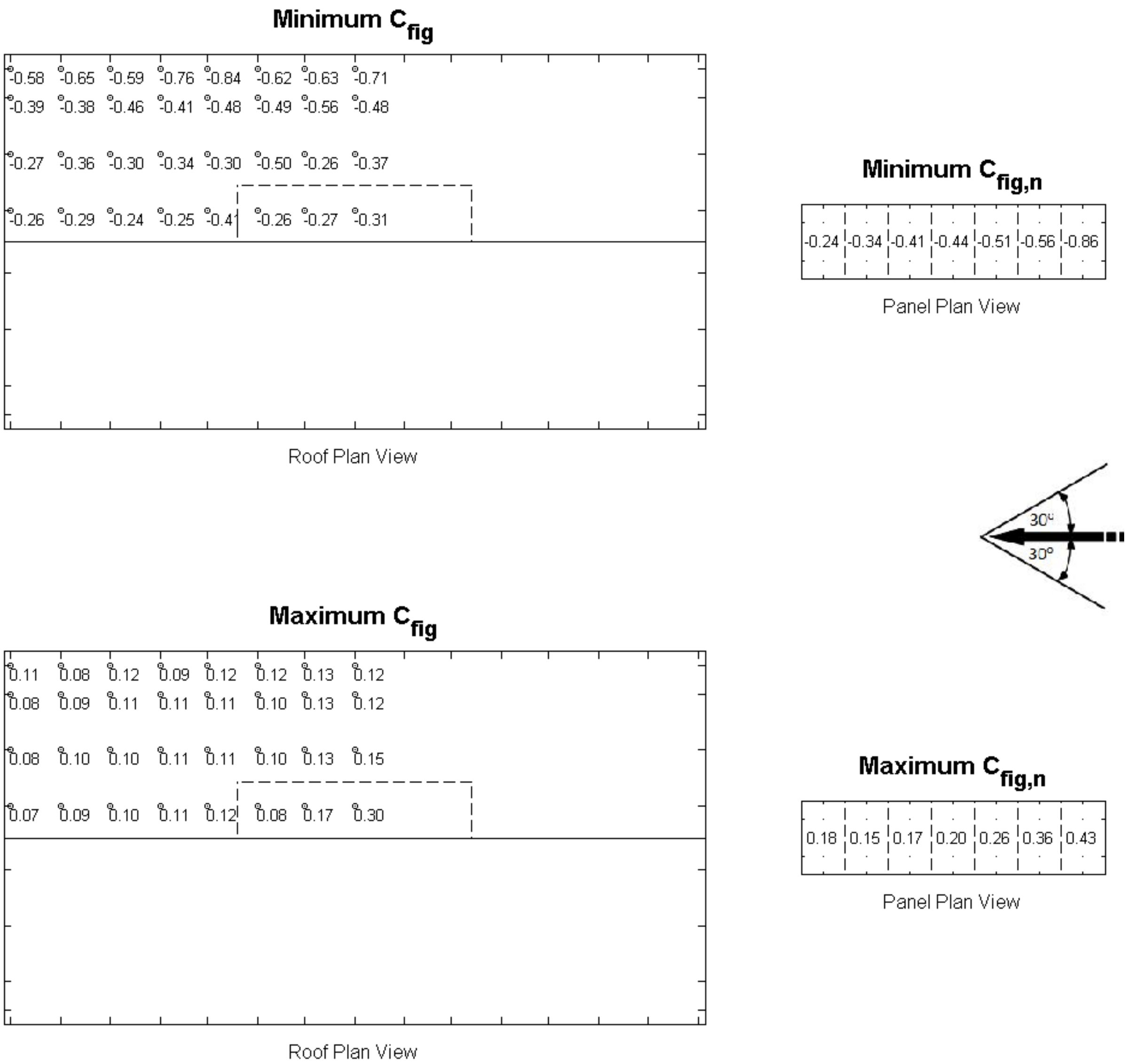


Figure A7-b. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 7.5°, Wind Direction 90° ± 30°

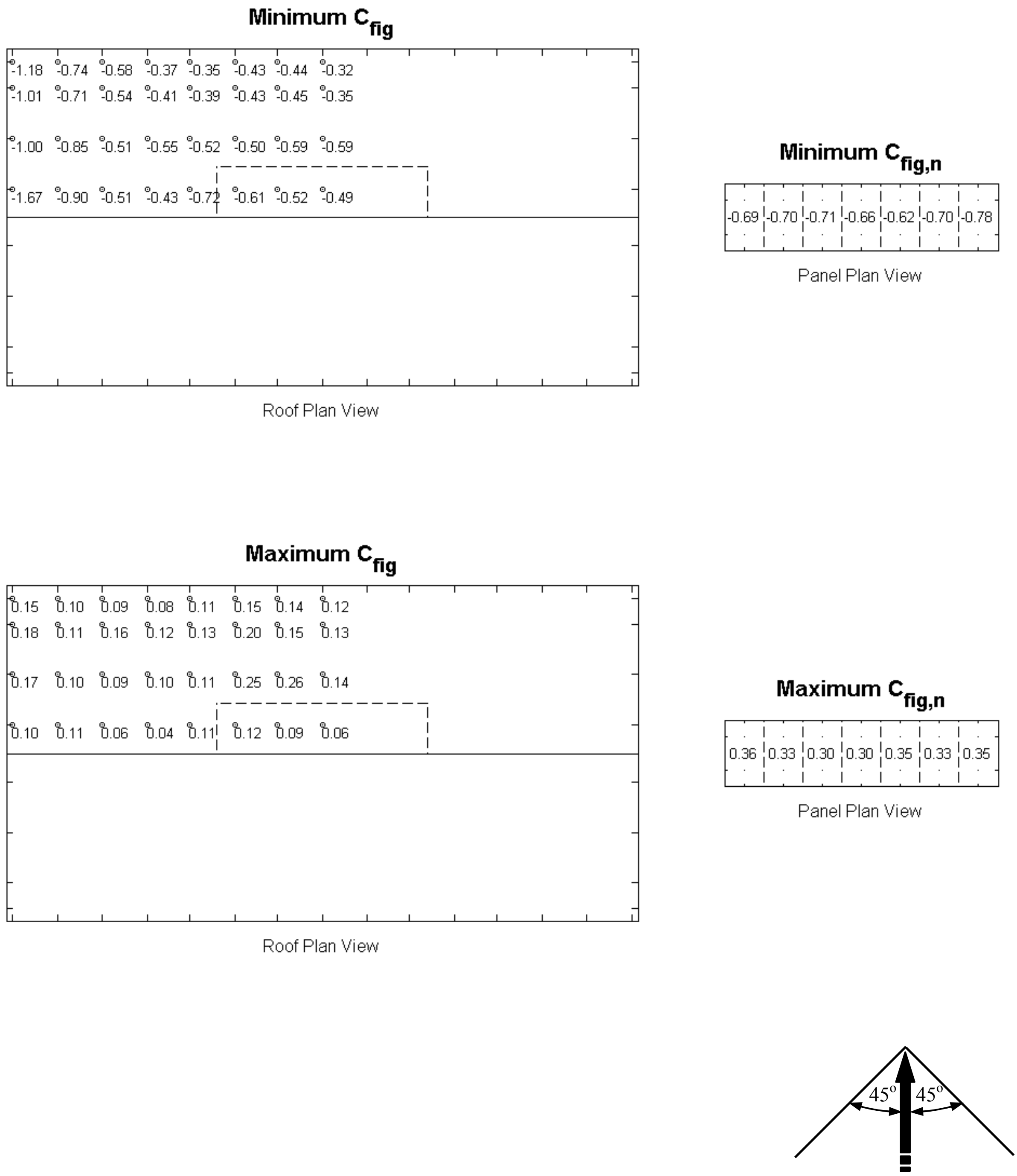


Figure A7-c. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 7.5°, Wind Direction 180° ± 45°

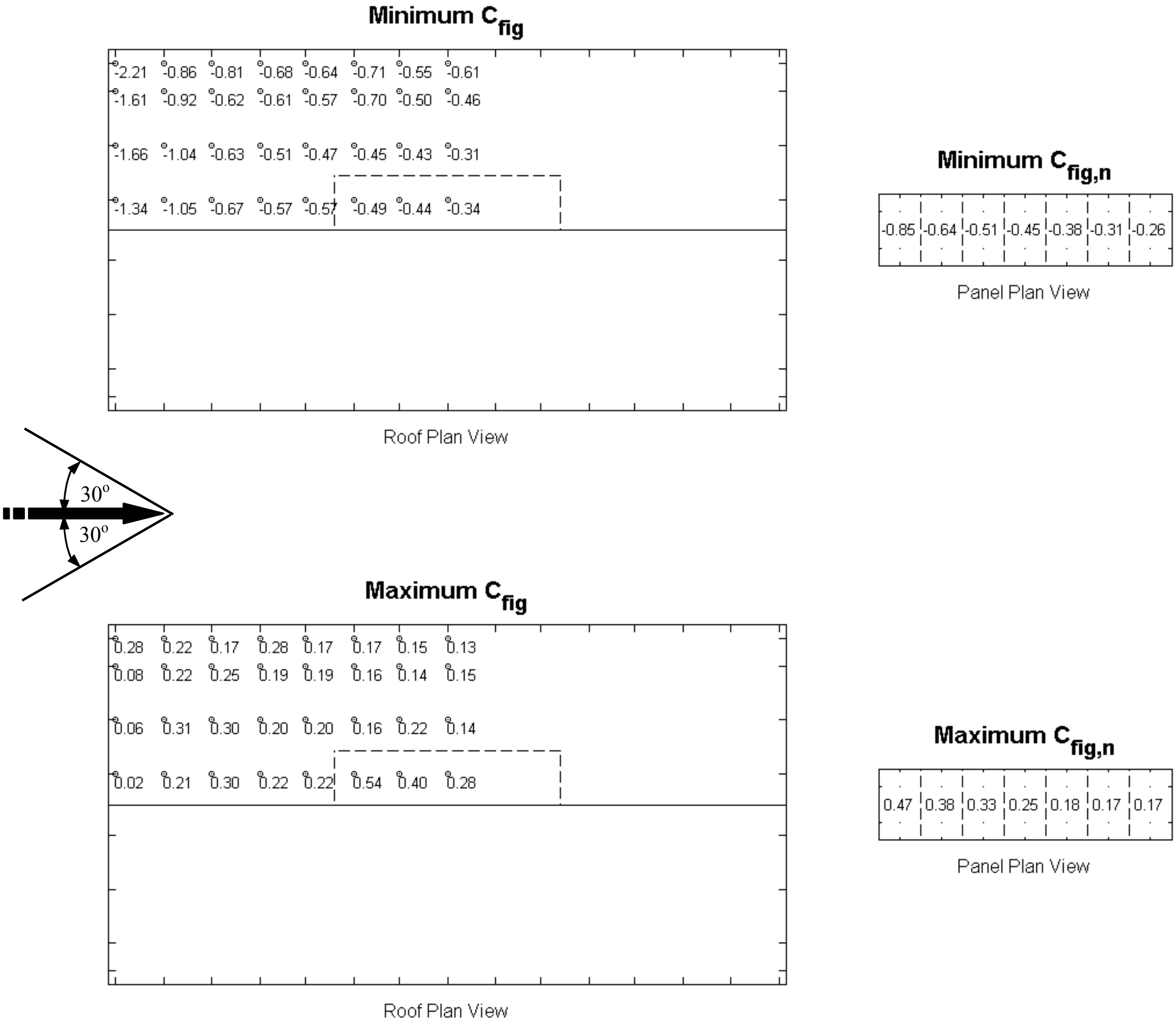
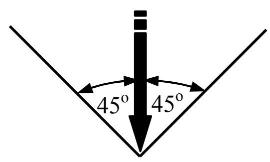
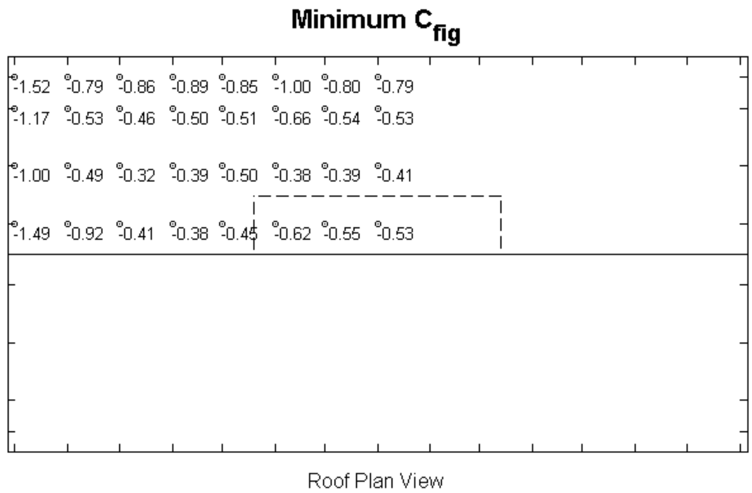
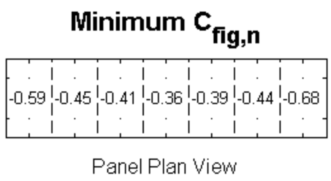
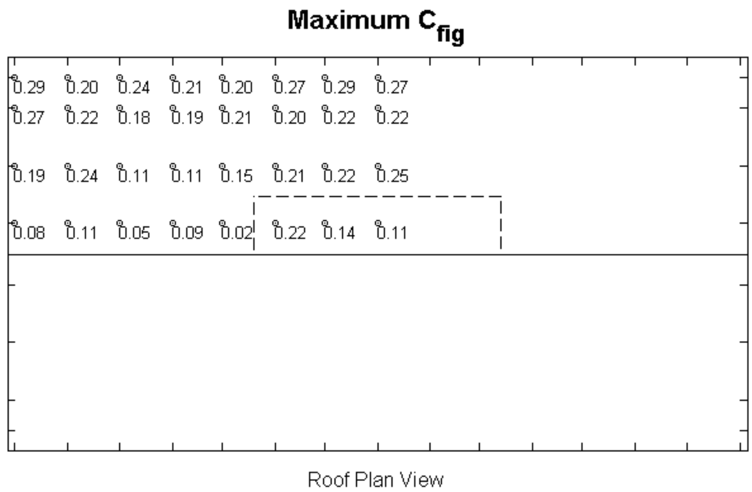


Figure A7-d. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 7.5^o, Wind Direction 270^o ± 30^o









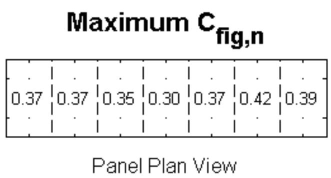


Figure A7-e. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 15^o, Wind Direction 0^o ± 45^o

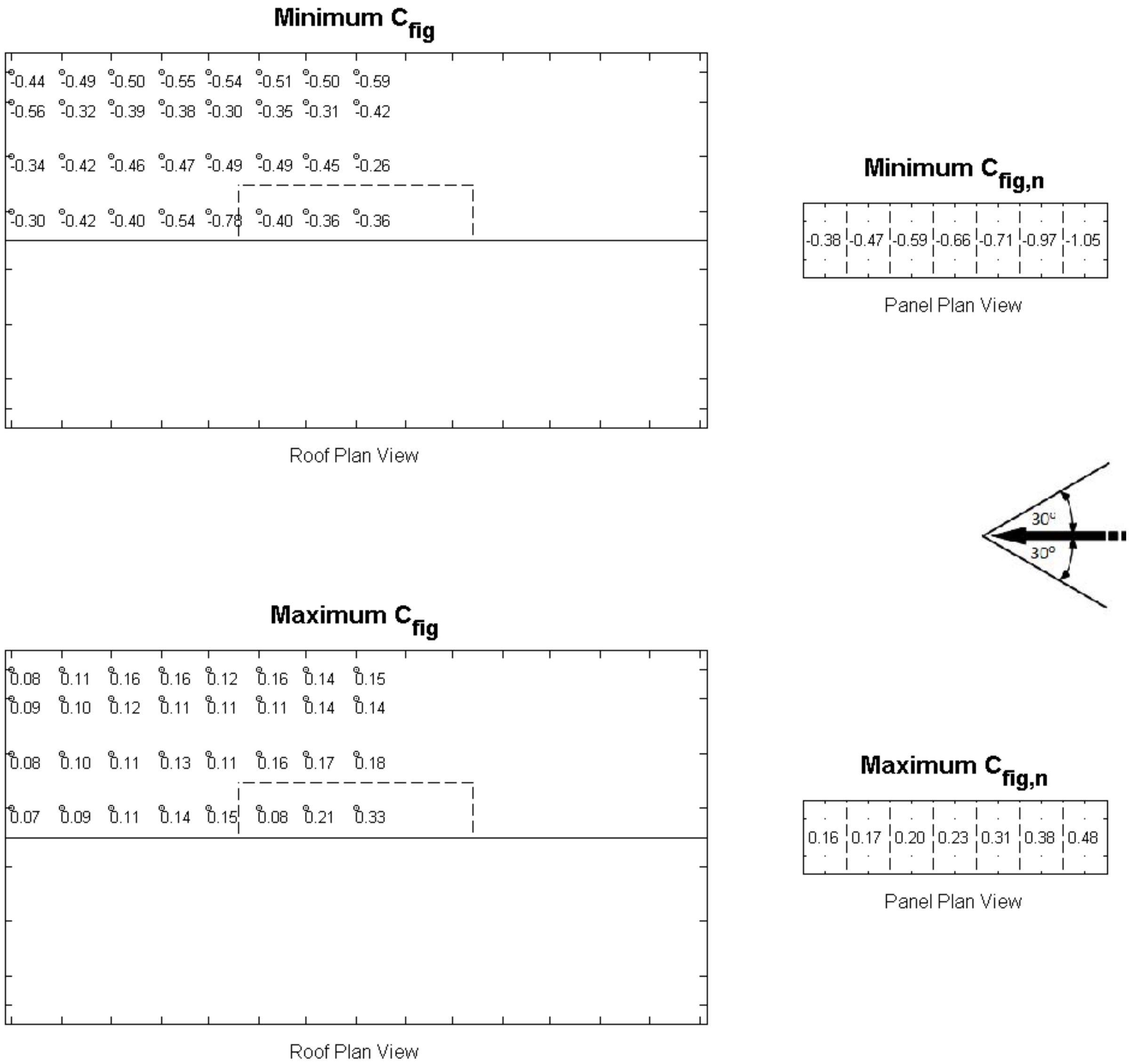
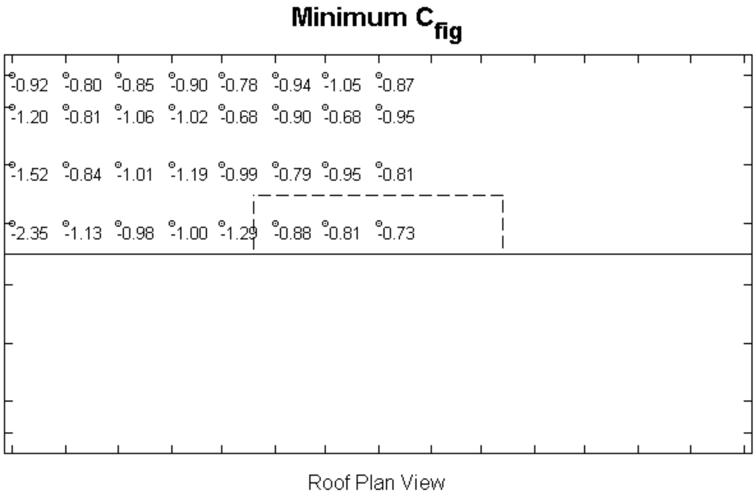
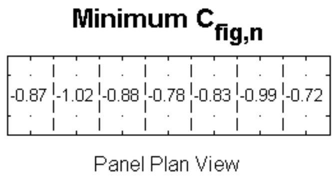
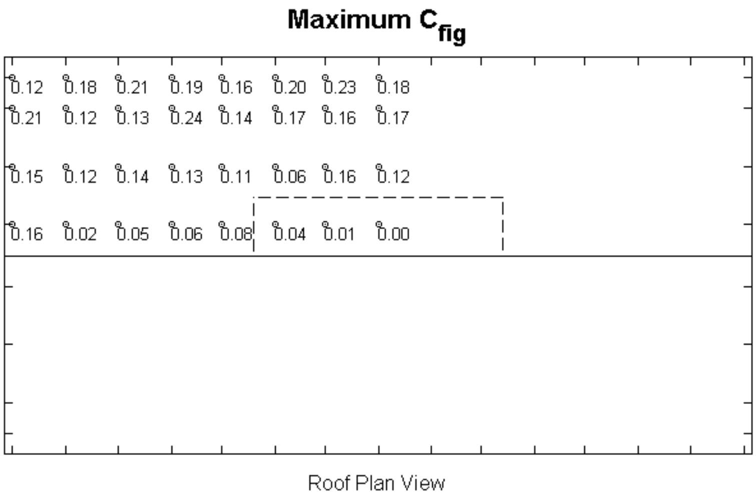
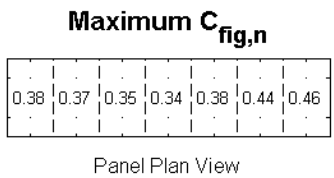


Figure A7-f. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 15°, Wind Direction 90° ± 30°









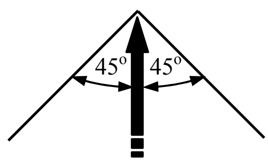


Figure A7-g. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 15°, Wind Direction 180° ± 45°

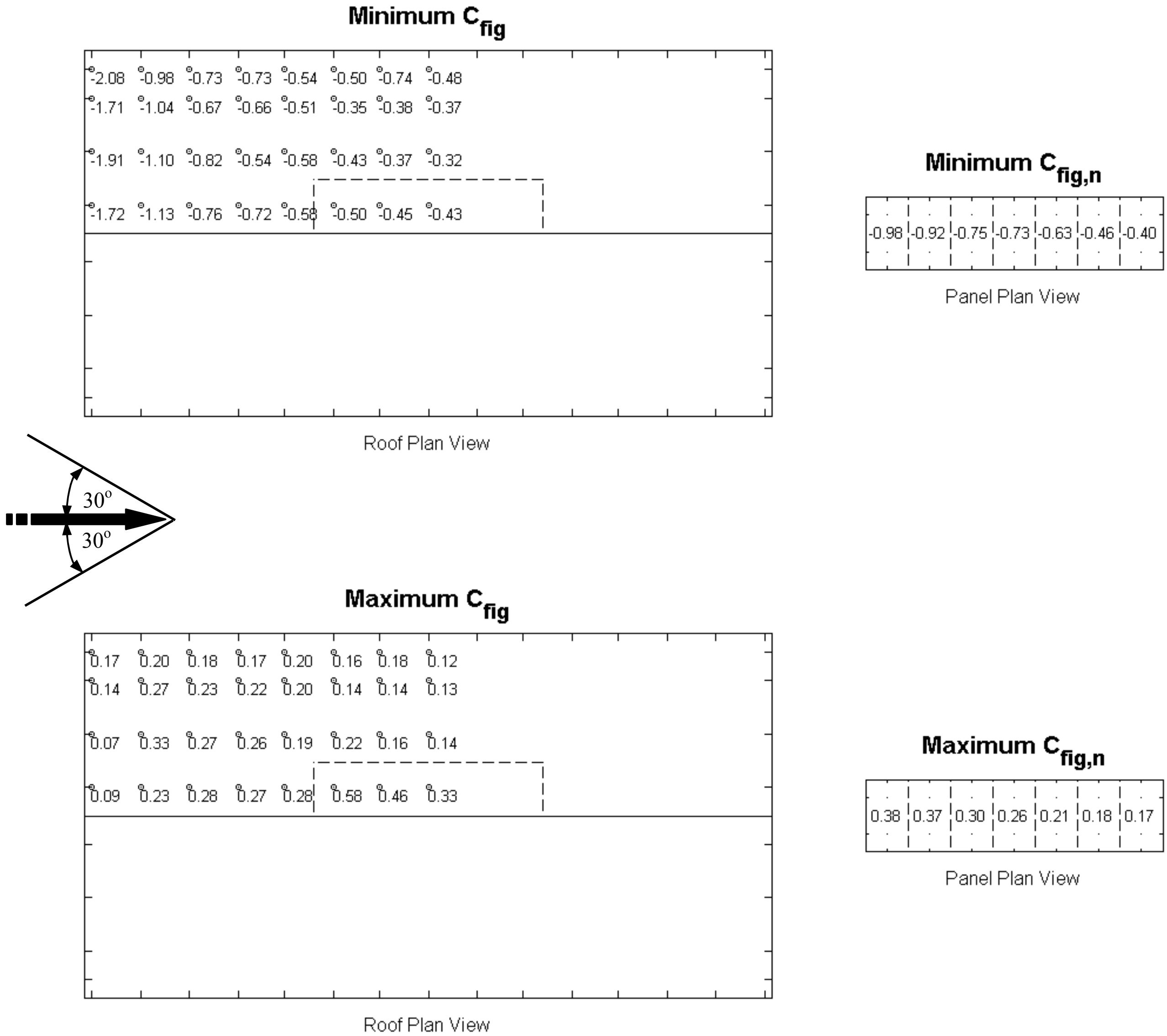
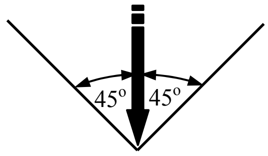
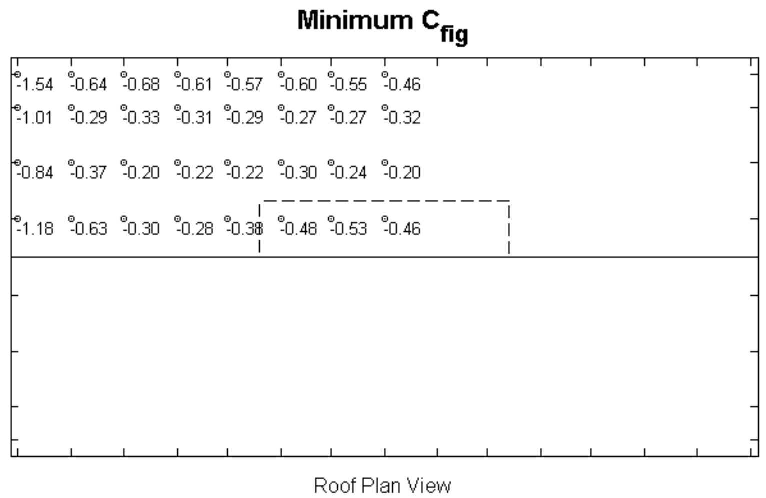
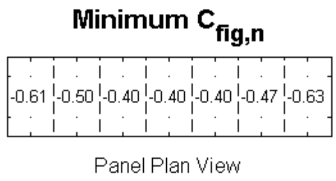
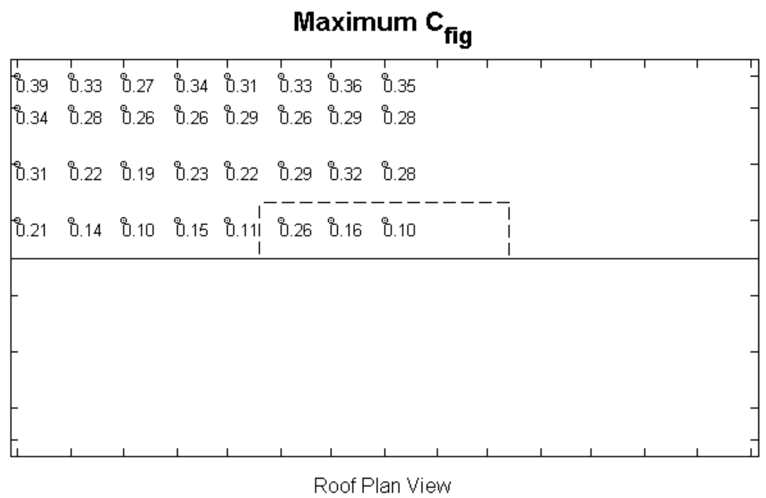


Figure A7-h. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 15°, Wind Direction 270° ± 30°









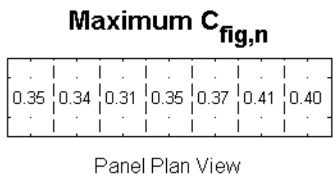


Figure A7-i.- C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 22.5°, Wind Direction 0° ± 45°

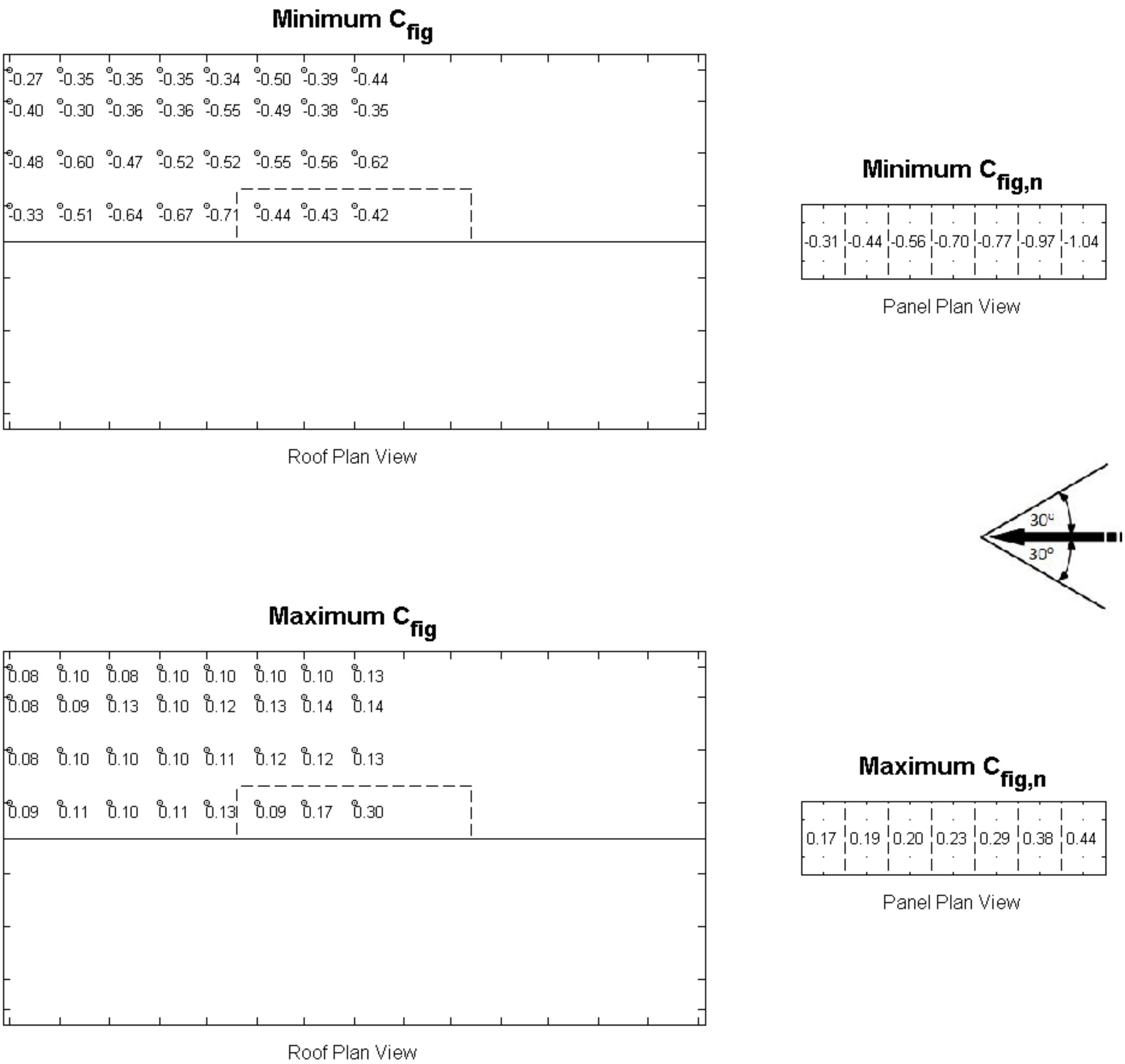
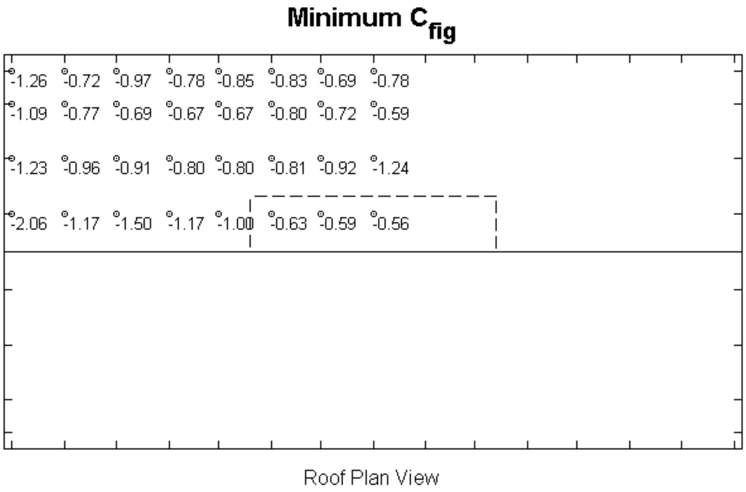
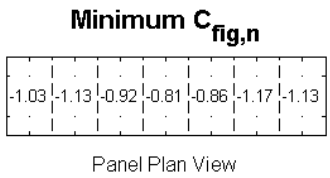
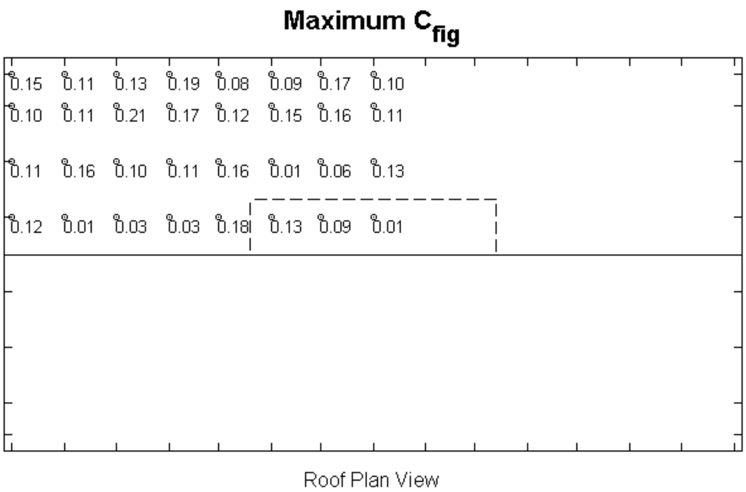
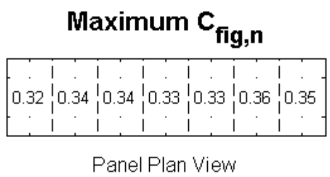


Figure A7-j. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 22.5^o, Wind Direction 90^o ± 30^o









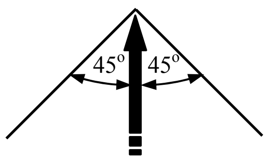


Figure A7-k. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 22.5^o, Wind Direction 180^o ± 45^o

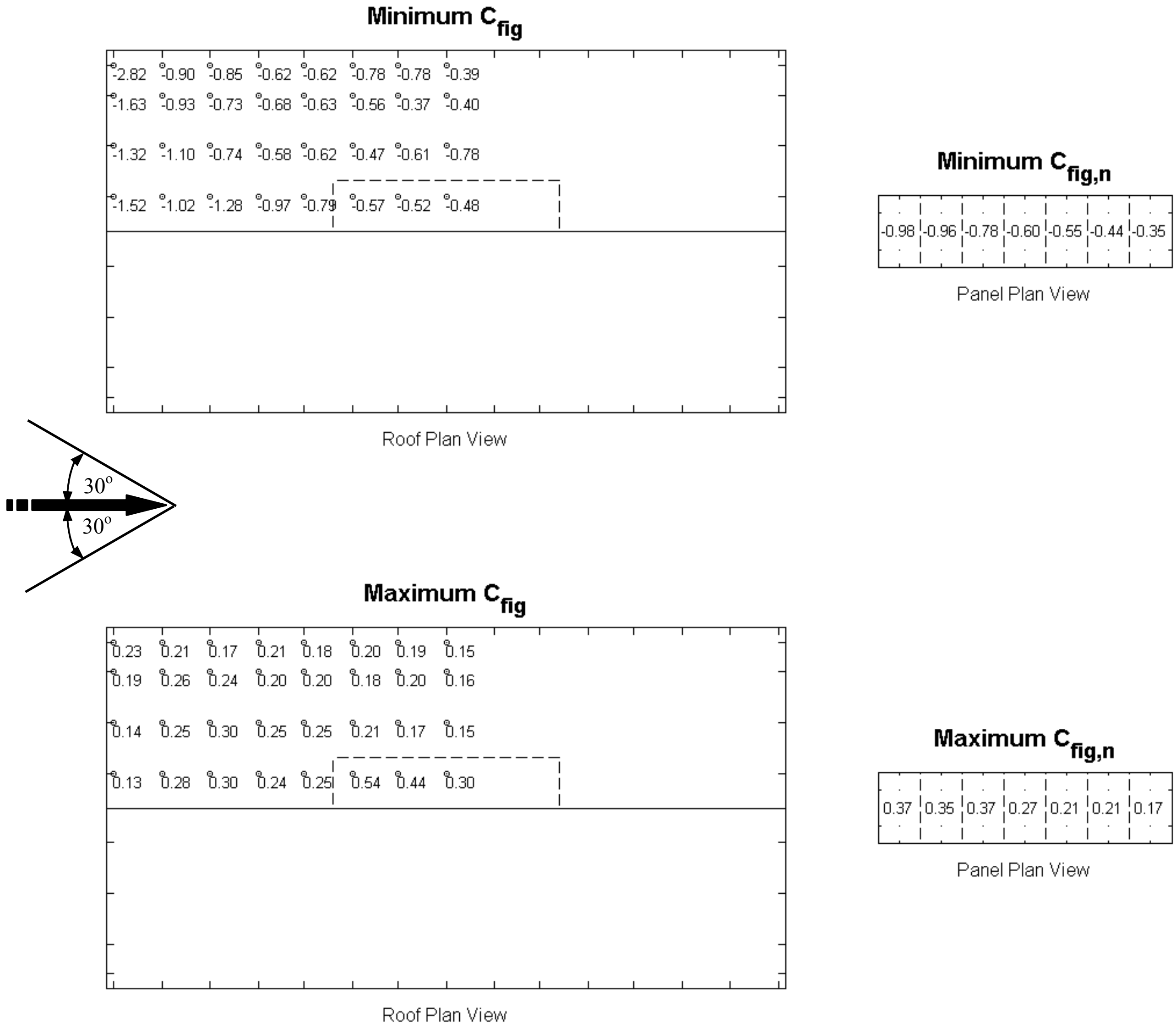


Figure A7-l. C_{fig} – Panel Position F, Gap 100mm - Roof Pitch 22.5°, Wind Direction 270° ± 30°

APPENDIX B

PART A – RESIDENTIAL BUILDINGS: SAMPLE DESIGN CALCULATIONS

Sample design wind load calculations are included here. The aim is to illustrate the process that a designer or testing authority would need to go through to determine the pressure that applies to a panel system. They would do this using the pressure coefficients developed in this report, along with some knowledge of the maximum design wind speed in a particular application or range of applications.

The examples use data collected for the 1 × 7 panel array with a 100mm gap located at various positions on a high, medium and low pitch roof in wind regions A, B and C. The results are also compared with external design pressures obtained from AS/NZS 1170.2 [1], to assess the validity of the statement found in the literature that the nett pressure across the panel system may be similar to the external pressure that applies to the roof cladding at the same location without the panel system in place.

Details for Sample Calculations:

For the external roof surface, the peak design wind pressure is calculated using the following formula, as:

$$p_{design} = 0.5\rho_{air}V_h^2 C_{fig} C_{dyn}$$

Where:

p_{design} is the design wind pressure applied to the roof surface

ρ_{air} is the density of air, taken as 1.2 kg/m^3

V_h is the design wind speed for the building (using 62 m/s for Example 1)

C_{fig} is the aerodynamic shape factor (taken as -0.9 x 2.0 for Example 1)

C_{dyn} is the dynamic response factor, taken as 1.0 as there is no dynamic wind sensitivity

For the solar panels, the net design pressure acting on the array is calculated using a very similar formula:

$$p_{design,n} = 0.5\rho_{air}V_h^2 C_{fig,n}\ C_{dyn}$$

Where the new parameters are:

$p_{desiign,n}$ is the net design wind pressure applied to the solar panel

$C_{fig,n}$ is the net aerodynamic shape factor from this study (see Fig A5-l for Example 1)

Example 1   22.5° roof in Cairns (Region C) V_h = 62 m/s, Wind Direction 270° ± 30°

Pressure within a distance of 1m from gable end (i.e. *a*/2, where a is as defined in AS/NZS 1170.2)
Design Pressure = (0.5 ×1.22×62×62/1000) × (-0.9×2.0) = -4.15 kPa

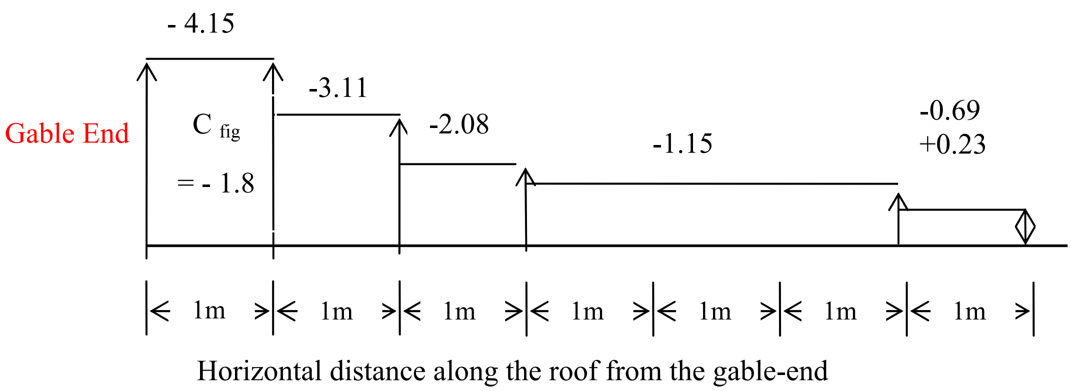
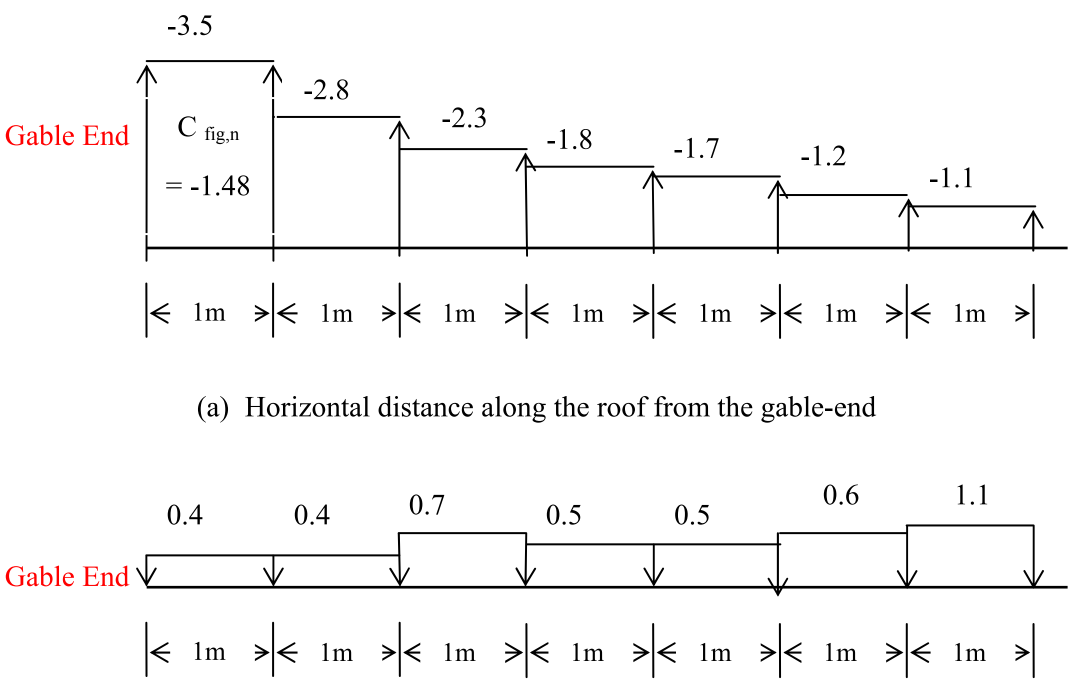


Figure B1 - External pressure on Baseline Building from AS/NZS 1170.2 (kPa)



(a) Horizontal distance along the roof from the gable-end

(b) Horizontal distance along the roof from the gable-end

Figure B2 - Net pressure on 1 × 7 Panel array at Position D from wind tunnel study (kPa)

Example 2. 15° roof in Brisbane (Region B V_h = 50 m/s, 1x7, Wind Direction 270° ± 30°

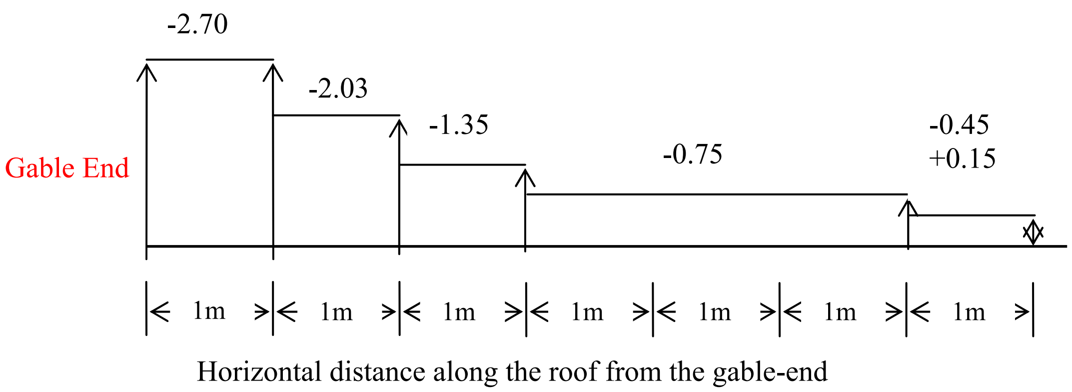


Figure B3 - External pressure on Baseline Building from AS/NZS 1170.2 (kPa)

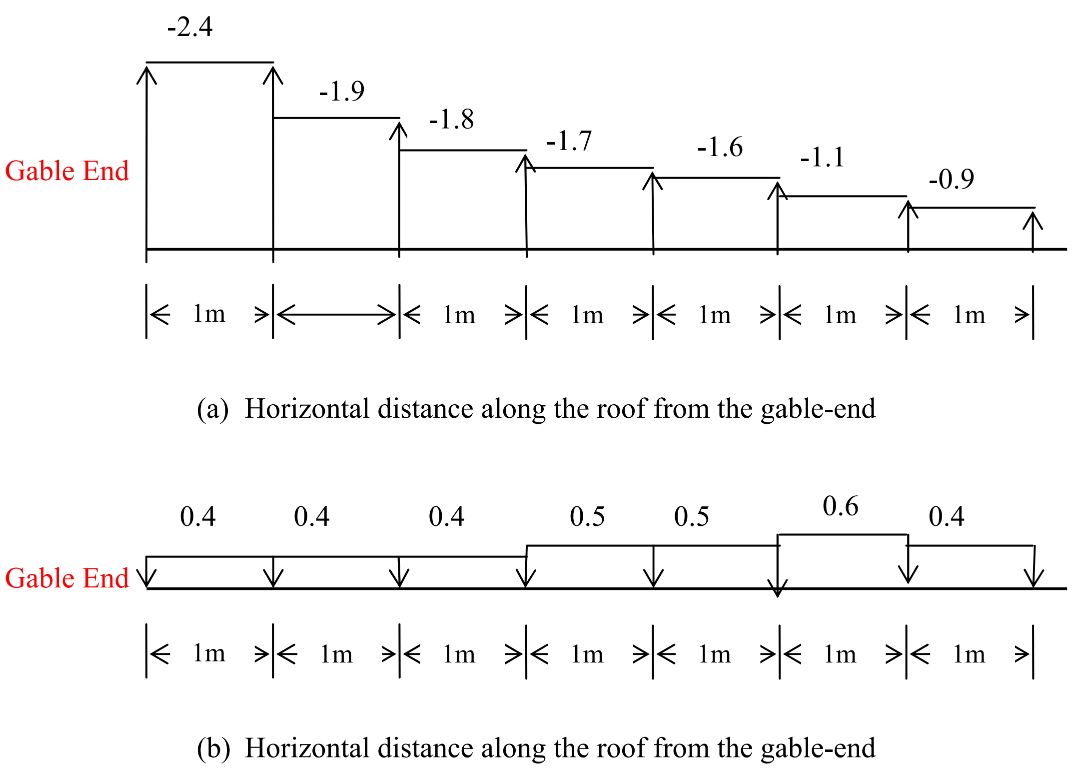
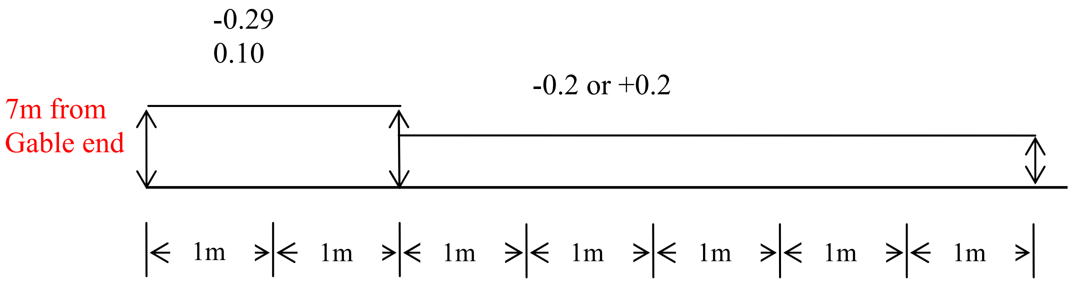


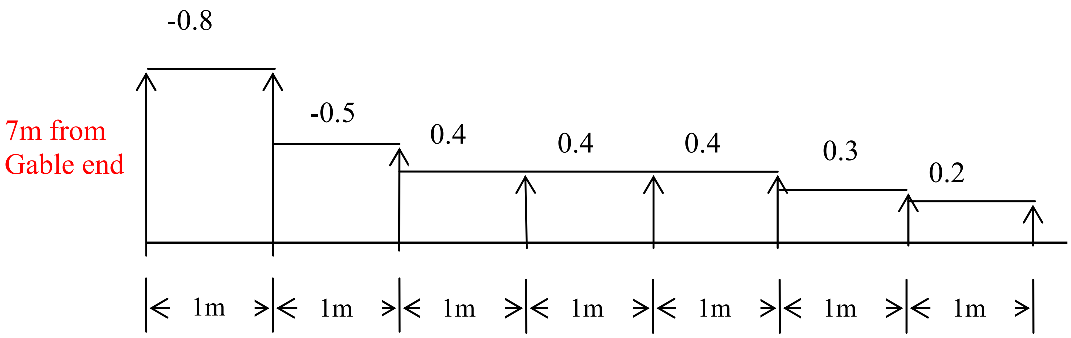
Figure B4 - Net pressure on 1 × 7 Panel array at Position C from wind tunnel study (kPa)

Example 3. 7.5° roof in Mount Isa (Region A, V_h = 40 m/s, Wind Direction 270° ± 30°

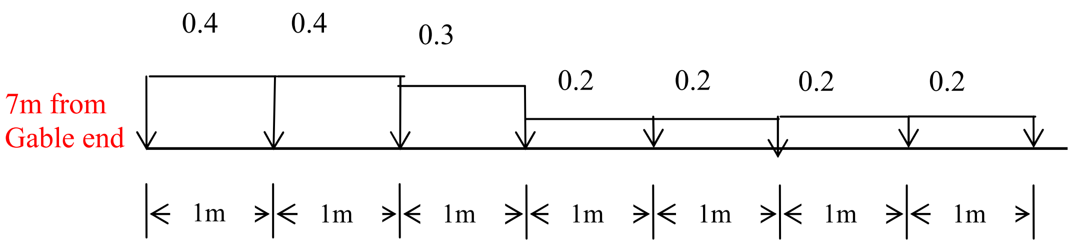


Horizontal distance along the roof starting 7m from the gable-end

Figure B5 - External pressure on Baseline Building from AS/NZS 1170.2 (kPa)



(a) horizontal distance along the roof starting 7m from the gable-end

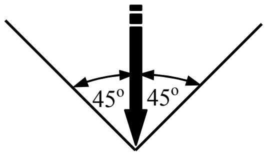


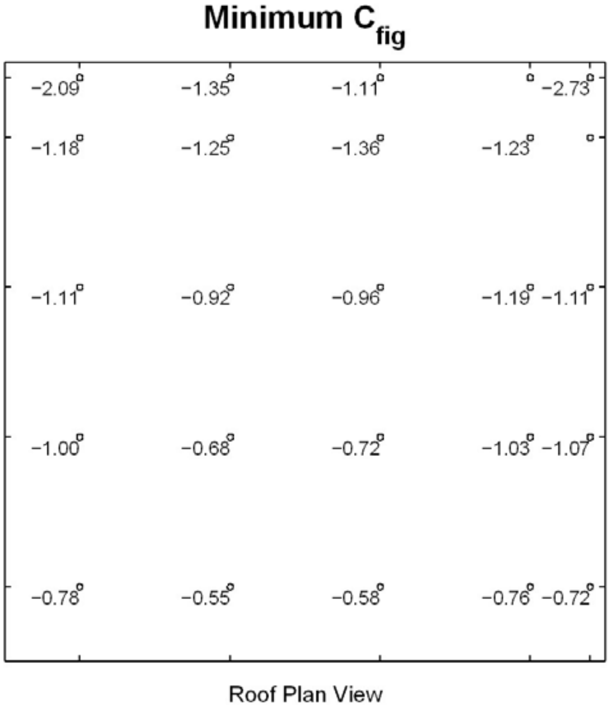
(b) horizontal distance along the roof starting 7m from the gable-end

Figure B6 - Net pressure on 1 × 7 Panel array at Position B from wind tunnel study (kPa)

APPENDIX C – PRESSURE COEFICIENTS

PART B – BASELINE FLAT ROOF BUILDING & PANELS INCLINED TO FLAT ROOF





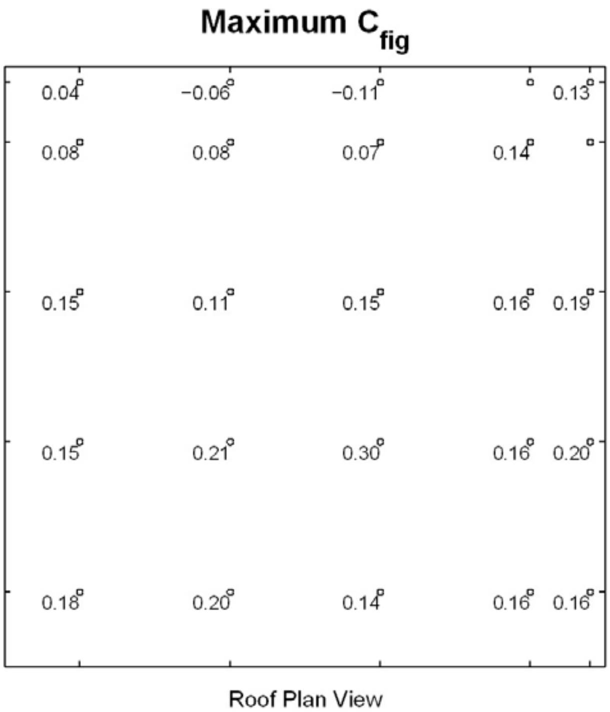


Figure C1-a. C_{fig} - Baseline building - Wind Direction $0^o \pm 45^o$

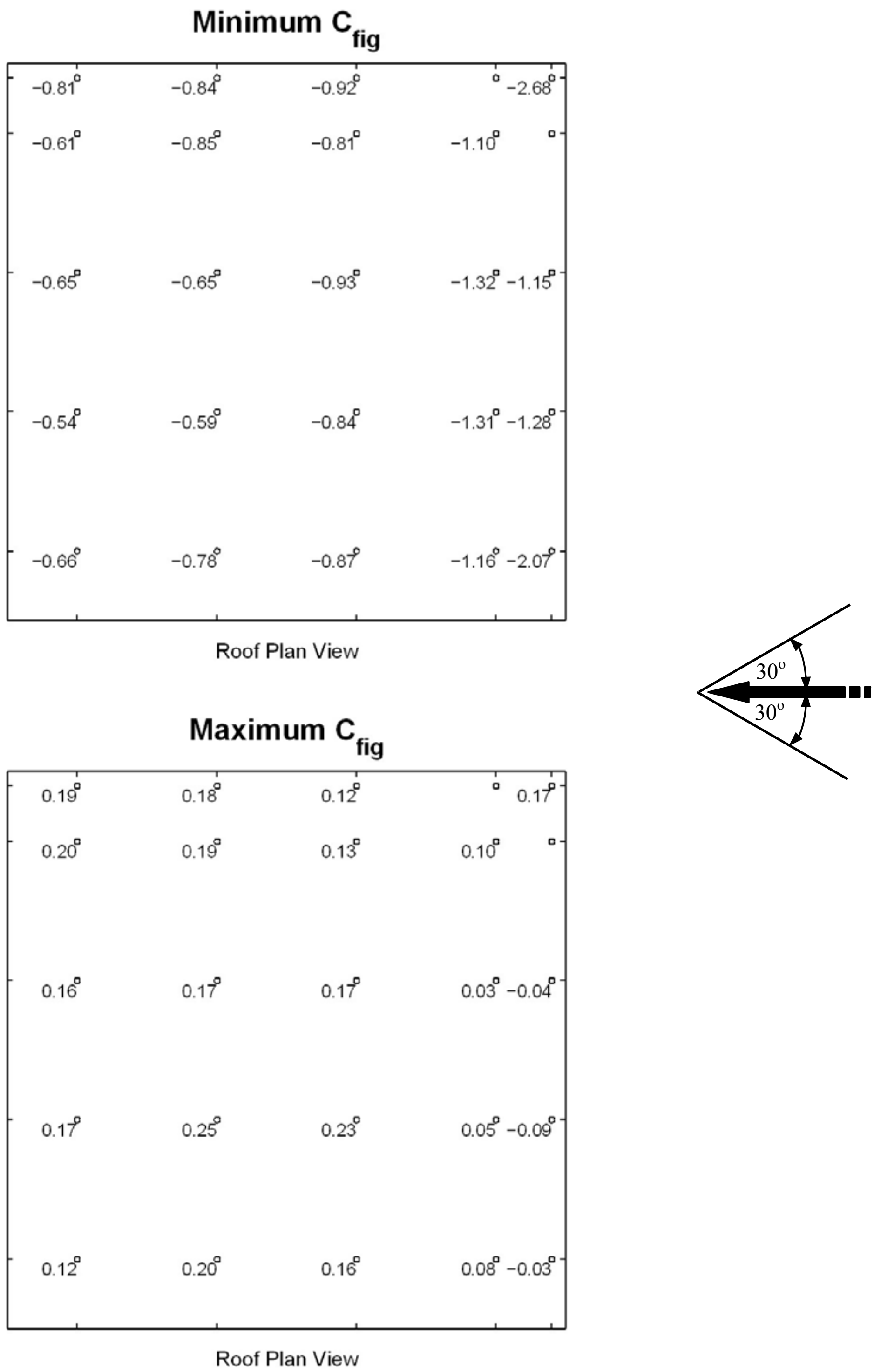
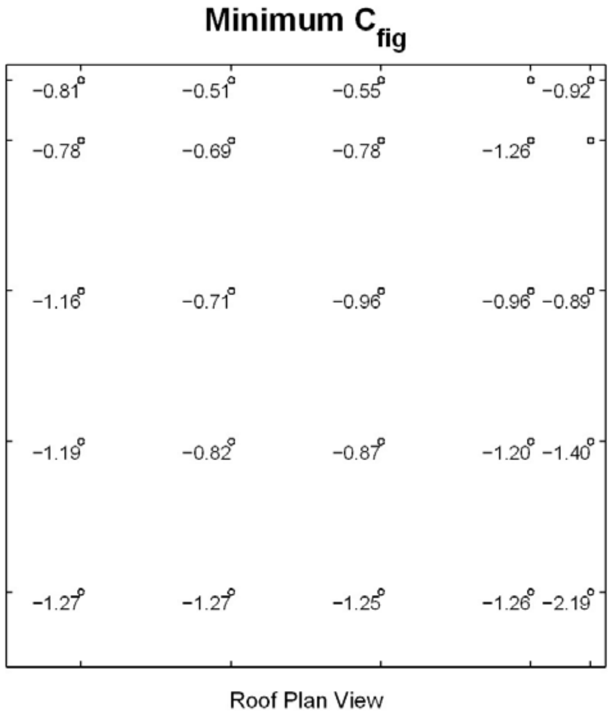
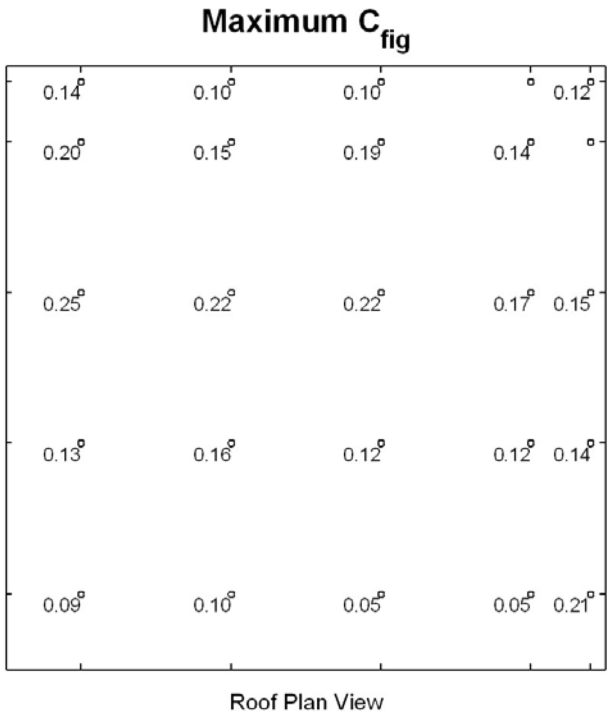


Figure C1-b. C_{fig} - Baseline building - Wind Direction 90° ± 30°





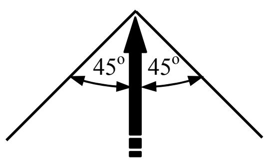


Figure C1-c. C_{fig} - Baseline building - Wind Direction $180^{o} \pm 45^{o}$

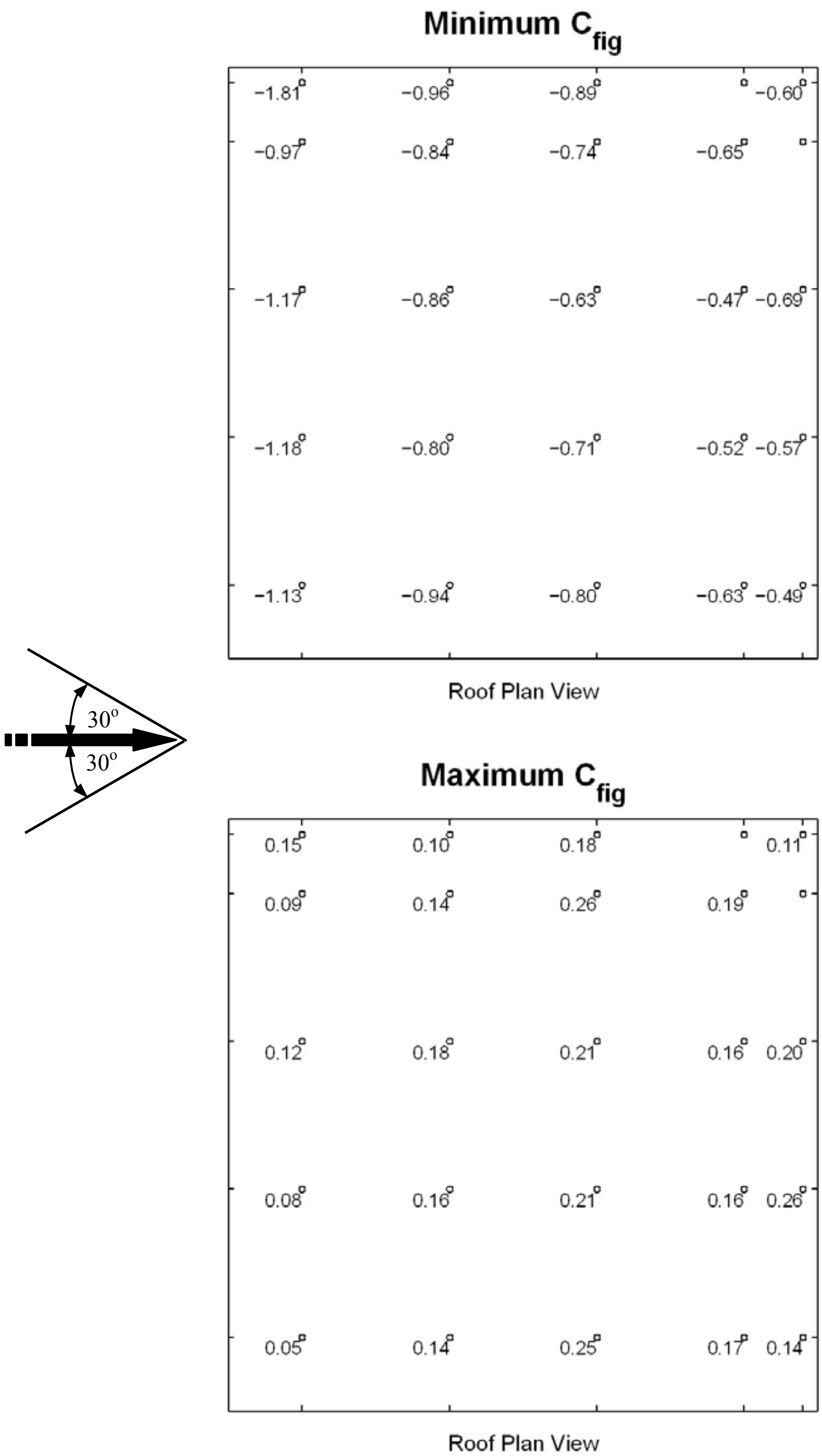


Figure C1-d. C_{fig} - Baseline building - Wind Direction $270^o \pm 30^o$

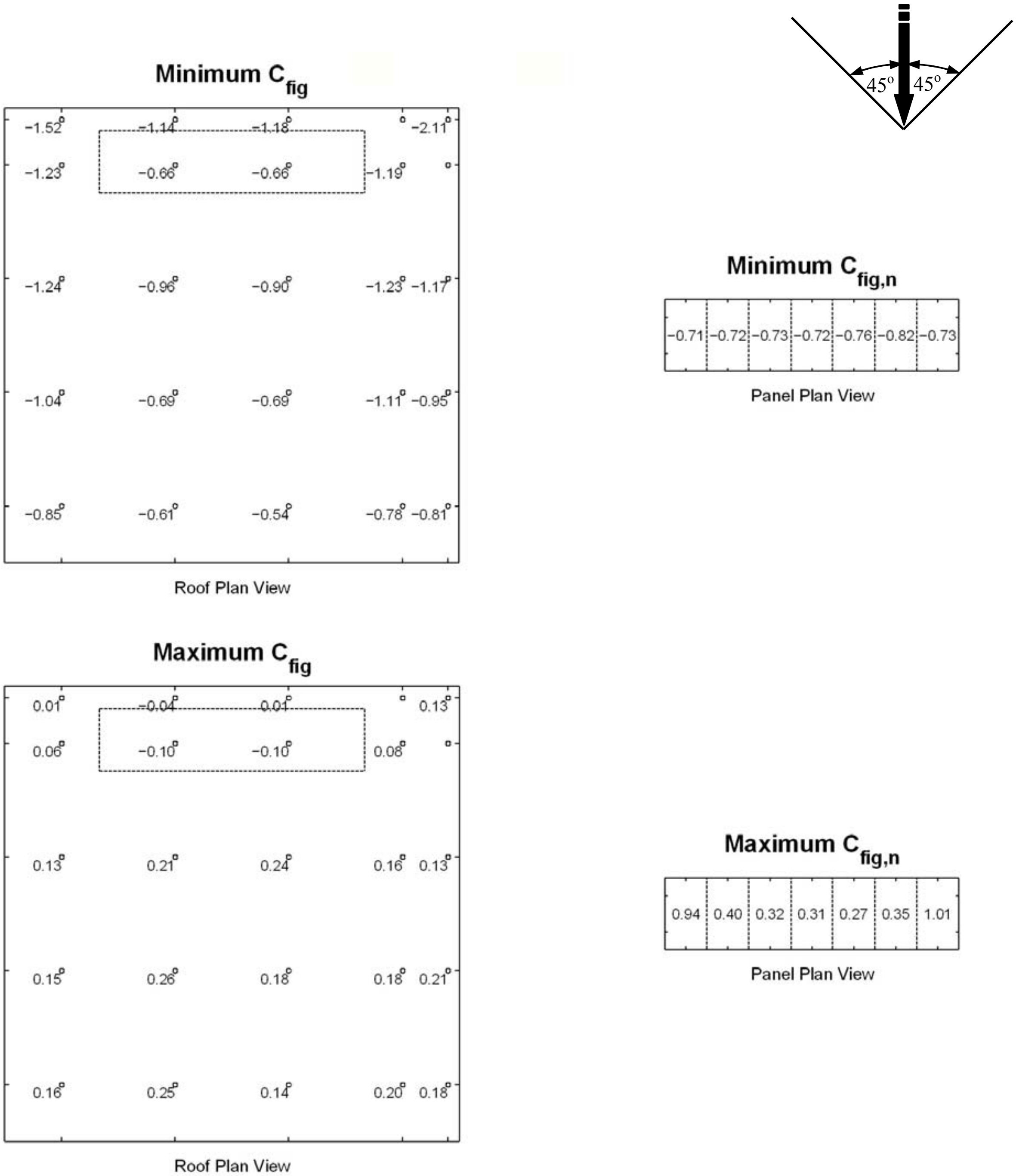


Figure C2-a.- C_{fig} – Panel Position A - 15° Incline, Wind Direction 0° ± 45°

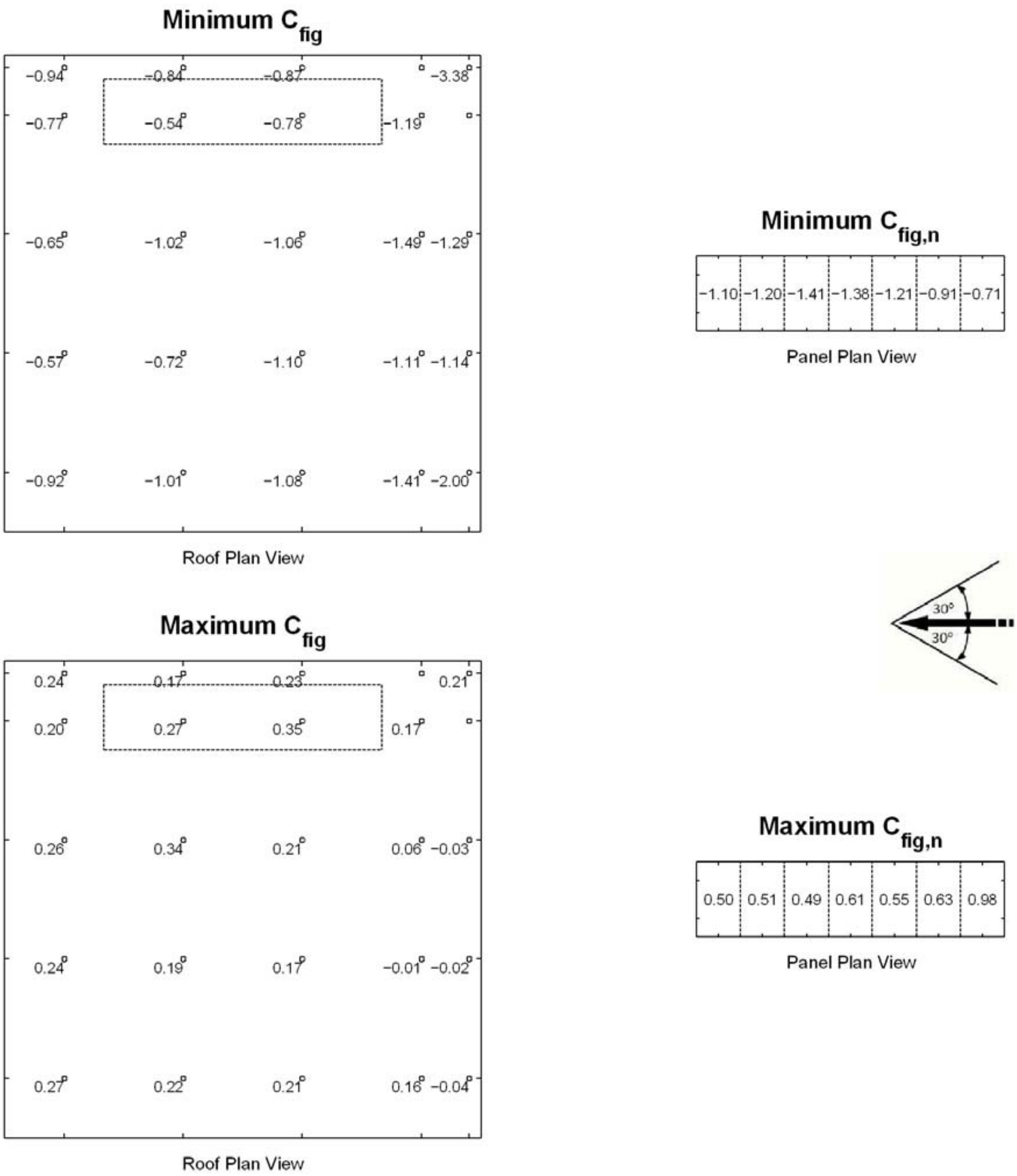


Figure C2-b. - C_{fig} – Panel Position A - 15° Incline, Wind Direction 90° ± 30°

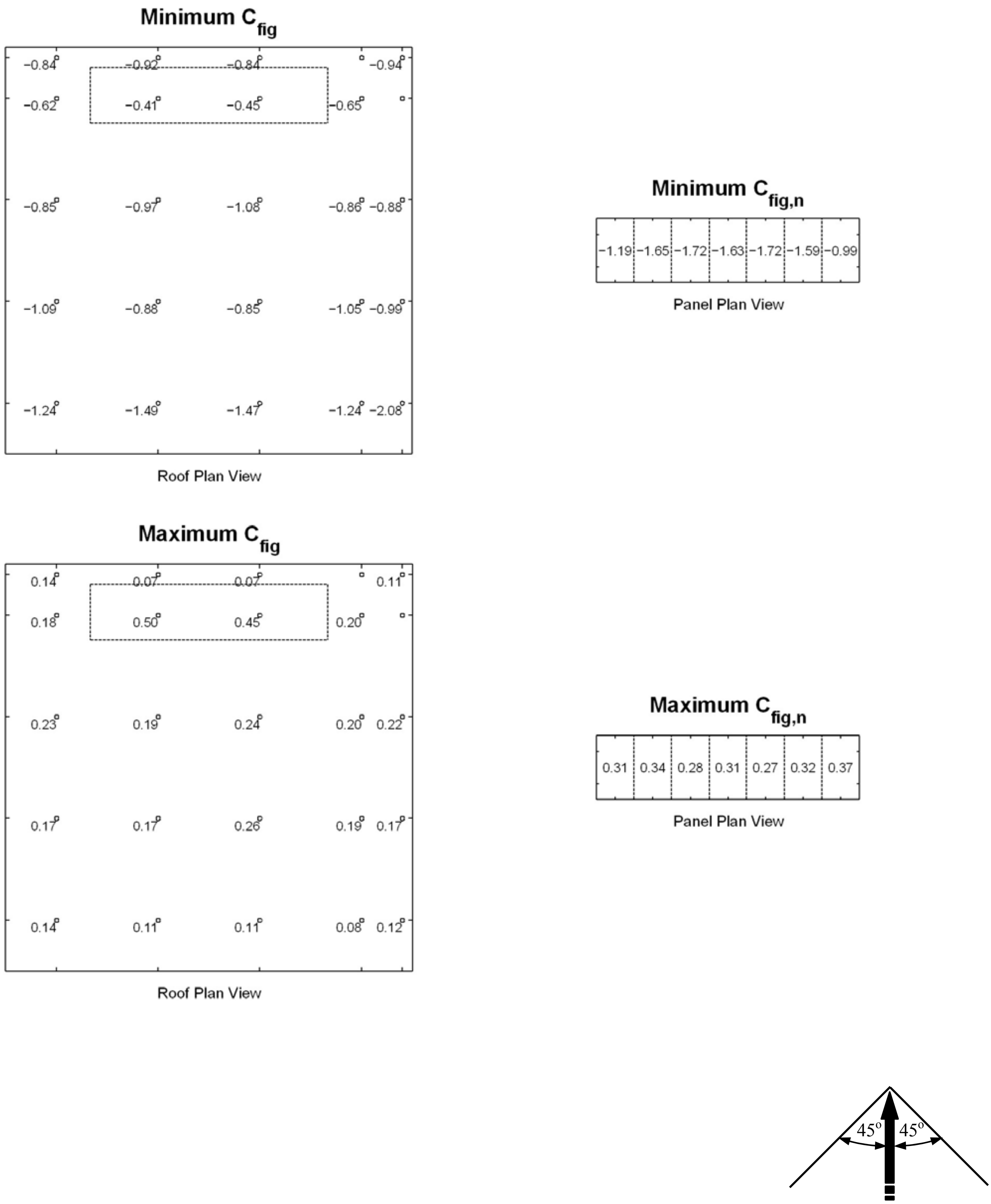


Figure C2-c. C_{fig} – Panel Position A - 15° Incline, Wind Direction 180° ± 45°

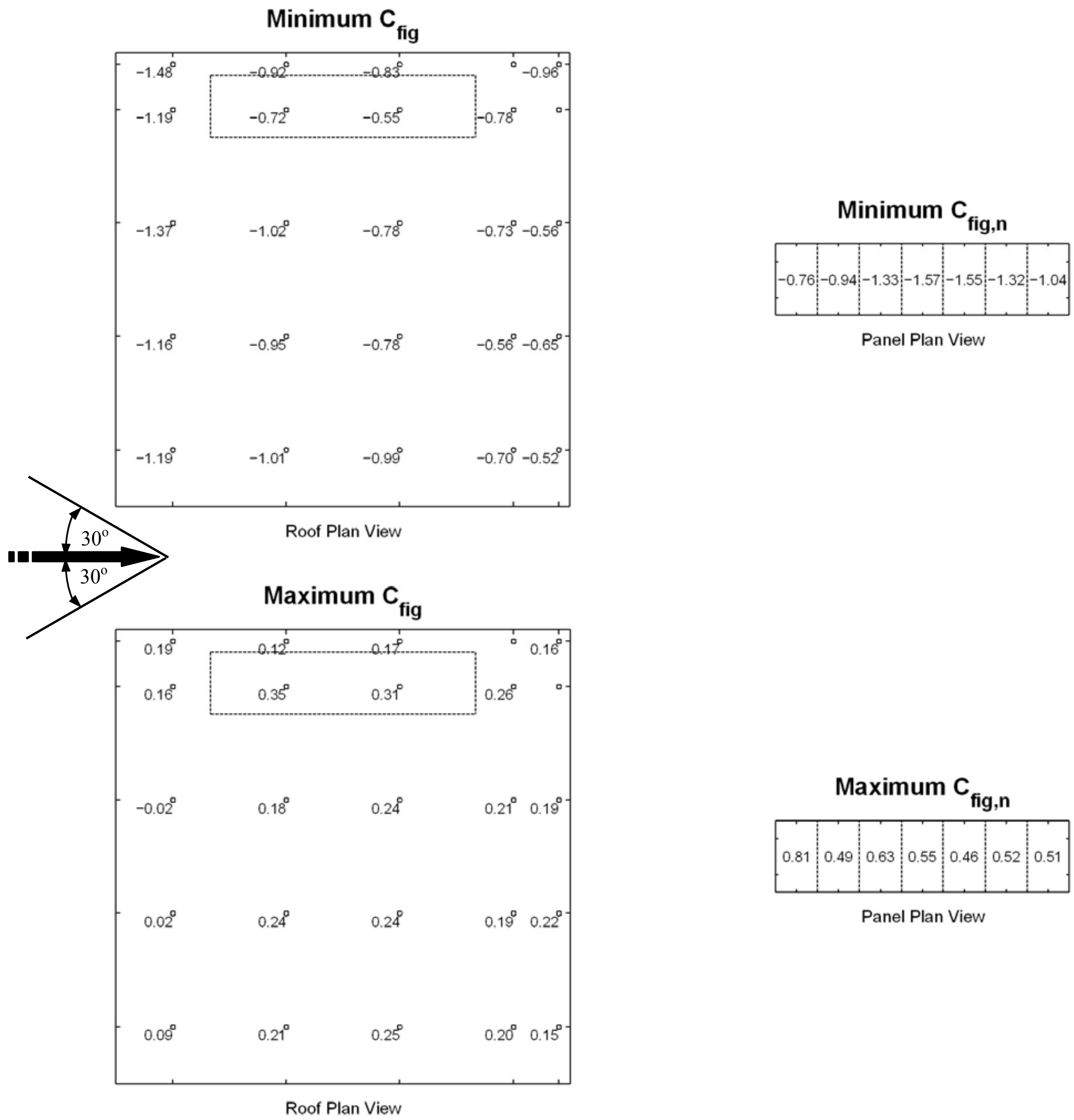
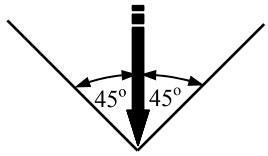
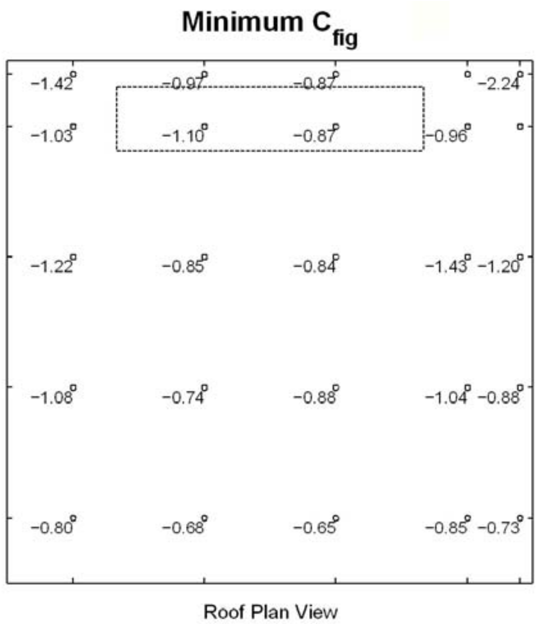
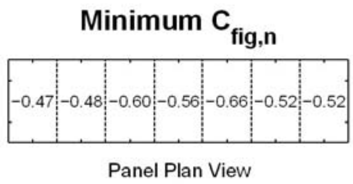
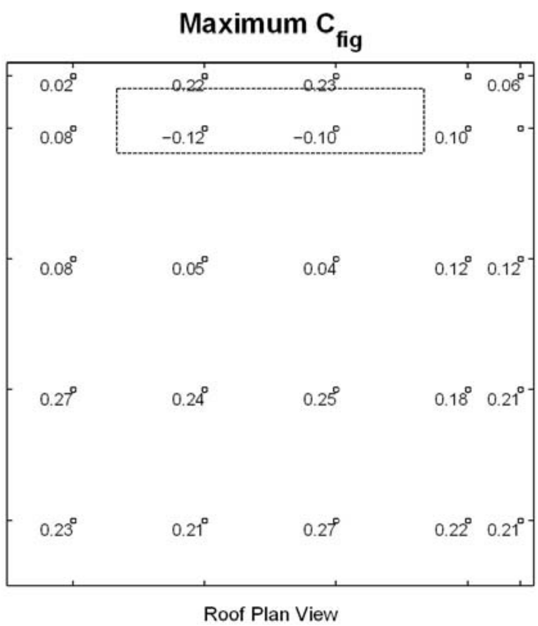


Figure C2-d.- C_{fig} – Panel Position A - 15° Incline, Wind Direction 270° ± 30°









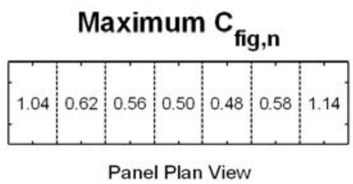


Figure C2-e. C_{fig} – Panel Position A - 30^o Incline, Wind Direction 0^o ± 45^o

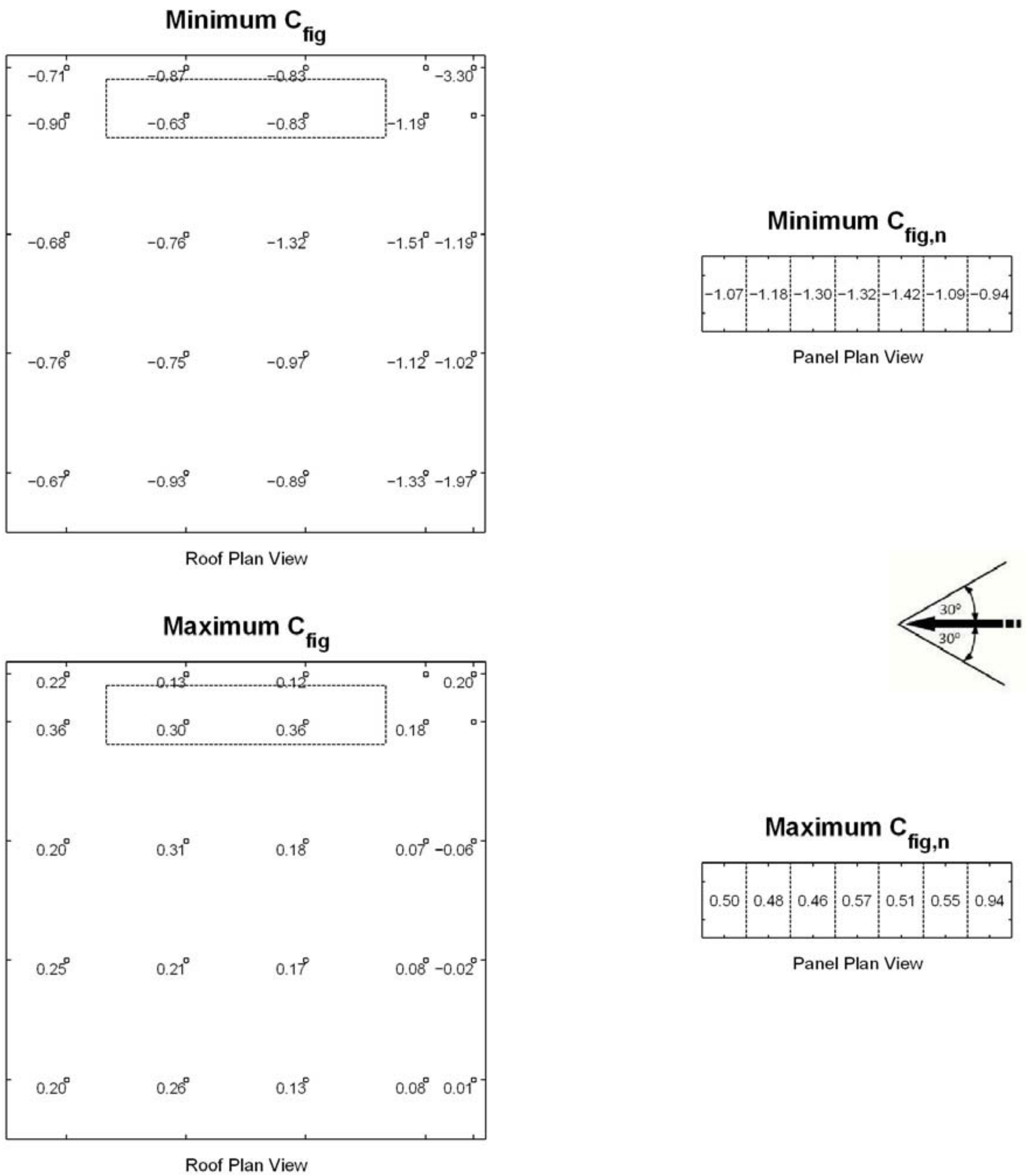


Figure C2-f. C_{fig} – Panel Position A - 30^o Incline, Wind Direction 90^o ± 30^o

Figure C2-g. C_{fig} – Panel Position A - 30° Incline, Wind Direction 180° ± 45°

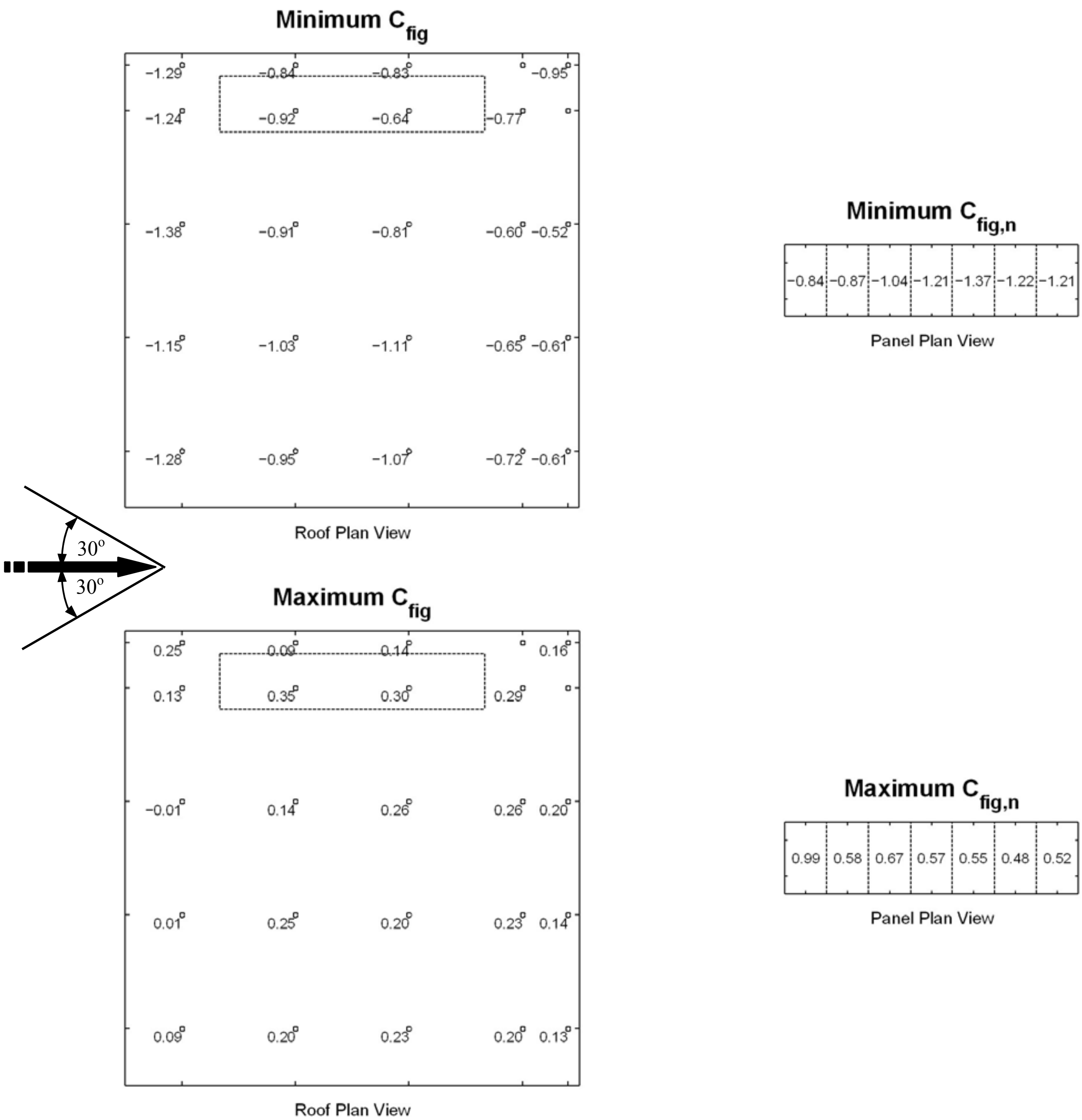


Figure C2-h. C_{fig} – Panel Position A -30° Incline, Wind Direction 270° ± 30°

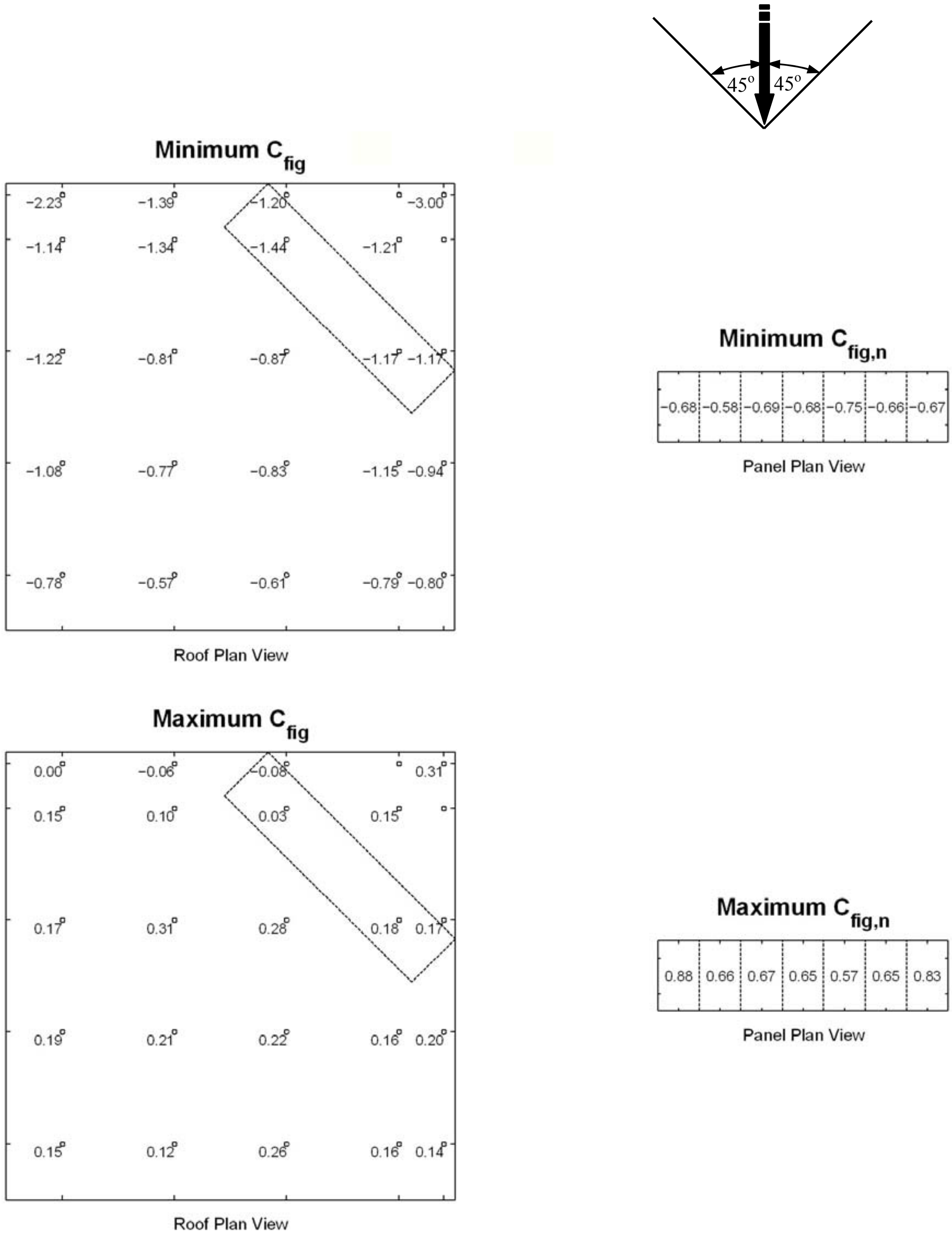


Figure C3-a. C_{fig} – Panel Position B - 15° Incline, Wind Direction 0° ± 45°

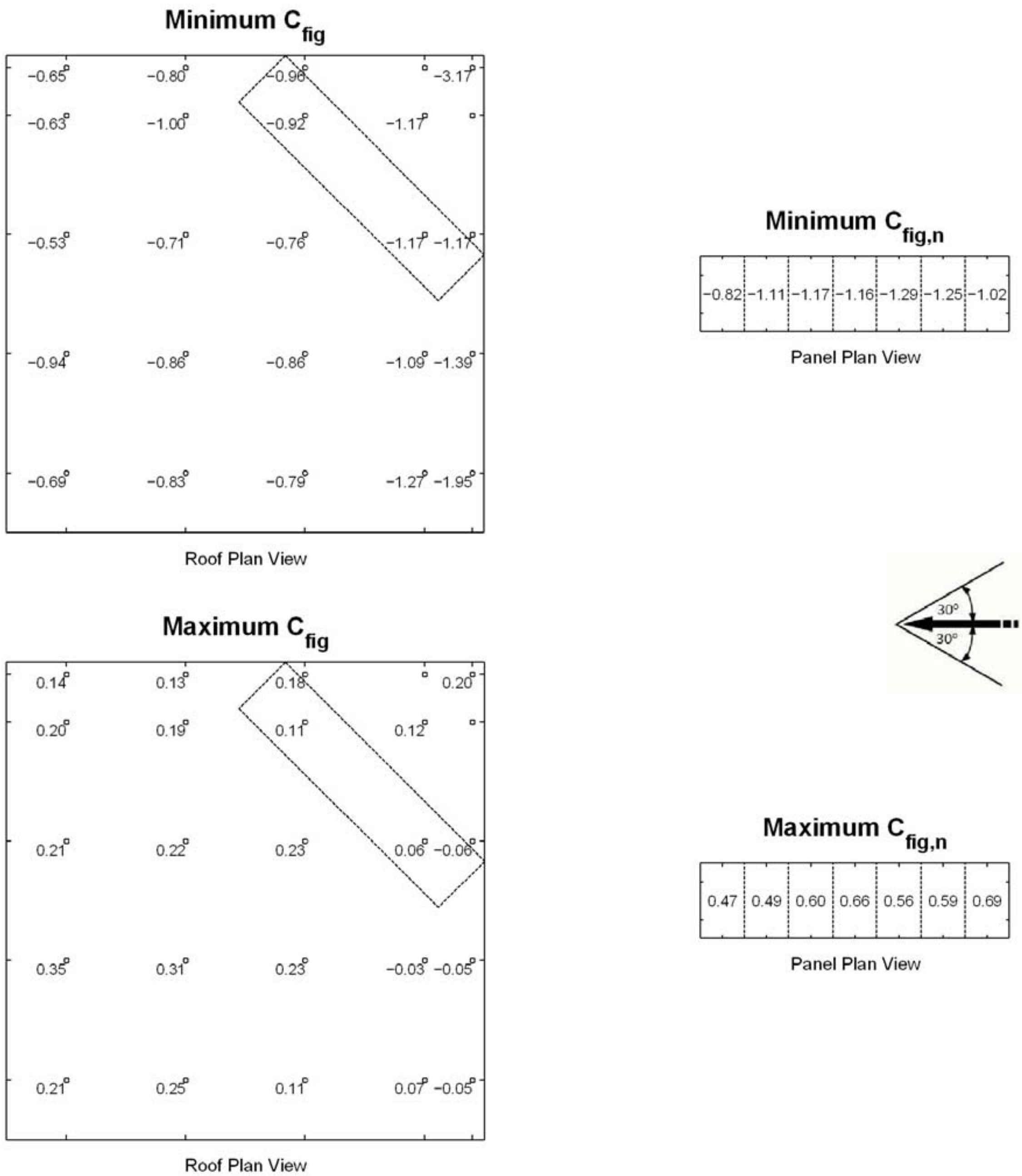
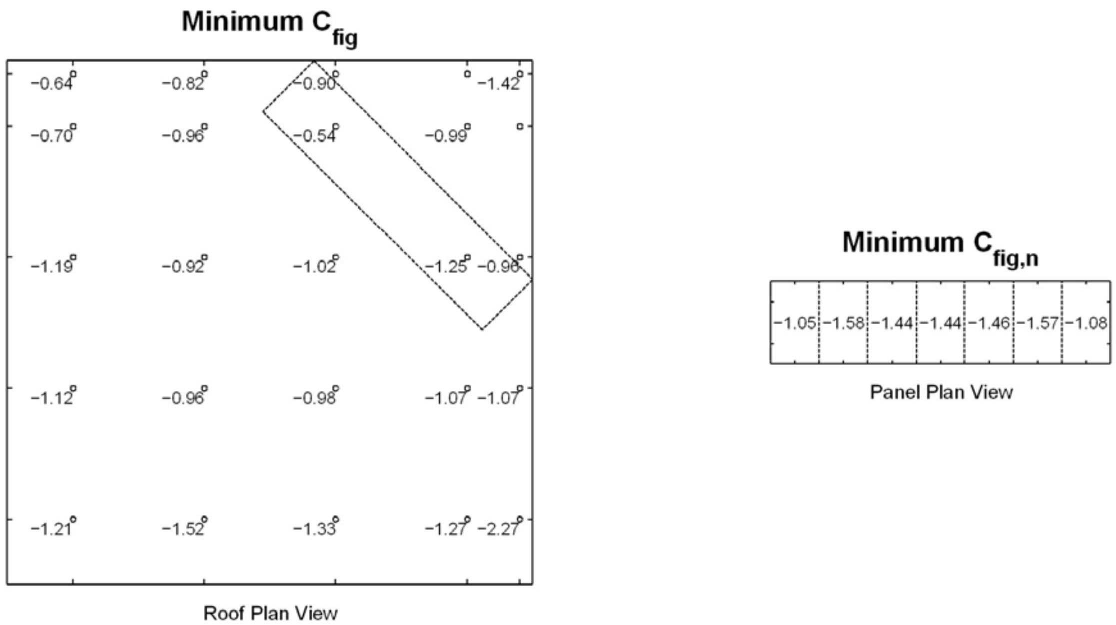
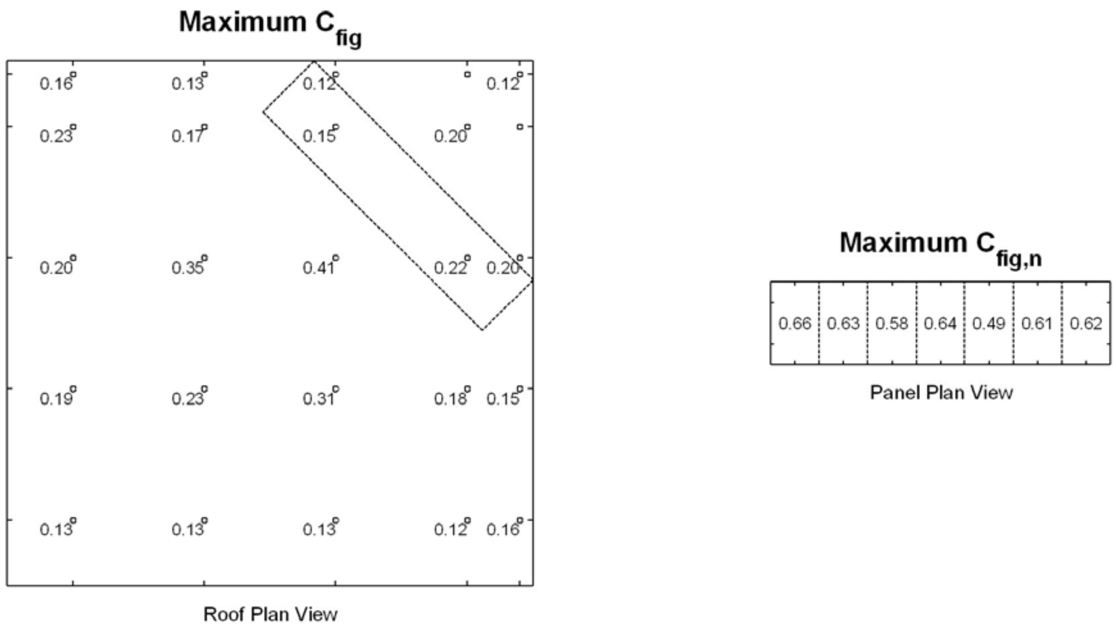


Figure C3-b. C_{fig} – Panel Position B - 15^o Incline, Wind Direction 90^o ± 30^o





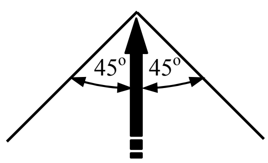


Figure C3-c. C_{fig} – Panel Position B - 15° Incline, Wind Direction 180° ± 45°

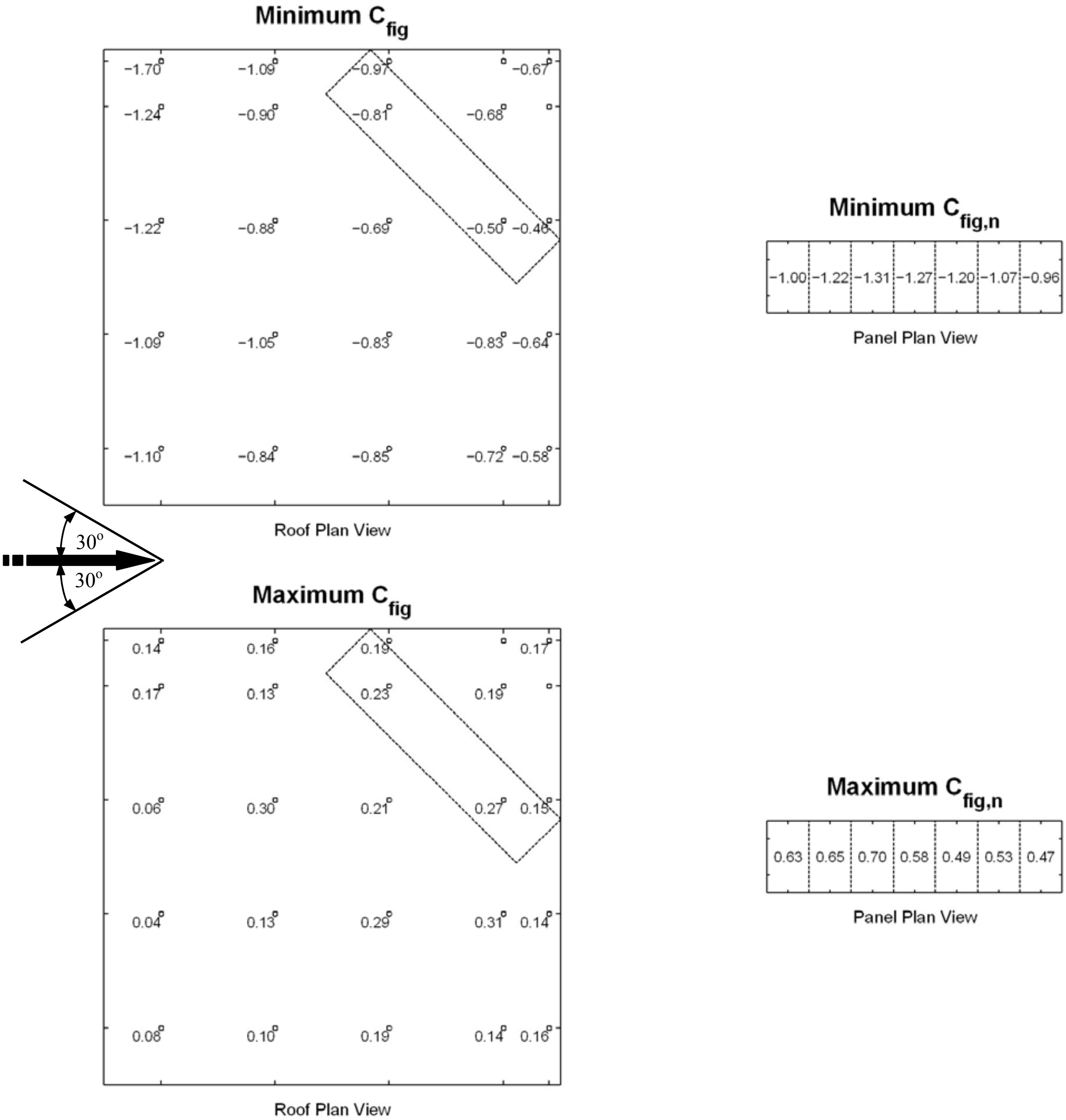


Figure C3-d. C_{fig} – Panel Position B - 15° Incline, Wind Direction 270° ± 30°

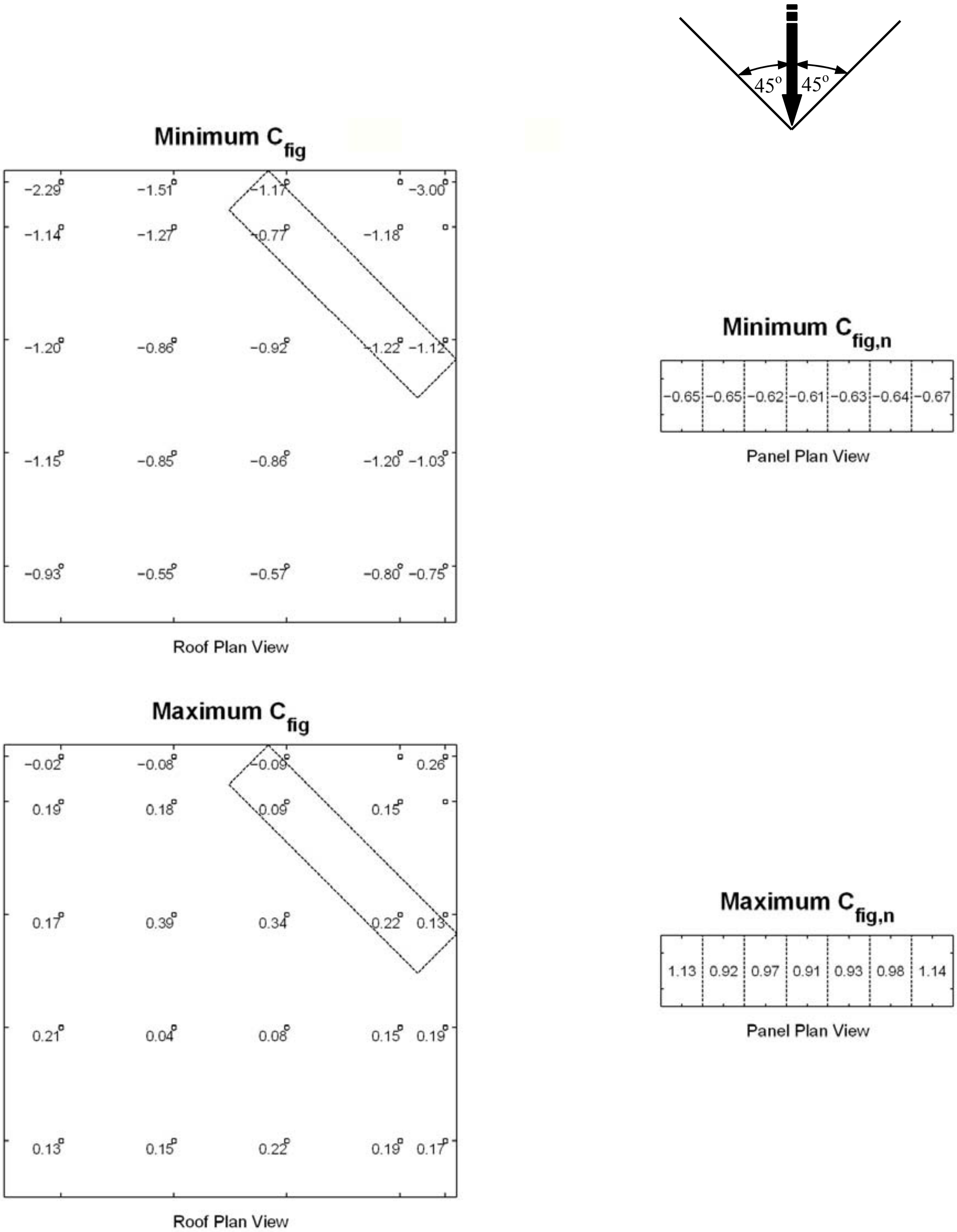


Figure C3-e. C_{fig} – Panel Position B - 30° Incline, Wind Direction 0° ± 45°

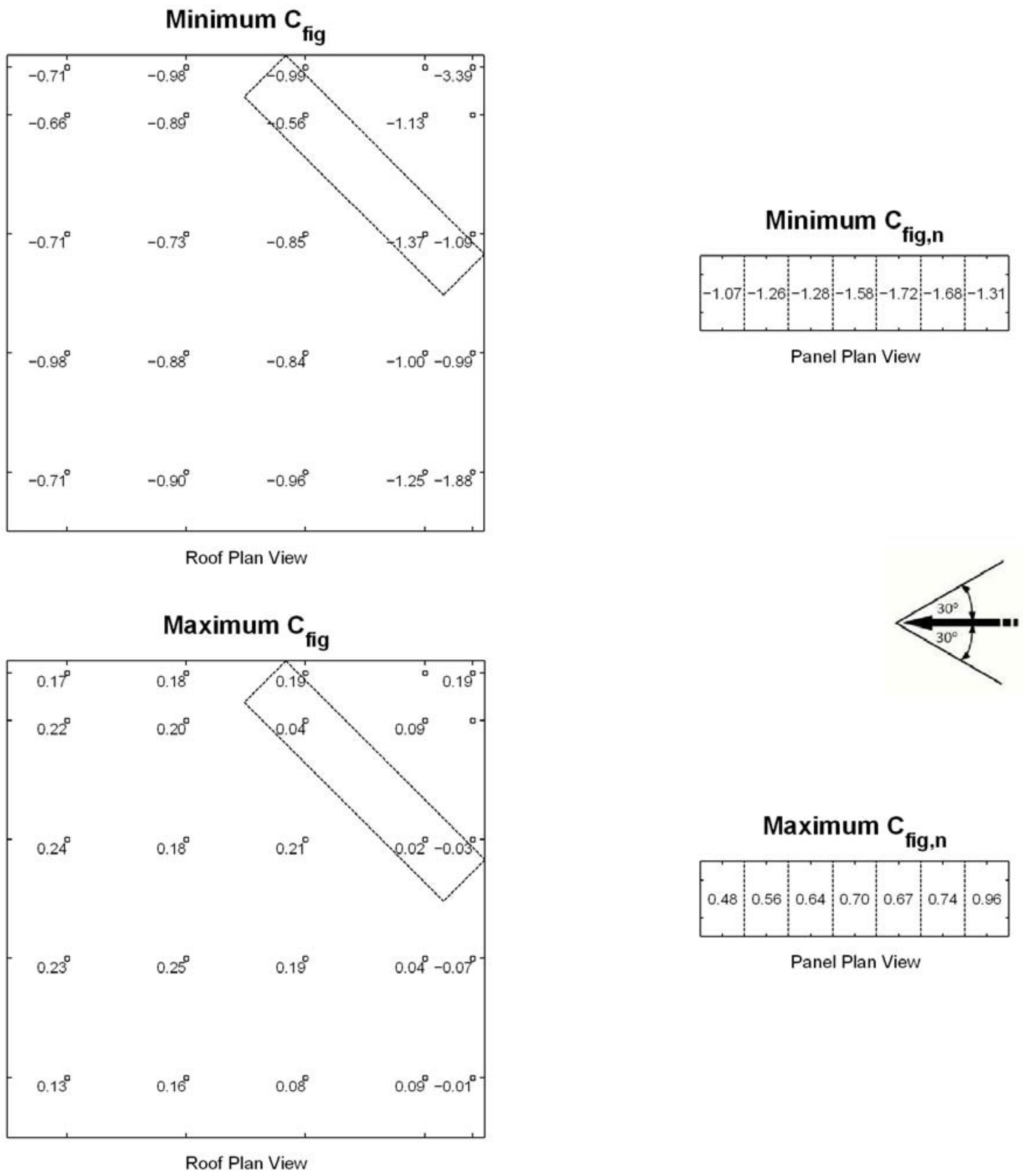


Figure C3-f. C_{fig} – Panel Position B - 30° Incline, Wind Direction 90° ± 30°

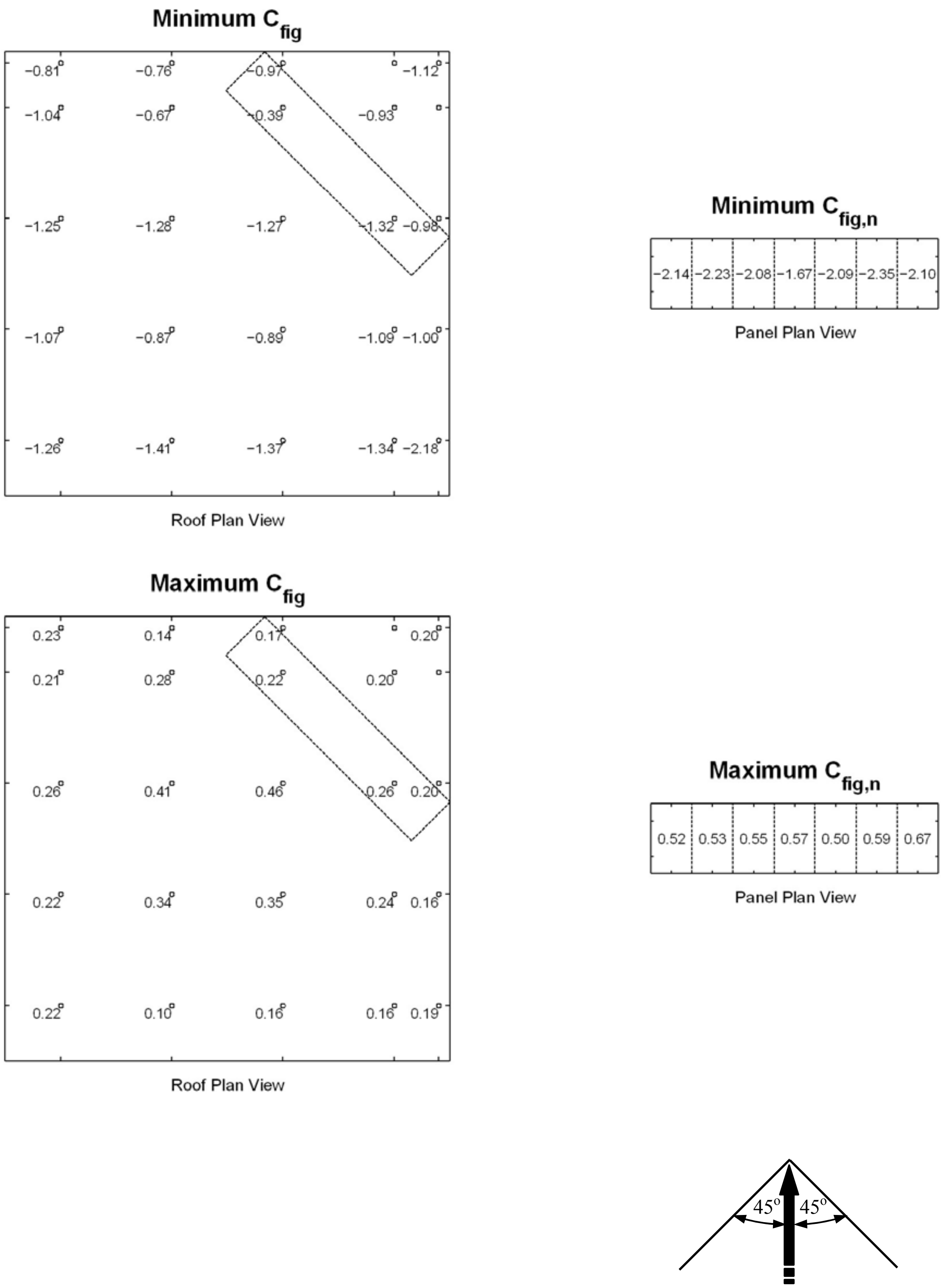


Figure C3-g. C_{fig} – Panel Position B - 30° Incline, Wind Direction 180° ± 45°

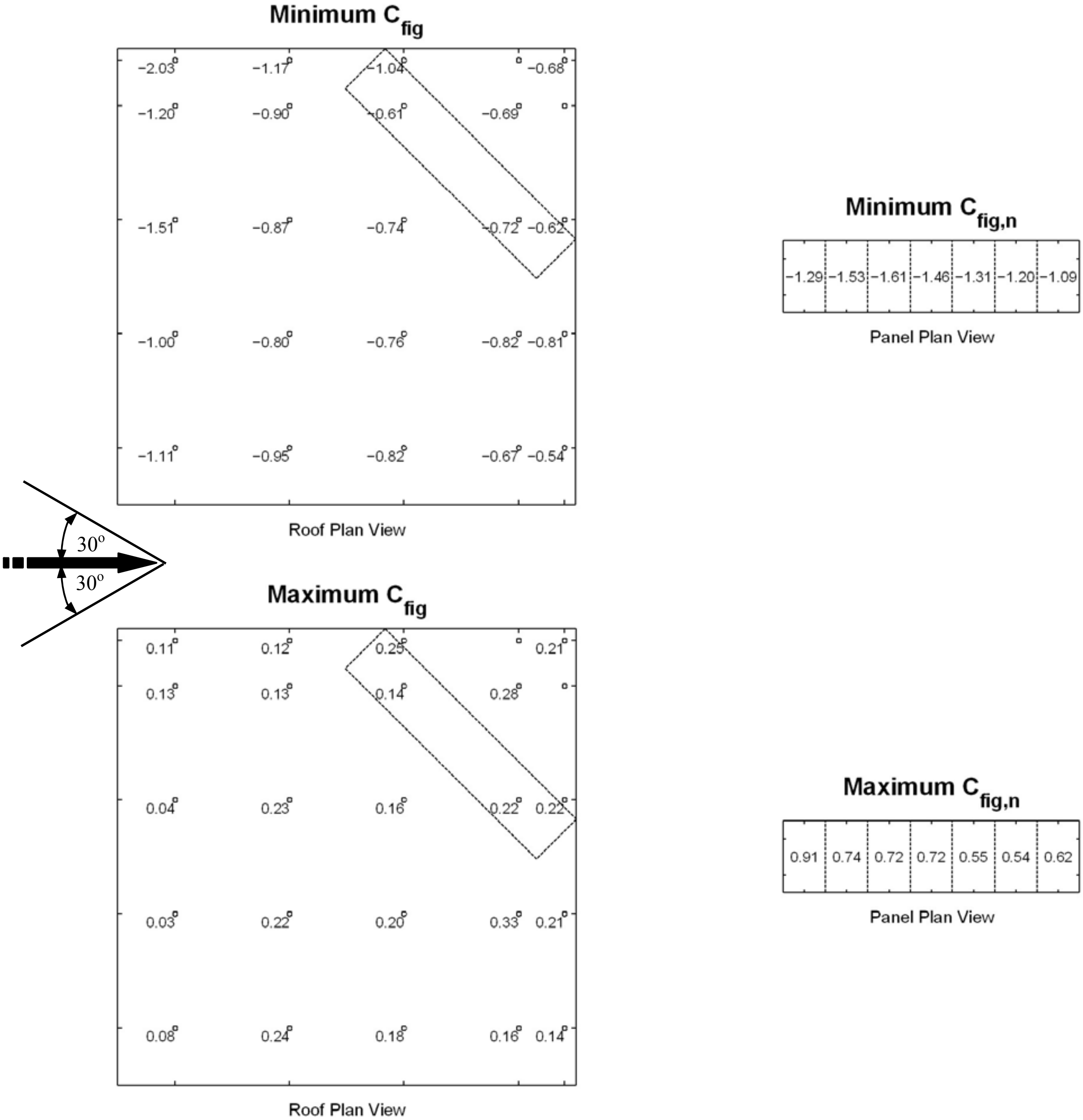


Figure C3-h. C_{fig} – Panel Position B -30° Incline, Wind Direction 270° ± 30°

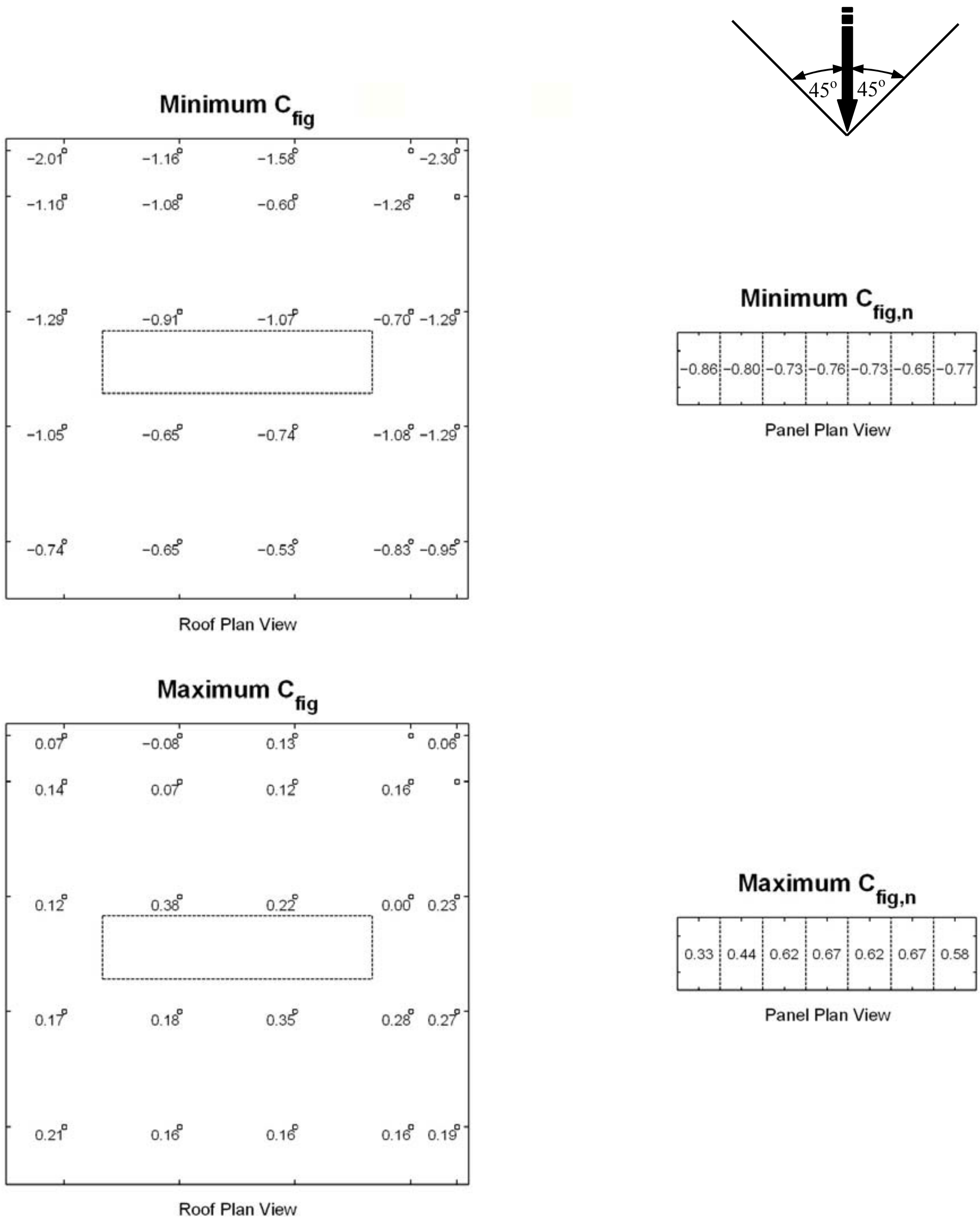


Figure C4-a - C_{fig} – Panel Position C - 15° Incline, Wind Direction 0° ± 45°

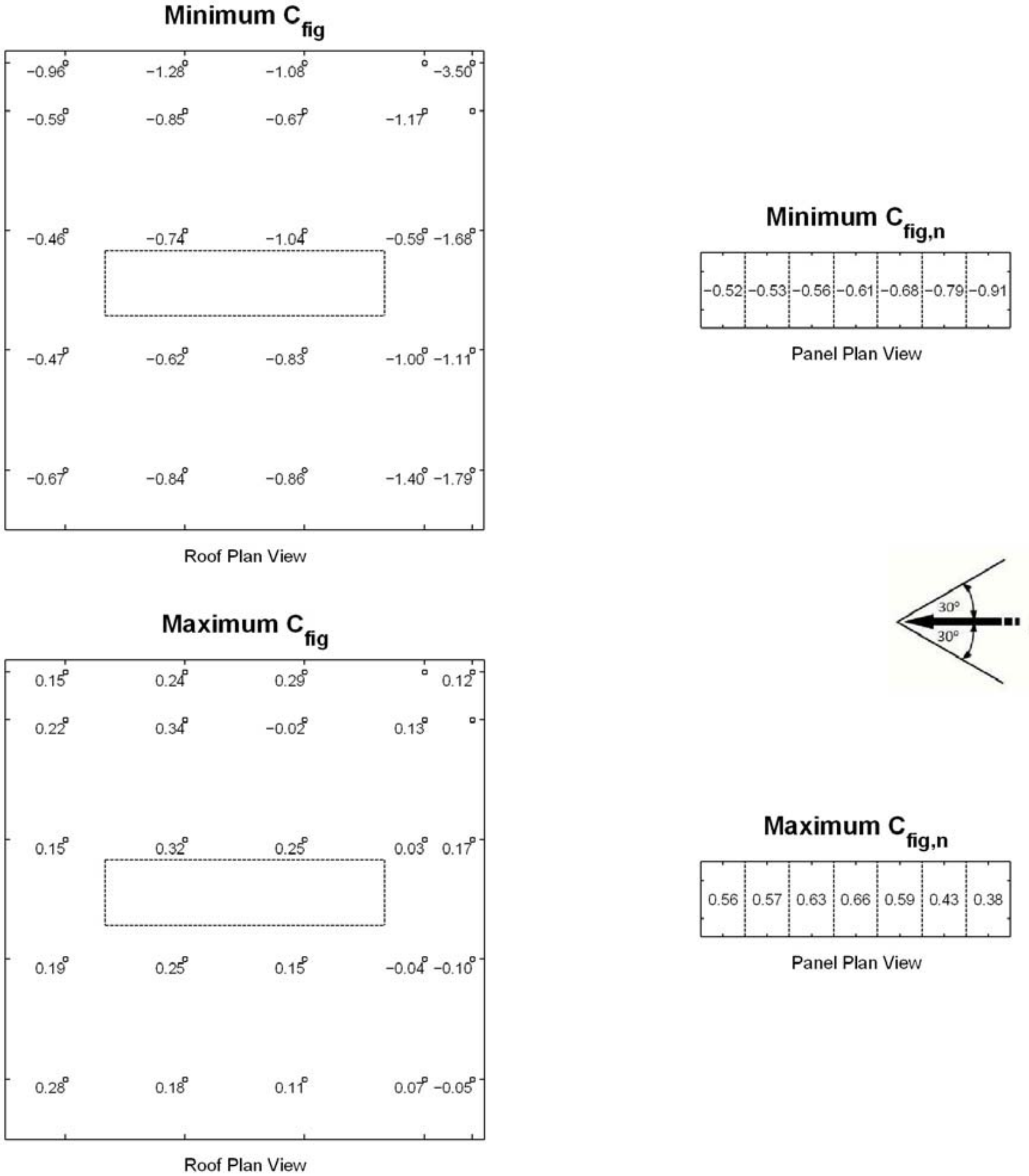


Figure C4-b. C_{fig} – Panel Position C - 15° Incline, Wind Direction 90° ± 30°

Figure C4-c. C_{fig} – Panel Position C - 15° Incline, Wind Direction 180° ± 45°

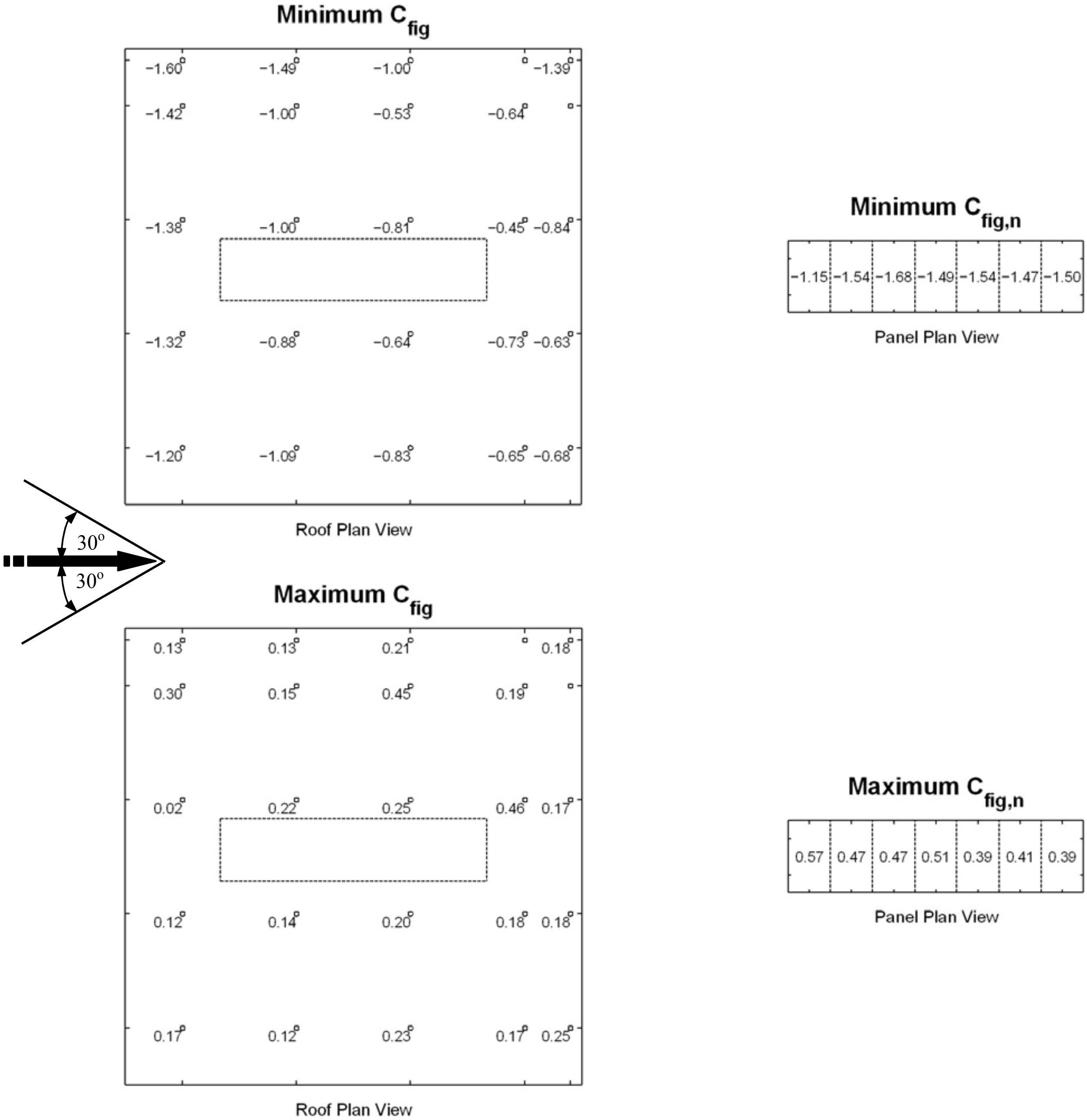


Figure C4-d. C_{fig} – Panel Position C - 15° Incline, Wind Direction 270° ± 30°

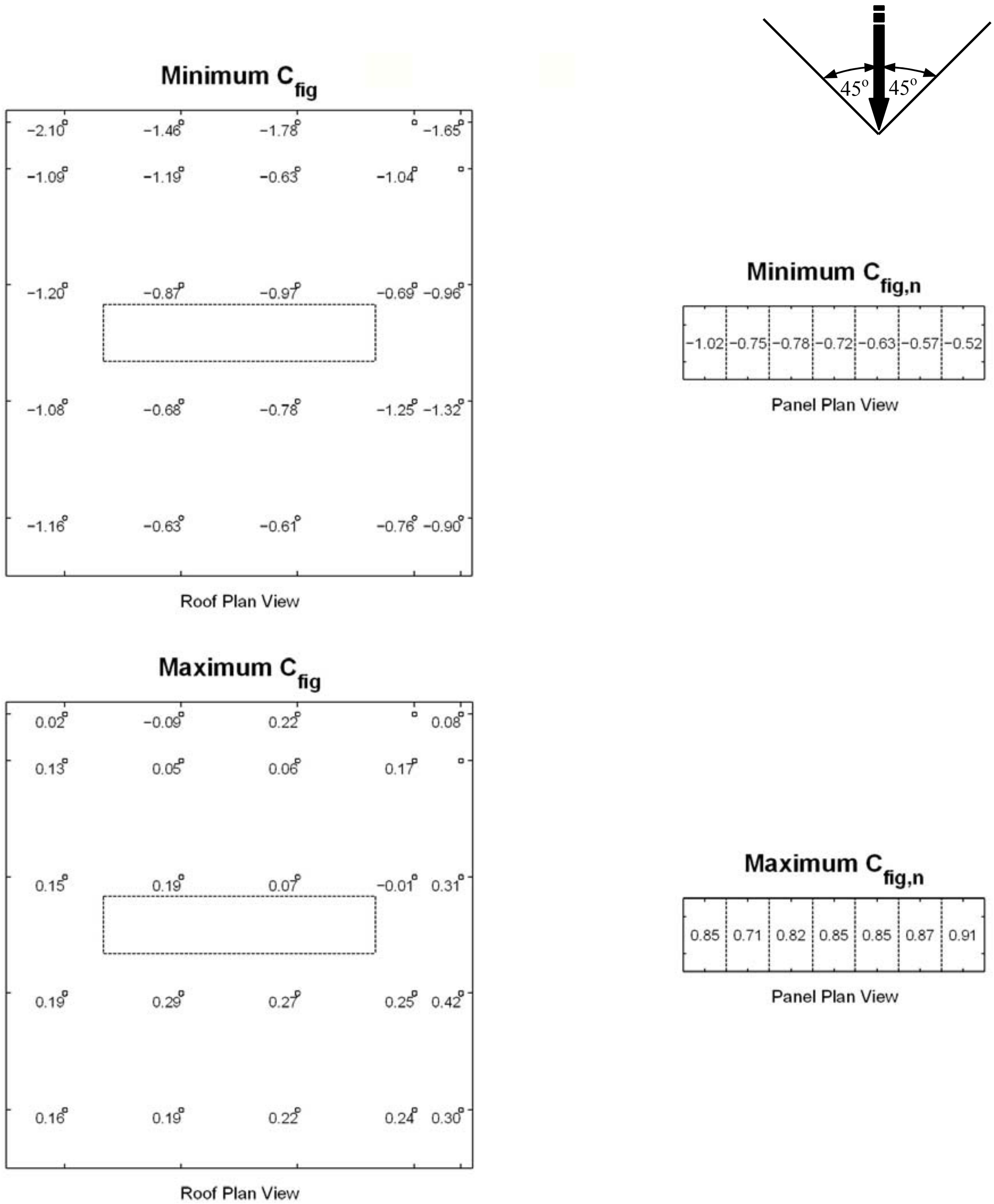


Figure C4-e. C_{fig} – Panel Position C - 30° Incline, Wind Direction 0° ± 45°

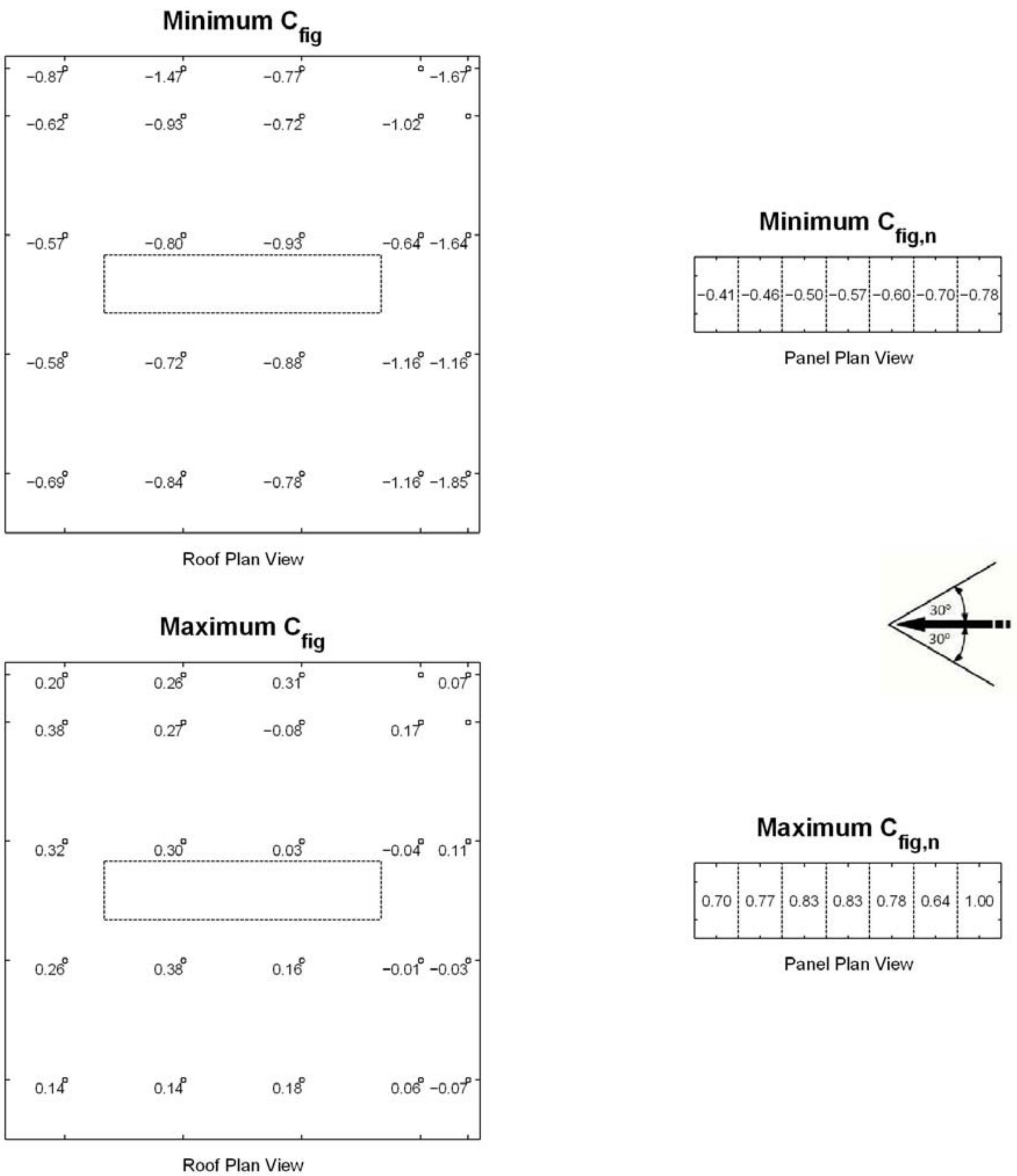
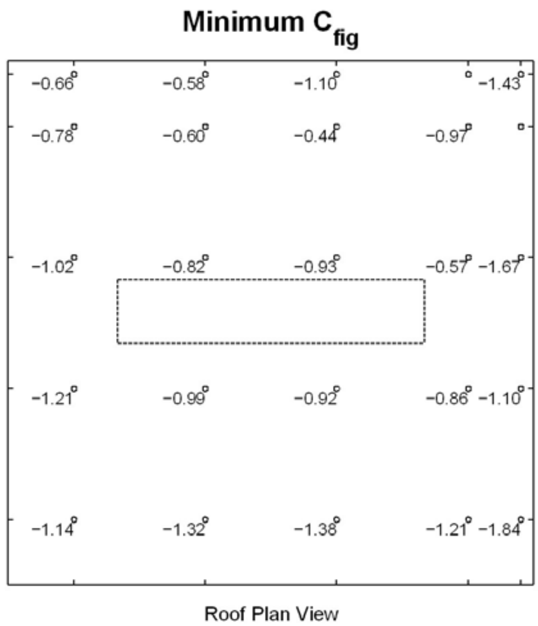
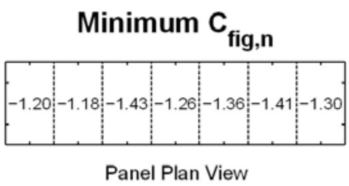
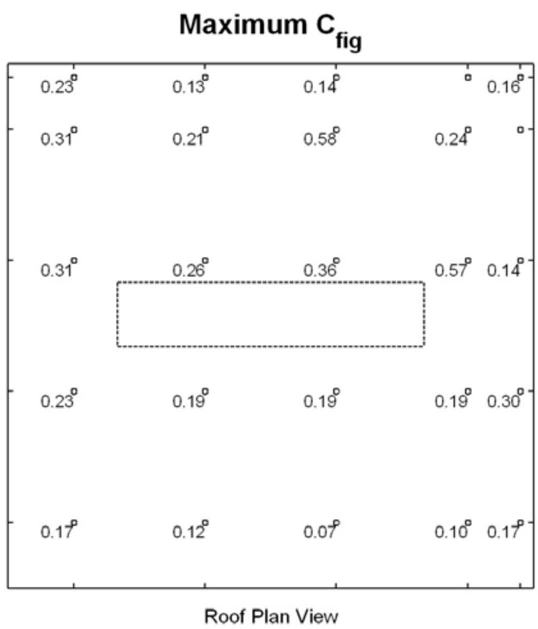
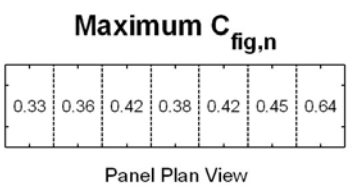


Figure C4-f. C_{fig} – Panel Position C - 30^o Incline, Wind Direction 90^o ± 30^o









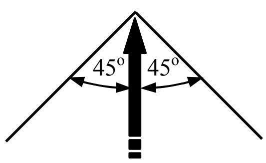


Figure C4-g. C_{fig} – Panel Position C - 30° Incline, Wind Direction 180° ± 45°

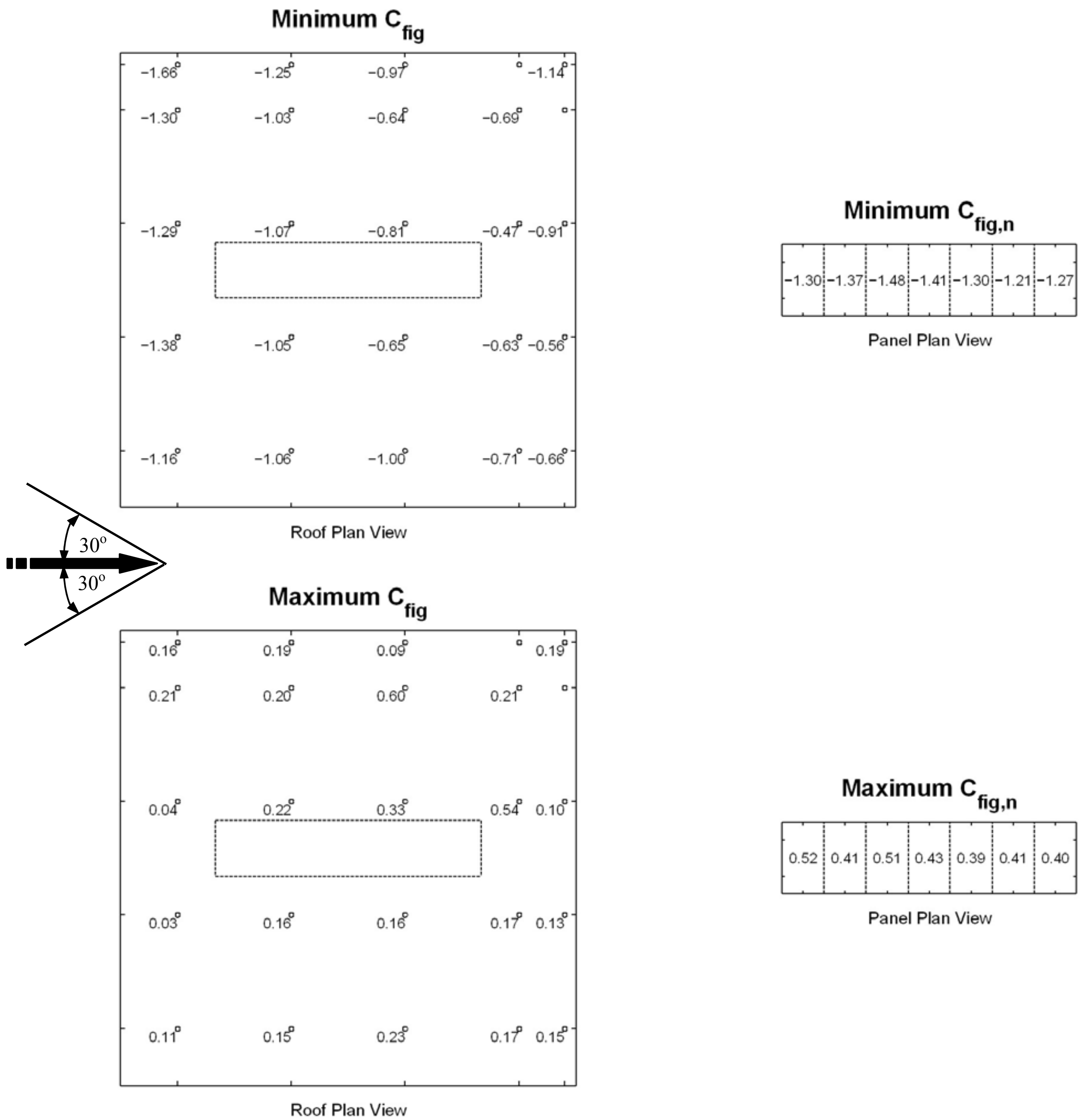


Figure C4-h. C_{fig} – Panel Position C -30° Incline, Wind Direction 270° ± 30°

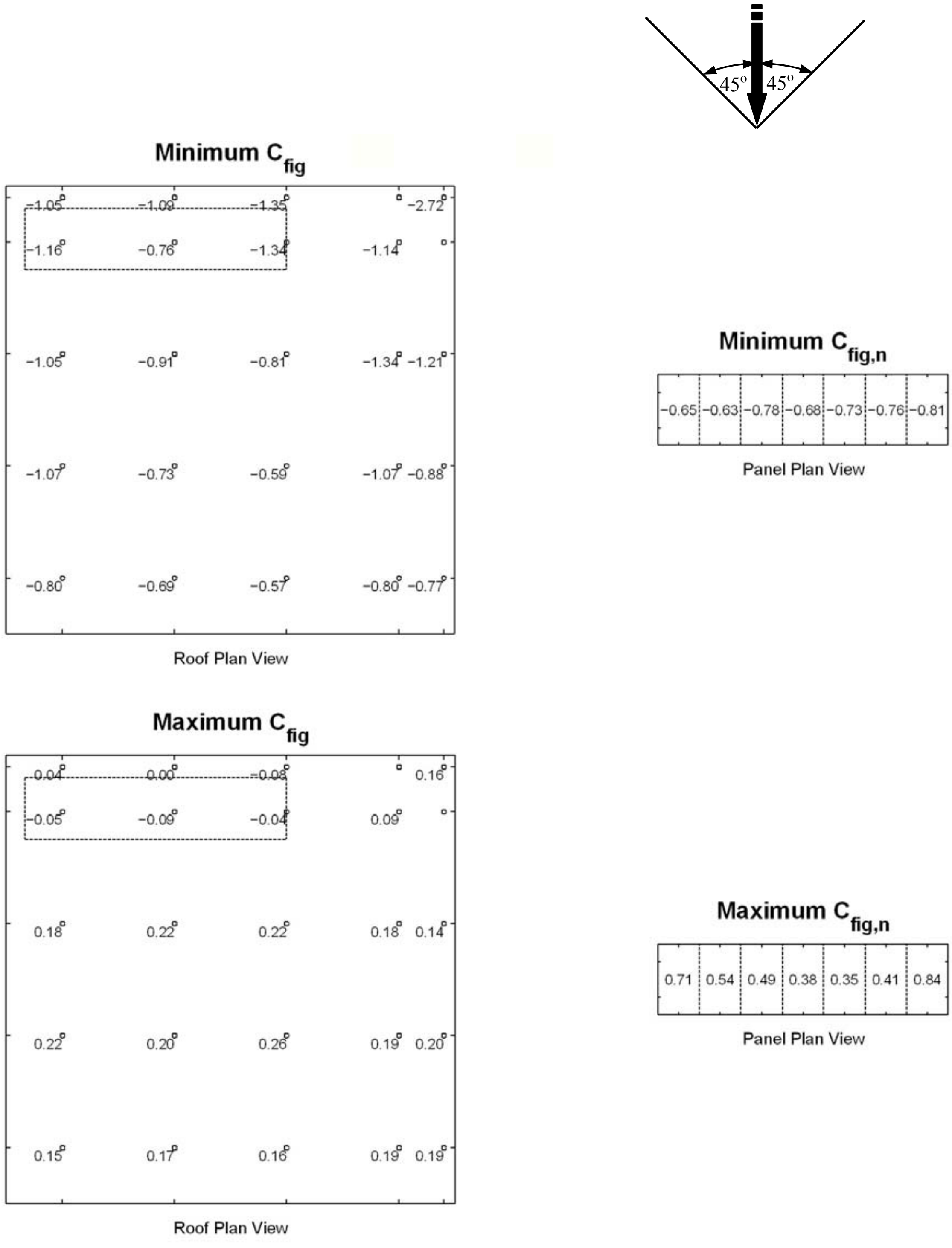


Figure C5-a. C_{fig} – Panel Position D - 15° Incline, Wind Direction 0° ± 45°

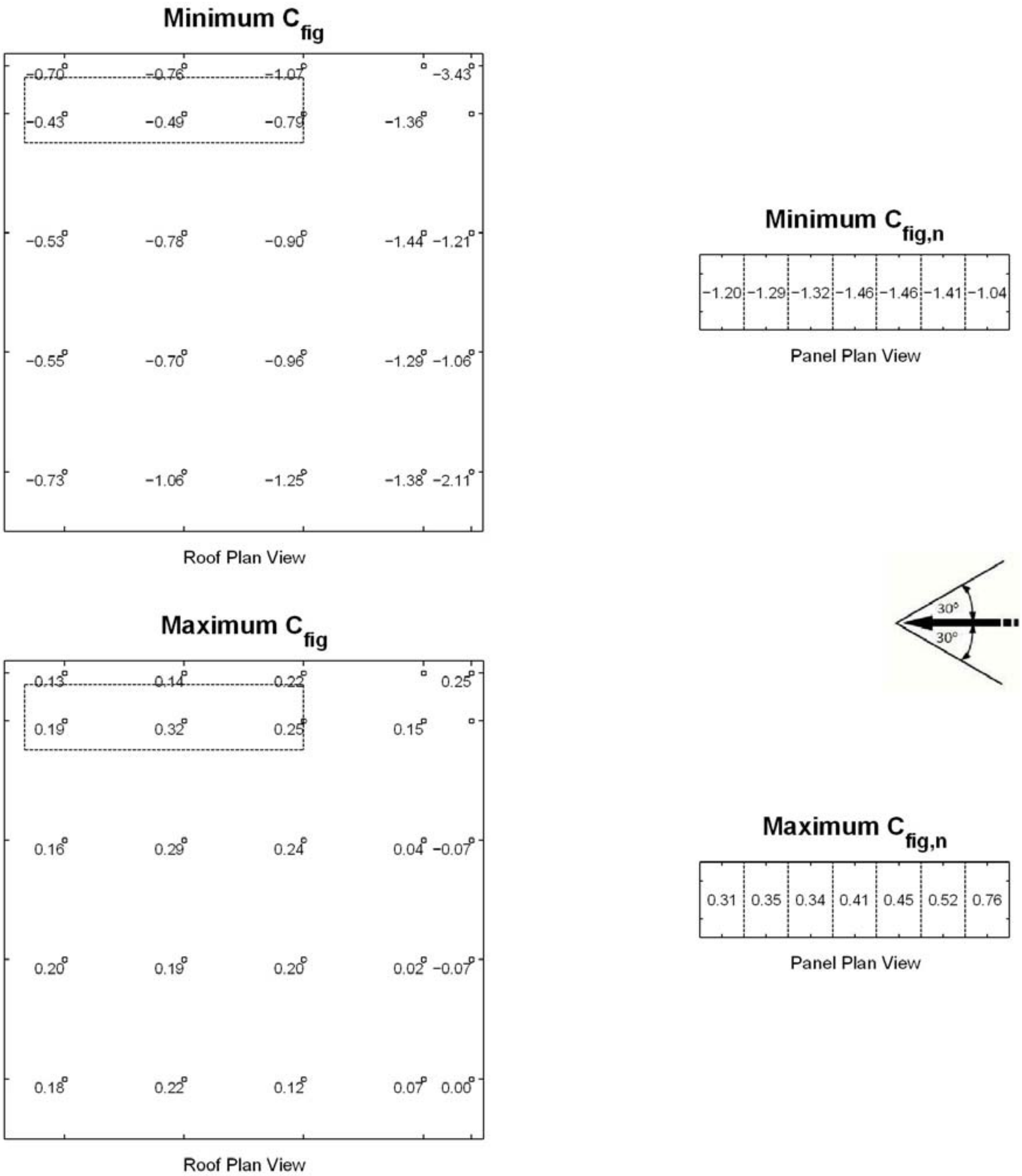
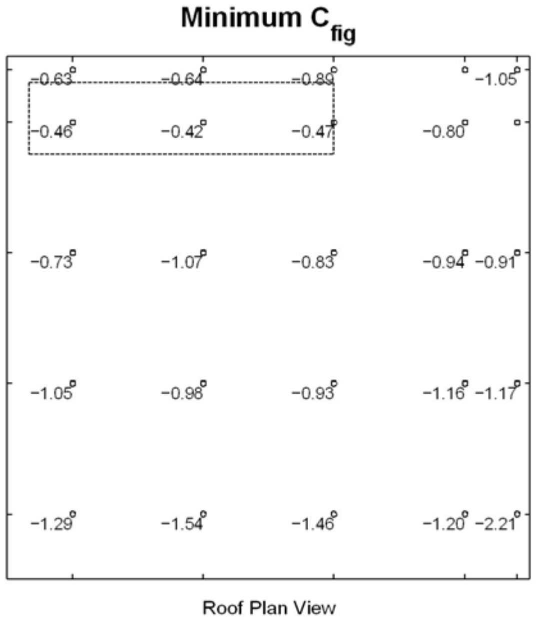
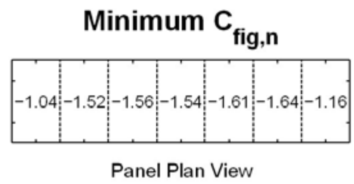
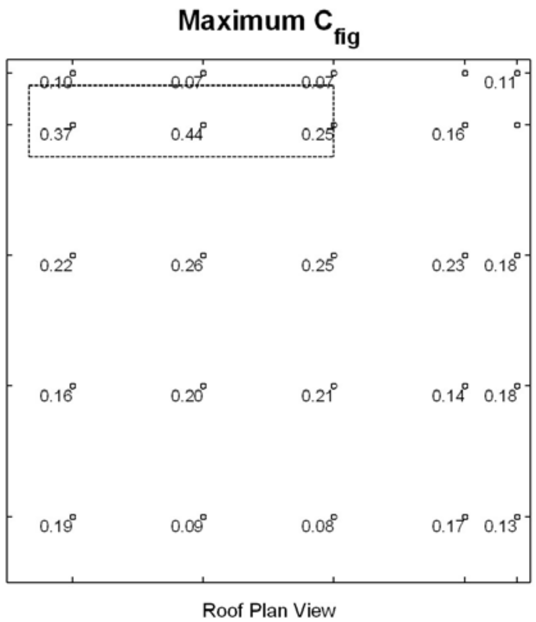
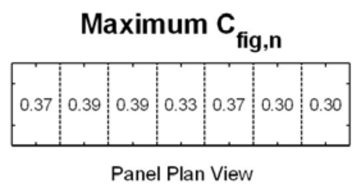


Figure C5-b. C_{fig} – Panel Position D - 15° Incline, Wind Direction 90° ± 30°









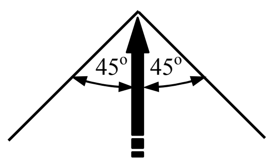


Figure C5-c. C_{fig} – Panel Position D - 15° Incline, Wind Direction 180° ± 45°

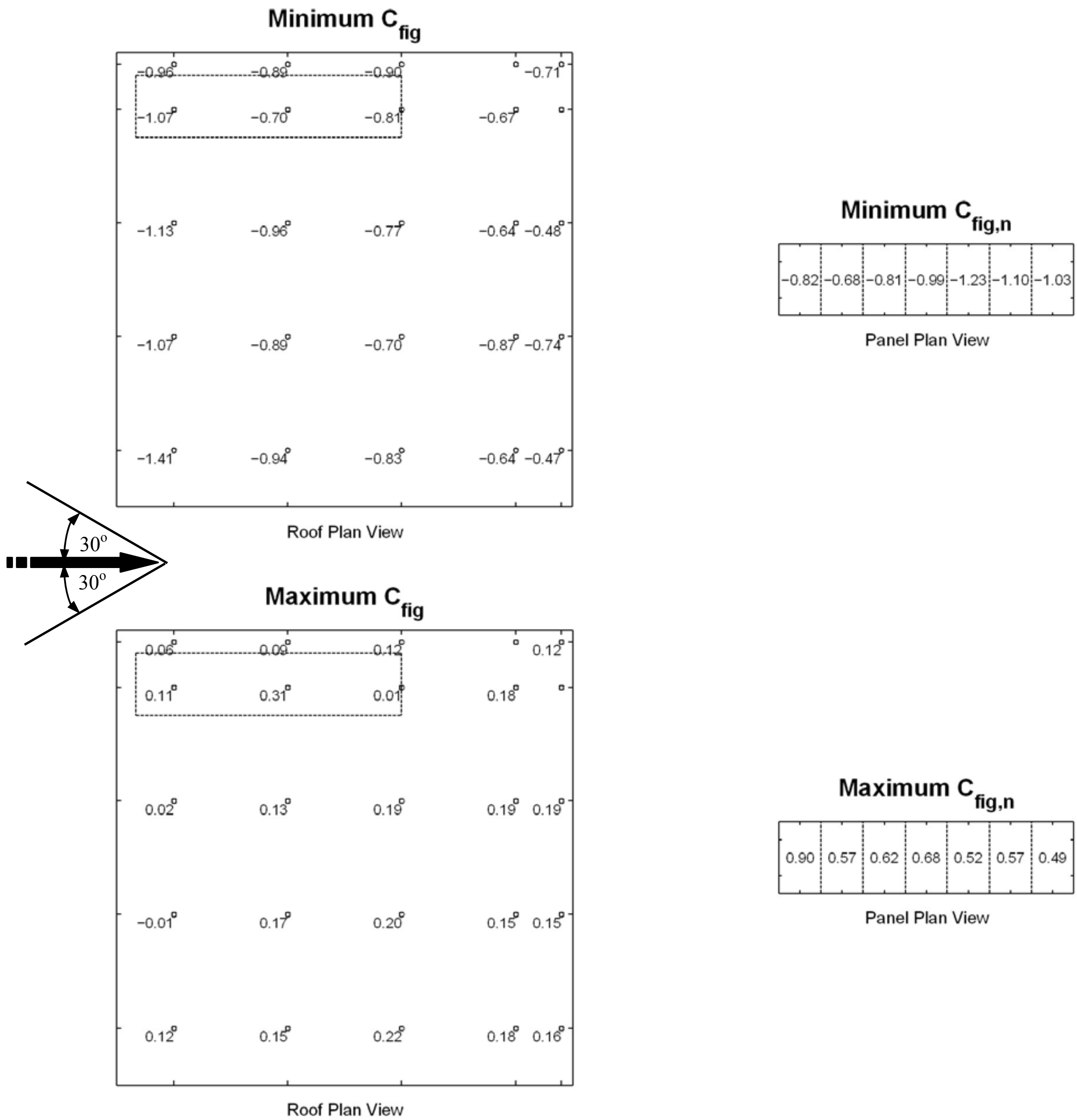


Figure C5-d. C_{fig} – Panel Position D - 15° Incline, Wind Direction 270° ± 30°

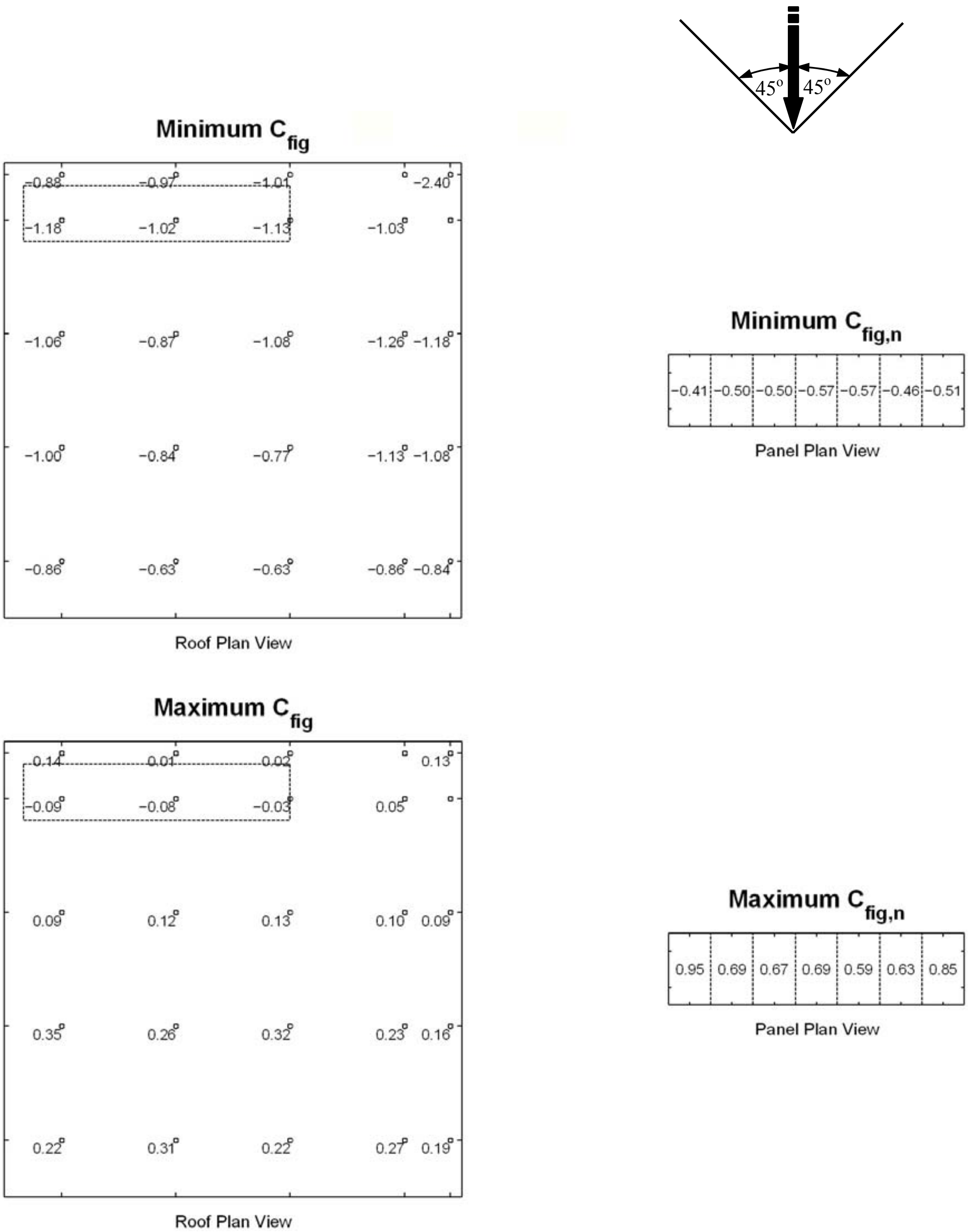


Figure C5-e. C_{fig} – Panel Position D - 30° Incline, Wind Direction 0° ± 45°

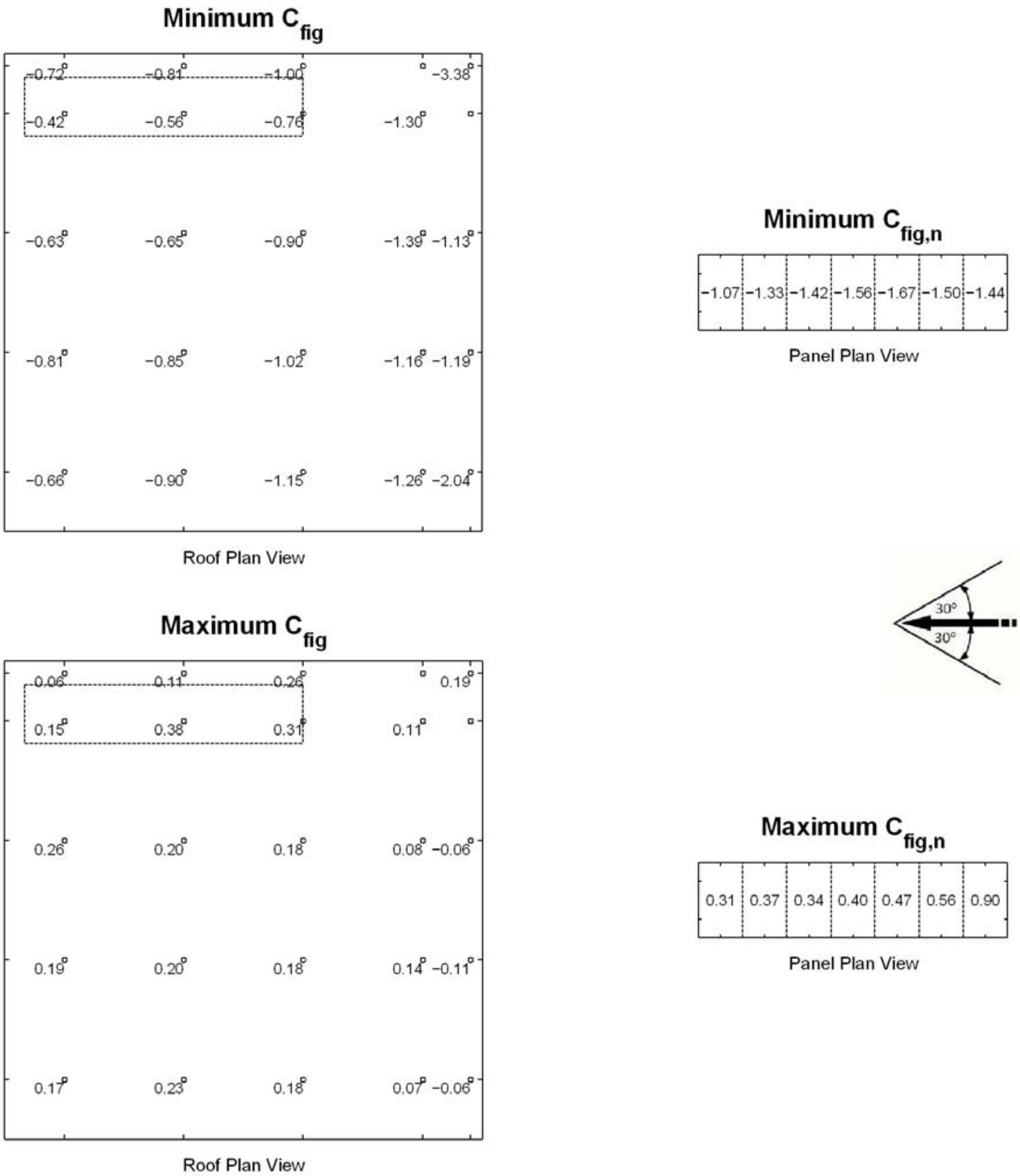


Figure C5-f. C_{fig} – Panel Position D - 30° Incline, Wind Direction 90° ± 30°

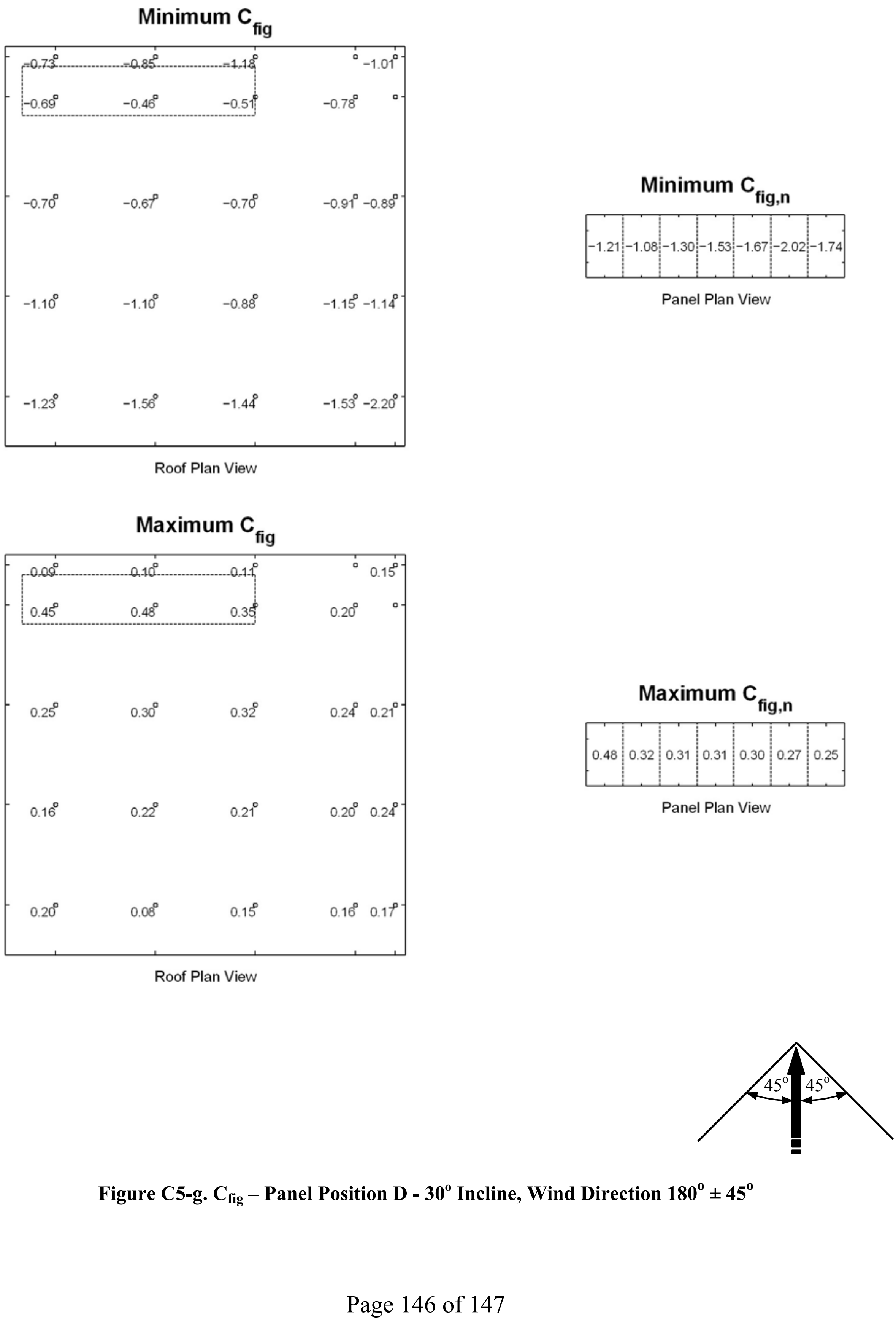


Figure C5-g. C_{fig} – Panel Position D - 30° Incline, Wind Direction 180° ± 45°

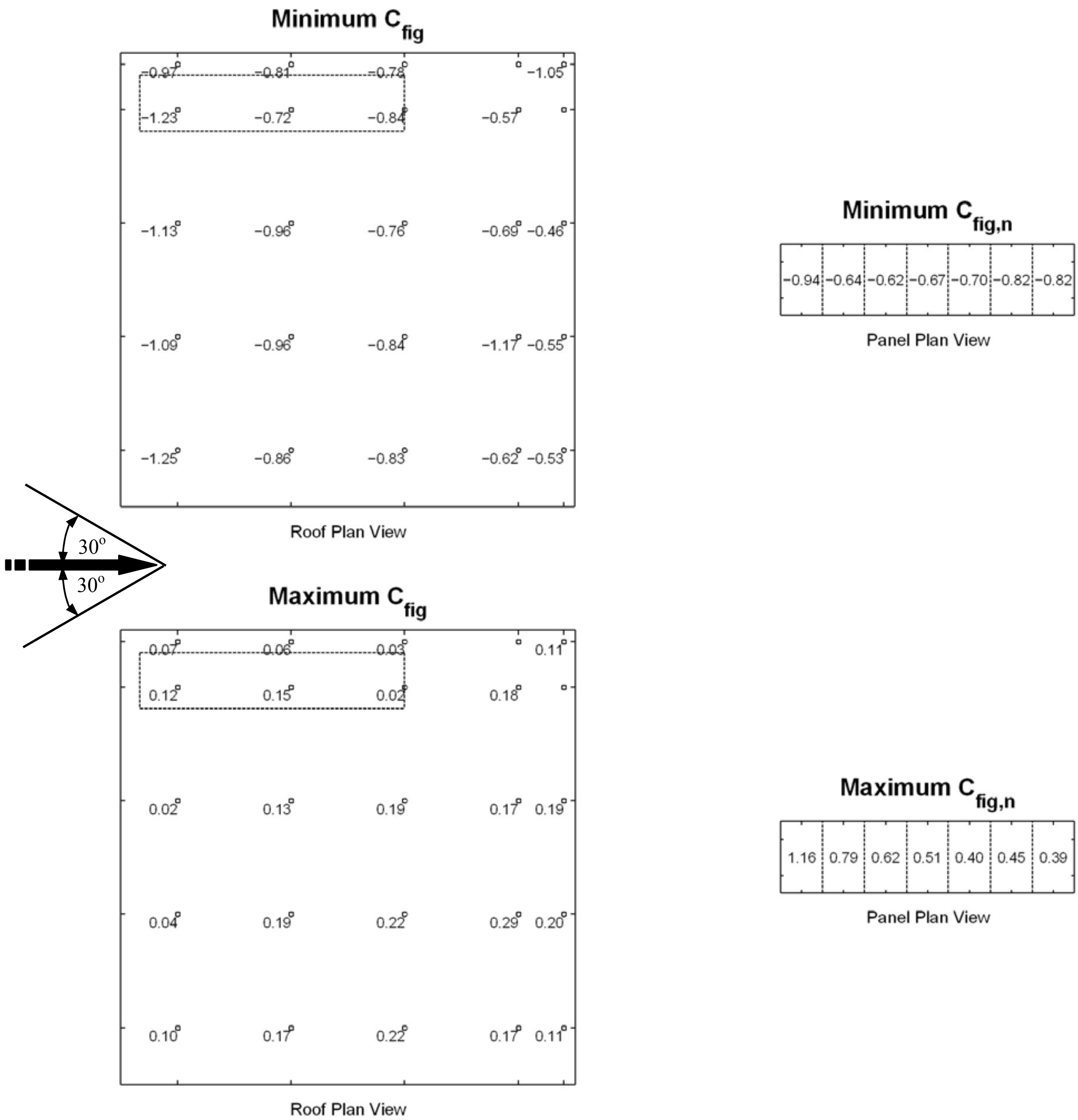


Figure C5-h. C_{fig} – Panel Position D -30^o Incline, Wind Direction 270^o ± 30^o