PREQUALIFICATION TESTING OF TEMPORARY PROPPING SYSTEMS FOR TILT-UP AND PRECAST PANELS

Nicholas Haritos¹, David Heath², Emad Gad³ and John Wilson⁴

ABSTRACT: Precast and tilt-up construction methods rely on temporary props to provide the necessary structural support to panels during erection. Traditionally, the design for wind loading of these temporary props follows the Basic Design Wind approach of AS1170.2 that yields a design equivalent static load. Cast-in ferrules are typically used when fixing the prop to the precast panel whilst post-installed brace fixture inserts are used for fixing the prop to the floor structure. This paper extends work by the authors on the investigation of modelling procedures for the fluctuating propping forces under design wind conditions for panel structures for the purposes of establishing a test loading regime for the prop connections to validate their sufficiency. Spectral based random phase modelling is considered both directly and indirectly for time domain simulation of prop forces in combination with a rainflow cycle counting technique, to develop such a test loading regime.

KEYWORDS: Tilt-up panels, precast panels, wind simulation, wind loading, cycle counts, spectral excitation models

1 INTRODUCTION

Tilt-up and precast panel construction methods offer economical structural solutions to low-rise residential, office and general commercial building forms and have become increasingly more popular worldwide. The construction method involves the use of temporary props for bracing the panels until they are able to be interconnected and become stable. Typical anchorage of the temporary prop when fixing to the precast panel includes cast-in ferrules and post-installed brace fixture inserts in the floor structure, (see Figure 1).

Despite the popularity and widespread use of this construction technique, the design for the temporary condition of propping panels has been fraught by controversy amongst the engineering profession, both in Australia and overseas, as to what design load conditions should be considered, given the “temporary” nature of this propping. The development of a dynamic test procedure for prequalification of anchor systems associated with this “temporary” propping condition for tilt-up construction forms part of this controversy.

In Australia, the design for wind loading on temporary props has traditionally been considered through the Basic Design Wind approach of AS1170.2 [1] that yields a design equivalent static load. A similar approach is used for the serviceability condition that is based on the ultimate wind load divided by a factor of safety.

The National Code of Practice for Precast, Tilt-up and Concrete Elements in Building Construction [2],

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¹ Nicholas Haritos, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Email: nharitos@swin.edu.au
² David Heath, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Email: djheath@swin.edu.au
³ Emad Gad, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Email: egad@swin.edu.au
⁴ John Wilson, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Email: jwilson@swin.edu.au
published by the Australian Safety and Compensation Council in 2008, governs all design aspects of tilt-up panel construction practice, including compliance with AS3850 Tilt-up concrete and precast concrete elements for use in buildings [3a] and AS/NZS 1170.2 Structural Design Actions – Wind actions [1]. For Importance level 2 “sites”, this requirement results in a 100 Year Return Period (YRP) design wind for ultimate conditions. The design of fixing elements for these conditions, but which may be in temporary service for just a few days, has been the source of some controversy amongst the engineering profession. The application of these design conditions to prop or brace elements that tend to be reused a large number of times on subsequent panel propping applications tends not to be as controversial. Wang and Pham [4] discuss various interpretation options for the appropriate design wind speed to be adopted for temporary structures whilst maintaining the rationale behind the Building Code of Australia [5]. They define a temporary structure as a structure with a total period of use to perform its intended purpose of less than one year. Wang and Pham also show that, depending on the Importance Level and reduced period of use of temporary structures and their support elements, design wind speeds could be reduced by up to 50% of those recommended in the BCA, whilst maintaining the probabilities of exceedance of wind loads for such temporary structures to be the same as for the annual probabilities of exceedance required by this Code. This translates to a corresponding reduction in wind loads of up to 75% for one week’s continuous use compared to one year of such use, for example. Notwithstanding possible future changes in the rationale of the BCA for its definition of temporary structures and their one-time use to include time periods corresponding to 6 months, 3 months, 1 month, or even as low as 1 week, the authors have “run with” the current definition as the design working life both for props/bracing as well as fixtures, in their investigations performed for this paper. Preliminary results that restricted investigation to Category 3 wind conditions only have been reported in Haritos et al [6]. This paper extends the investigation over the full range of Wind Category conditions in support of a Simplified Testing Procedure they propose for prequalification of anchor fixtures in tilt-up and precast panel applications.

2 WIND LOADING ON PANELS

Holmes [7] provides a comprehensive treatment of wind, its characteristics and loading effects on structures, that includes dynamic response. Much of this treatment and understanding forms the basis of codes of practice for the wind loading on structures of several countries, including Australia and New Zealand.

A wind loading model for the along-wind response of a rectangular precast/tilt-up panel using the spectral modelling approach originally described by Davenport [8], (that also appears in Holmes [7]), is developed and modified here by the authors to more realistically depict the properties of wind drag.

2.1 MODELLING RESPONSE OF TILT-UP PANELS TO ALONG-WIND TURBULENT WIND LOADING

Consider a single propped, tilt-up panel (as in Figure 1) of width $B$ and height $H$, and exposed area $A_p = B \times H$, responding dynamically to wind with a one-hour mean speed of $\bar{U}$ and along-wind fluctuations of $u(t)$, with a displacement amplitude $\eta(t)$ at the centroid of the panel. The drag (or pressure) coefficient for the panel is $C_d$. If the fluctuating wind force at the panel centroid is taken as $F_u(t)$, air density is $\rho$ and relative velocity $U(t)$ of the moving panel against the wind at the centroid is responsible for this forcing, then, for panel velocity given by $\dot{\eta}(t)$, we have:

$$F_u(t) = \rho \ A_p \ C_d \left[ \frac{1}{2} \rho U_v^2 (t)^2 \right] A_p \ C_d \quad (1)$$

$$F_u(t) = \frac{1}{2} \rho \ A_p \ C_d \left[ (U + u(t))^2 - \eta^2 \right]$$

$$= \frac{1}{2} \rho \ A_p \ C_d \left[ (U + u(t))^2 + \eta^2 - 2\eta(U + u(t)) \right]$$

$$= \frac{1}{2} \rho \ A_p \ C_d \left[ U^2 + (u_{rms}^2) \right] + \frac{1}{2} \rho \ A_p \ C_d \times 2Uu(t)$$

$$- \frac{1}{2} \rho \ A_p \ C_d \times 2U \dot{\eta}$$

$$= \rho \ A_p \ C_d U \dot{\eta}$$

$$- \rho \ A_p \ C_d U \dot{\eta}$$

From Equation (2) the mean wind force on the panel at the centroid is given by:

$$F = \frac{1}{2} \rho (U^2 + u_{rms}^2) A_p C_d = \frac{1}{2} \rho U^2 (1 + I_a^2)$$

where $I_a$ is the intensity of along-wind turbulence for the site category in which the panel is located.

In addition, fluctuating force at the panel centroid, $F_u(t)$, is given by:

$$F_u(t) = \rho \ \bar{U} \ A_p \ C_d \ u(t) = 2\rho \frac{U(t) U}{U}$$

From Equation (4) it follows that the coefficient of variation of fluctuating wind force is twice the intensity of along-wind turbulence, $I_a$. In addition, fluctuating wind force is seen to now be directly proportional to fluctuating wind speed – a consequence of performing what is effectively a “linearising” process.

Now the dynamic equation of equilibrium for fluctuating displacement response of the panel at the centroid of $\eta(t)$ can be modelled using a Single Degree of Freedom (SDOF) assumption in which $c_2$ is the structural damping coefficient, $m$ is the effective mass of the pivoted panel at the centroid, and $k$ the effective horizontal spring stiffness of the props, also at the panel centroid, so that:
\[ m \ddot{\eta} + c \dot{\eta} + k \eta = F(t) \quad (5) \]
\[ m \ddot{\eta} + (c_s + c_a) \dot{\eta} + k \eta = \bar{F} + F_s(t) \quad (6) \]
in which \( c_a = \rho A_p C_d \overline{U} \) represents, so-called aerodynamic damping.

The mean displacement at the centroid is given by \( \overline{\eta} = \overline{F} / k \) and the fluctuating component \( \eta(t) \) can be obtained from Equation (6) by omitting the mean force term.

2.2 SPECTRAL MODEL OF “DYNAMICALLY-
ENHANCED” ALONG-WIND WIND
LOADING ON TILT-UP PANELS

As an alternative to the time-domain definition of Equation (6), a spectral modelling procedure can instead be adopted which allows for the introduction of an aerodynamic admittance function, \( \chi_a(f) \). This function effectively accounts for the influence of the area or size effects of the panel in reducing the loading from the higher frequency, smaller sized eddies/gusts, as they tend not to be capable of enveloping the whole area (become less correlated) at progressively higher frequencies.

Our interest here is centred on the horizontal “spring force” at the panel centroid, given by \( k \eta(t) \). This force can alternatively be interpreted as a dynamically enhanced fluctuating wind load at the panel centroid which from the fluctuating force in the props can then be determined using statics and the basic geometry of the propping arrangement.

The spectral model for the dynamically enhanced wind load at the panel centroid is described diagrammatically in Figure 2. In this model, \( S_d(f) \) and \( S_r(f) \) are the spectral densities for along-wind turbulence and “dynamically enhanced” wind force at the panel centroid for the site conditions of interest, respectively; \( \zeta \), represents the critical damping ratio associated with combined structural and aerodynamic damping; \( f_o \) is the natural frequency of the pivoted panel and prop assembly; \( T(0) = \rho \overline{U} A_p C_d(0) \) whilst \( T(f) \) is given by \( \rho \overline{U} A_p C_d(f) \) which allows for frequency dependence in the drag coefficient, \( C_d \); \( \frac{\sigma^2}{\eta^2} \) and \( \frac{\sigma^2}{\eta^2} \) represent the variances in wind and wind force respectively. \( \chi_a(f) \) is the structure magnification function given by:

\[ \chi_a(f) = \frac{1}{\sqrt{\left[1 - \left(\frac{f}{f_o}\right)^2\right]^2 + \left[2\zeta \left(\frac{f}{f_o}\right)\right]^2}} \quad (7) \]

In situations where \( f_o \) is higher than say 4 or 5 Hz, (normally the case for propped panel assemblies), then \( \chi_a(f) \) can be taken as 1 – there is no dynamic amplification and the response is “quasi-static”.

2.3 SIMULATION OF “DYNAMICALLY-
ENHANCED” ALONG-WIND WIND
LOADING ON TILT-UP PANELS

A spectral based random phase model can be used to simulate the dynamically-enhanced along-wind wind loading on tilt-up panels, \( F_d(t) \), based upon the procedure outlined in §2.2 above, (see Haritos et al. [6]). Consider a time series for \( F_d(t) \) consisting of \( N \) points obtained at a regular time step of \( \Delta t \) over a time period of duration of \( T_d \) (where \( T_d = N \Delta t \)), then a Fourier series representation of \( F_d(t) \) for \( f = n/T_d \) \( df = 1/T_d \) and \( \phi = (0 - 2\pi) \), becomes:

\[ F_d(t) = \sum_{n=1}^{N/2} (a_n \cos \frac{2\pi nt}{T_d} + b_n \sin \frac{2\pi nt}{T_d}) ; \quad (8) \]

\[ a_n = \sqrt{2S_r(f)} \cos(\phi), \quad b_n = \sqrt{2S_r(f)} \sin(\phi) \]

In order to “drive” Equation (8) for the applicable site design wind conditions, \( T(0) = T(0) \) can be adopted and functional forms for \( \chi_a(f) \), and for the along-wind speed spectrum, \( S_d(f) \) are required. An expression proposed by Vickery [9] can be used for the aerodynamic admittance function,

\[ \chi_a(f) = \frac{1}{1 + \left[2\pi f \frac{\sqrt{A_p}}{\overline{U}}\right]^{3/2}} \quad (9) \]

For the along-wind wind speed spectrum, \( S_d(f) \), there are a number of forms one can choose. Here, Davenport’s form [8] is adopted, viz:

\[ f S_d(f) = \frac{2 n_f}{\sigma^2} = \frac{2}{3}\left(1 + n_f^2\right)^{1/3} ; \quad n_f = \frac{L_u f}{U_{10}} \quad (10) \]

Equation (8) can be realised using an Inverse Fast Fourier Transform (IFFT) available in most scientific packages, eg Matlab, Labview, etc, and even in spreadsheets, such as MS-EXCEL. Such an implementation produces the dynamically-enhanced along-wind loading on the tilt-up panel under consideration for any condition including the ultimate design wind condition, ie for the 100 YRP wind. What remains to be determined in the model is the value of \( \overline{U} \) from knowledge of \( V_{des} \) - the design value of “3-second gust wind-speed”, for the site conditions concerned, and a 100 YRP.
2.4 RELATIONSHIP BETWEEN WIND SPEEDS FOR DIFFERENT AVERAGING PERIODS

Holmes and Allsop [10] and Holmes and Ginger [11] discuss some issues that can arise when raw anemometer data based upon different anemometer types are used in design codes without modification to account for variation in their “response times”. The so-called “3-second” gust still remains coined as the “averaging period” for the peak gust value in a one-hour storm period in AS/NZS 1170.2, whereas the averaging time is closer to 0.2 seconds for more modern anemometer data. Earlier versions of AS1170.2 provided relationships (Gust Factor) values for different site conditions that allowed evaluation of $V_{des}$ from $U$; the later versions of this code have instead adopted the modelling approach of Figure 2 to evaluate $C_{dyn}$ and no longer provide these relationships. $C_{dyn}$ is expressed as:

$$C_{dyn} = \left(1 + 2I_s \left( g_s^2 B_s + \frac{H_s g_s^2 SE_x}{\zeta} \right)^{-0.05} \right)$$  \hspace{0.5cm} (11)

AS/NZS 1170.2 defines all terms in Equation (11) for the spectral model, and suggests that $g_s = 3.7$ and $C_{dyn}$ be taken as 1.0 for natural frequencies, $f_\omega$ greater than 1 Hz - the expected condition for propped tilt-up or precast panels which, as stated in §2.2, is near equivalent to setting $\theta(f) = 1$ in the model of Figure (2).

From Equation (11), and $I_s$ being turbulence intensity at the top of the panel, we obtain:

$$1 + 2I_s \left( g_s^2 B_s + \frac{H_s g_s^2 SE_x}{\zeta} \right)^{-0.05} = 1 + 2g_s I_s$$  \hspace{0.5cm} (12)

and, by equating the Mean Wind Force at the centroid of the panel times the Dynamic Gust Factor to the peak “3-second” Design Wind Force therefor, we obtain:

$$\frac{1}{2} \rho C_{d,2} A \bar{u}^2 \left(1 + I_s^2\right) \times \left(1 + 2g_s I_s\right) = \frac{1}{2} \rho C_{d,2} A V_{des}^2$$  \hspace{0.5cm} (13)

so that

$$\frac{V_{des}}{\bar{u}} = \sqrt{\left(1 + I_s^2\right) \times \left(1 + 7.4 \times I_s\right)}$$  \hspace{0.5cm} (14)

which is a form of Gust Factor for peak “3-second” wind gusts from the mean one-hour wind.

3 APPLICATION TO AN EXAMPLE PANEL

Here, we consider an example application of the methodology detailed in §2 to a typical precast panel.

3.1 PROPERTIES OF EXAMPLE PANEL

Figure 3 depicts some of the basic features of the example tilt-up panel being considered here to illustrate the alternative approaches for simulating the prop forces acting on the base fixtures from the 1-hour along-wind Design Wind storm. In addition, a dynamic modal analysis suggests the first mode frequency to be approx. 18 Hz ($\gg$ 1 Hz), with mode shape as depicted in Figure 3. Hence the Basic Design Wind approach can be used to determine the peak Design Force on the panel, $F_{des}$.

The panel is 3m wide and 4m tall, 0.12m thick, approximately 4 tonne in mass, and restrained by two props inclined at 45 degrees. Table D2(A) of AS/NZS1170.2 provides equations that allow the drag coefficient $C_{p,n}$ to walls, to be determined as 1.28 from the geometry of this panel.

3.2 DESIGN WIND CONDITIONS ON PANEL FOR SIMULATION OF WIND FORCES

The panel is considered to be located in non-cyclonic regions A1 to A7 typical of conditions within or near Melbourne where $V_{100} = 41$ m/s from Table 3.1 of AS/NZS1170.2. If we consider wind incident from any direction $M_d = 1$, no shielding, $M_t = 1$, or topographic effects, $M_p = 1$, then the design ultimate 3-sec gust speed, $V_{des} = M_{cat} \times V_{100}$. Table 1 extracts $M_{cat}$ from Table 4.1(A) of AS/NZS1170.2, for $z < 10m$, and terrain categories 1 to 4, to obtain the design ultimate 3-sec gust speed, $V_{des}$, and panel ultimate wind force, $F_{des}$, whilst Table 2 similarly extracts $I_s$ from Table 6.1 to obtain $I_s$ for the mid-height panel position, and $I_s$ for $z = h = 4m$. Equation (14) is then used for $z = 2$ to obtain $\bar{u}$ which is also presented in Table 2.

Tables 1 and 2 indicate that for the higher categories (Categories 3 and 4), wind speed properties such as peak-3-sec gust and turbulence intensity are considered to essentially be constant for $z \times 10m$ by AS/NZS1170.2.

<table>
<thead>
<tr>
<th>Category</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z \leq 3m$</td>
<td>0.99</td>
<td>0.91</td>
<td>0.83</td>
<td>0.75</td>
</tr>
<tr>
<td>$z = 5m$</td>
<td>1.05</td>
<td>0.91</td>
<td>0.83</td>
<td>0.75</td>
</tr>
<tr>
<td>$z = 10m$</td>
<td>1.12</td>
<td>1.00</td>
<td>0.83</td>
<td>0.75</td>
</tr>
<tr>
<td>$M_{cat}$</td>
<td>0.99</td>
<td>0.91</td>
<td>0.83</td>
<td>0.75</td>
</tr>
<tr>
<td>$V_{des}$ (m/s)</td>
<td>40.6</td>
<td>37.3</td>
<td>34.0</td>
<td>30.8</td>
</tr>
<tr>
<td>$F_{des}$ (kN)</td>
<td>15.2</td>
<td>12.8</td>
<td>10.7</td>
<td>8.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Turbulence Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z \leq 3m$</td>
</tr>
<tr>
<td>$z = 5m$</td>
</tr>
<tr>
<td>$z = 10m$</td>
</tr>
<tr>
<td>$I_2$</td>
</tr>
<tr>
<td>$I_4$</td>
</tr>
<tr>
<td>$\bar{u}$ (m/s)</td>
</tr>
<tr>
<td>$F$ (kN)</td>
</tr>
</tbody>
</table>
This situation (“freezing” design wind properties in the first 10 metres above ground in categories 3 and 4 by AS/NZS1170.2) is also generating controversy amongst the engineering fraternity. This approach may be conservative under certain circumstances as it is possibly an attempt by code writers to account for the complexity of nearby local features and their effects, in these high category value terrain conditions, that would especially influence wind properties in the vicinity of the structure of interest.

In Australia, the majority of man-made and natural infrastructure (housing, low-rise buildings - whether or not using tilt-up or precast construction, orchards and urban or forest trees) is located in the 0 – 10m height zone. Any deserving improvement in design guidance for wind properties in this zone would be especially welcomed by engineers faced with design and/or assessment of new or existing infrastructure in this zone.

4 WIND LOADING SIMULATIONS ON EXAMPLE PANEL

The spectral modelling approaches outlined in §2.3 can be interpreted in a number of ways depending upon the modelling conditions to which they relate. Here, we have noted that as a result of a somewhat high ($\gg 1$ Hz) natural frequency of the example panel, there is virtually no dynamic enhancement associated with its structural properties. This would suggest $\chi_u(f) = 1$ in Figure 2, and we have a design wind scenario that corresponds to Basic Design wind conditions.

4.1 SIMULATING WIND FORCE VIA SPECTRAL BASED RANDOM PHASE MODELS FOR BASIC DESIGN WIND CONDITIONS

In this approach, instead of operating on a linearised model for the wind force in Equation (8) to simulate wind force traces, we can instead simulate wind speed fluctuations from the wind speed spectrum using an IFFT and random phase model similar to the description of Equation (8). This approach is equivalent to setting $T(f) = \chi_u(f) = 1$ in Figure 2 and replacing $F_u(t)$ with $u(t)$ and $S_u(f)$ with $S_u(f)$ in Equation (8), to produce simulated along-wind wind speed traces for a 100 YRP design wind storm. We then use Equation (1) directly to simulate a fully non-linear version of the along-wind force on the example panel, bypassing the linearization procedure for the Spectral model for wind force. Here the suggestion is made that for a reasonably rigid panel $U(t) = U(t)$ so that the along-wind wind speed simply becomes $U(t) = \overline{U} + u(t)$.

Equation (1) allows determination of a simulated design along-wind force time-history on the tilt-up panel under consideration for the example chosen, on the basis that there is no appreciable “dynamically-enhancement”, equivalent to the Basic Design wind approach. In line with this approach, simulated traces should reflect the so-called 3-sec gust condition. Modification of the force for area size effects of the panel would then require evaluation of the area reduction factor, $K_a$, which is obtained via linear interpolation of entries in Table 5.4 of AS/NZS 1170.2. For $A = 12 \text{ m}^2$, $K_a = 0.987 \approx 1.0$.

This resultant force trace can then be investigated to interpret the loading applied at the prop fixtures.

A load testing machine that can operate in load control (as opposed to displacement control) to an arbitrary control input (such as the load history acting on a prop fixture obtained via the above simulation), can be directly used to test the performance of a proposed fixture configuration for its “fitness for purpose”.

Alternatively, the detailed content of the fixture force time history obtained from such a simulation can be investigated to obtain “equivalent” regular cyclic load testing regimes, eg via cycle counting using a rainflow analysis, (Ariduru, [12]), which can perhaps more easily be applied using available load testing systems.

4.1.1 Comparison of panel wind load simulations from linearised and non-linear versions of the IFFT spectral-based random phase models

A comparison study of the design wind panel force traces produced from the linearised spectral-based modelling procedure outlined in Figure (2) and Equation (8) with those produced using the non-linear modelling procedure described above was performed to note distinctive differences between them and their properties. Sixteen simulation records were produced separately for all four terrain category conditions, for the two random phase spectral based modelling techniques (linearised force model and non-linear force model) using the IFFT of the Data Analysis Add-in option of MS-EXCEL with each record being 4096 points long using a time step (dt) of one second. A 3-second moving average was then performed on a 3600 second long time trace extracted from each record.

Typical traces for the resultant linearised and non-linear 3-second panel force records over a one hour period for Terrain Categories 1 to 4 are depicted in Figures 4 to 7 respectively, for the purposes of making comparisons. In each of the pairs of traces of Figures 4 to 7 it is observed that the non-linear simulations, (the (a) traces), result in higher peaks and more positive troughs than for their linear counterparts, (the (b) traces). In fact, for Terrain Categories 3 and 4 (Figures 6 and 7), the (b) traces show force reversal (some negative troughs) generally not observed in the corresponding non-linear versions of these traces.

Figures 8, 9 and 10 present three additional samples of traces for Category 1 panel force obtained from type (a)

![Figure 4: Sample of simulated Terrain Category 1 design 3-sec wind panel force traces (a) non-linear (b) linear](image-url)
Simulations to illustrate the trace to trace variability in these simulated non-linear panel force time histories. Of particular interest to us in the modelling here is the peak value of 3-sec panel wind force in the 1-hour simulated traces. From inspection of the peak values in Figure 4(a) (pertains to trace#10 of 16), and the traces depicted in Figures 8 - 10, it would seem that the record to record variability of peak 3-sec panel wind force is reasonably pronounced and is associated with all Terrain Categories. In order to better gauge this variability, Figure 11 plots the observed peak 3-sec panel non-linear wind force values, simulated for the design 100 year return period wind and Category 1 conditions, by way of example,
little variability within several of the highest ranked peaks within the record (as observed in Trace#2 of Figure 8). These two conditions correspond to the traces with the highest and lowest valued peaks of the 16 simulations conducted here. If we follow this line of reasoning and rank a set of 16 separate simulation traces according to their observed peak values, we could exclude the first and last 3 traces from consideration and choose our candidate for use in pre-qualification testing from the remaining 10, whether randomly or otherwise. Such a strategy would be similar to selecting candidate traces that exhibit a peak value that is approximately within one standard deviation of the mean peak value of the peaks associated with the set of 16 traces, based upon a Normal distribution of these peaks.

For the sample of 16 traces simulated for Terrain Category 1 conditions with peak values as depicted in Figure 11, the mean value of the peaks is observed to be 14.9 kN and the standard deviation, 1.5 kN. Hence traces in this set with peaks in the range 13.4 kN to 16.4 kN would qualify for such candidates. As it turns out, on this occasion, it is observed that all but the first and last ranked traces would qualify, which is attributed to the rather “spikey” peak of Trace#9 in raising the value of the standard deviation of the peaks in this set of traces.

4.2 THE “EQUAL AREA” INTERPRETATION OF THE SPECTRAL MODELLING TECHNIQUE

Another simulation approach for developing design panel force traces, is to use a simplified interpretation of the spectral modelling procedure of §2, applied to the along-wind wind speed spectrum, which is divided into a number of equal area divisions, (equal amplitude Fourier harmonics) with a random phase \((0 - 2\pi)\). A Fourier series, much reduced in number of terms in the summation, is then used to produce the simulated along-wind wind speed trace, (Haritos, [13]). The time-history of the along-wind Force for the panel, is then evaluated via Equation (1).

For N Fourier wavelets in the series, the amplitude of each, \(A_n\), simply becomes, \(A_n = \sqrt{2/\pi} \sigma_n\) which for \(N = 16\), for example, equates to \(\sigma_n/\sqrt{2}\). The corresponding frequency of the wavelet is taken to be at the half area position within the area segment associated with the wavelet sequence number, \(n\), under consideration. The frequency for the \(n^\text{th}\) wavelet in the series, \(f_n\), is then obtained from:

\[
\int_{f_n} S_n(f) \, df = \frac{2(N-n)+1}{2N} \sigma_n^2
\]

(15)

The maximum along-wind wind speed in this model, \(U_{\text{max}}\), occurs when all wavelets are in phase, so that

\[
U_{\text{max}} = U + \sqrt{2N \sigma_n^2}
\]

(16)

which for \(N = 16\) equates to \(4\sqrt{2}\) times the RMS value. This value is significantly greater than the value of 3.7 for \(g\), and the Dynamic Gust Factor of \(1 + 2g, f_n\), suggesting that using \(N = 16\) would not be unreasonable for modelling the panel along-wind wind speed time history to a reasonably good approximation, using this equal amplitude wavelet reduced summation method.

A closed form solution to Equation (15) for \(f_n\) is realisable for the Davenport spectrum, viz:

\[
f_n = \frac{L_{\text{th}}}{L_v} \left(\frac{2N}{2(N-n)+1}\right)^{-1}
\]

(17)

4.2.1 Choosing the number of wavelets in the equal area spectral modelling technique

The example value of \(N = 16\) above, was to a degree, quoted somewhat arbitrarily. Haritos et al [6] performed a study using Category 3 conditions for simulating turbulent wind for 100 year return period conditions and compared the statistics of the exceedance probabilities of wind traces using the modelling technique of §4.1 with those obtained via the equal area spectral modelling technique of Haritos. The study used one hour’s of simulated wind data at 1 second intervals (3600 data points per record) to demonstrate that using as few as 8 wavelets in the equal amplitude wavelet reduced summation method produced simulated wind traces that were statistically reasonably closely similar to 3600 second long traces extracted from 4096 sec simulated wind speed records using the IFFT random phase spectral modelling approach. For \(N = 16\) wavelets, this statistical comparison was found to be even closer.

A more formal criterion for choosing \(N\) in the equal amplitude wavelet reduced summation method is based on the frequency of the last wavelet matching that of the frequency of the trace being simulated, ie \(f_n = 1/dt\) where \(dt\) is the time step in the simulated record. Setting \(n = N\) and \(f_n = f_n = 1/dt\) in Equation (17), results in a closed form solution to \(N\), viz:

\[
N = \left[1 + \left(\frac{L_{\text{th}}}{L_v} \frac{1}{U_{\text{th}}}\right)\right]^{1/3}
\]

(18)

Table 3 summarises results for \(N\) “rounded” to the closest integer for the conditions associated with the example panel that is obtained via Equation (18) as a function of terrain category and time step in the simulation record.

It is observed from this table that using \(N = 8\) in the equal amplitude wavelet reduced summation method of Haritos would be suitable for generating wind speed records in Terrain Category 3 at time step intervals of 3 seconds, whilst \(N = 16\) would similarly be suitable for records generated at 1 second intervals. This latter result, (\(N=16\) noted above), is consistent with the observation by Haritos et al [6] of improved statistical matching.

<table>
<thead>
<tr>
<th>Category</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U) (m/s)</td>
<td>26.7</td>
<td>23.2</td>
<td>18.9</td>
<td>15.5</td>
</tr>
<tr>
<td>(U_{\text{th}}) (m/s)</td>
<td>30.2</td>
<td>25.5</td>
<td>18.9</td>
<td>15.5</td>
</tr>
<tr>
<td>(F) (kN)</td>
<td>6.77</td>
<td>5.17</td>
<td>3.55</td>
<td>2.47</td>
</tr>
<tr>
<td>(dt)</td>
<td>Number of wavelets, (N) via Equation (18)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>13</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>0.5</td>
<td>19</td>
<td>21</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>0.2</td>
<td>34</td>
<td>38</td>
<td>47</td>
<td>53</td>
</tr>
</tbody>
</table>
4.2.2 Comparing wind force simulations via equal area random phase spectral models with those from IFFT random phase spectral models

Statistical comparisons were conducted of the non-linear formulation of the example panel wind loading using wind speed traces simulated by the equal area spectral modelling technique with those obtained from IFFT spectral-based random phase models. A one-hour record of wind speed data at 1-second regular time intervals (3600 data points) was again chosen, with all four Terrain Categories being treated in the investigation. Values of \( N \) of 12, 13, 16 and 18 (as noted in Table 3) were adopted for Terrain Categories 1 to 4 in sequence, respectively, for the equal area spectral modelling technique. The random phases for the lower frequency wavelet sequence in this latter model were maintained in moving up the Terrain Category sequence (for increasing \( N \)) to maintain some semblance of “correlation” between simulated traces for the purposes of comparison. The traces were then subjected to a 3-sec moving average filter to render the resultant forms as equivalent measurements of 3-sec gusts.

Peak values (in kN) are clearly observed in these traces for Terrain Category sequence 1 to 4 as: 15.8 (15.2), 13.1 (12.8), 11.2 (10.7) and 9.1 (8.7). The bracketed values, extracted from Table 1, correspond to the Basic Design Wind peak panel forces and are in excellent agreement.

Statistical comparisons were conducted on the 3600 second long panel force traces using non-linear formulations of drag force and wind speed data simulated via the equal area random phase spectral modelling technique and separately via the IFFT random phase spectral-based modelling method. The traces depicted in Figure 12 were paired with Trace#7 of the 16 traces simulated via the IFFT random phase spectral-based modelling method for this comparison for each Terrain Category condition.

Figure 13 depicts the Probability of Exceedance plots for these paired simulated traces as the basis for this statistical comparison.

**Figure 12:** Simulated non-linear wind panel force traces using the equal area spectral modelling technique after 3-sec moving average filtering for Terrain Categories 1 to 4.

**Figure 13:** Comparison of exceedance probabilities of non-linear wind panel force traces using the equal area and IFFT spectral modelling techniques (Cat. 1 to 4)
It is clear, (given that these are logarithmic plots), that the simulation techniques yield traces which correspond statistically quite closely for Cat1 and very closely for Cat2 – Cat4, and that the correspondence improves with increase in Terrain Category number.

It can therefore be argued that either of the two nonlinear spectral based wind load simulation techniques can be chosen to reliably generate panel wind load time histories using wind speed traces simulated for the 100 year return period design one-hour wind storm.

5 SIMPLIFIED TEST PROCEDURE FOR PREQUALIFICATION OF ANCHOR SYSTEMS

A simplified dynamic test procedure for the prequalification of anchor systems for props in tilt-up or precast construction has been recently proposed in DR2 AS 3850.2 (2013), [3b]. This procedure is based upon using a peak cyclic load of 1.5 times the Working Load Limit (WLL) of the prop – the WLL is taken as 40% of the prop’s ultimate load, viz (ultimate load)/2.5, leading to a peak load of 60% ultimate. In this simplified test procedure, a test rig is set up with loading applied cyclically in tension to the anchor system from 0 to 60% of ultimate prop force for 1000 cycles at 1 to 2 Hz.

The question arises as to how does this testing regime relate to wind loading conditions, especially in terms of conditions for ultimate wind loading?

An attempt to answer this question for this Simplified Test Procedure (STP) is made here by performing cycle counting of the simulated 100 YRP wind loading traces of our example panel.

5.1 Cycle Counting of Design Wind Force Traces on Propped Panel

Figure 14 depicts details of the Range-Mean cycle counts obtained for the simulated non-linear wind panel force traces via the equal area spectral modelling for Terrain Categories 1 to 4, depicted in Figure 13, as obtained from program StoFlo, [14].

Block cycle testing using the Range-mean counts in Figure 14 provide us with an alternative testing procedure to that of the original force time history trace itself for investigating the performance of prop-fixture assemblies under ultimate wind loading conditions. A fine grid of 12 range value and 28 mean value ranges leading to a rather large number of cycle bins has been adopted by way of example in Figure 14. The cycles can be split into a quarter this number of bins by merging ranges in mean and range values in sequential pairs and summing the counts in the four sub-bins to produce the count for the new replacement bin, thereby further simplifying this Block Cycle testing procedure.

Alternatively, a conservative testing procedure can be extracted from Figure 14 that instead is based on the use of test cycles from 0 to an associated peak value despite actual troughs in the cycles possessing non-zero positive values. Table 4 interrogates the counts in the bins of Figure 14 to identify the number of cycles containing peak values (Mean + Range/2) within five blocks of peak ranges expressed as a percentage of Ultimate panel wind load, in support of such a testing procedure.

<table>
<thead>
<tr>
<th>Category</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;95 %Ult</td>
<td>4</td>
<td>2.0%</td>
<td>5</td>
<td>1.9%</td>
</tr>
<tr>
<td>(85-95)%Ult</td>
<td>4</td>
<td>2.0%</td>
<td>5</td>
<td>1.9%</td>
</tr>
<tr>
<td>(75-85)%Ult</td>
<td>10</td>
<td>5.1%</td>
<td>13</td>
<td>4.9%</td>
</tr>
<tr>
<td>(65-75)%Ult</td>
<td>31</td>
<td>15.7%</td>
<td>32</td>
<td>12.2%</td>
</tr>
<tr>
<td>&lt;65 %Ult</td>
<td>149</td>
<td>75.3%</td>
<td>208</td>
<td>79.1%</td>
</tr>
</tbody>
</table>

Figure 14: Comparison of cycle counts of 1-hour simulated design wind traces via StoFlo (Cat. 1 to 4)

Table 4: Proportion of peaks in simulated force trace cycle content of example panel that lie within defined ranges of % ultimate load for Terrain Categories 1-4
If results based upon the sample simulated traces in Table 4 are considered to be typical of their Terrain Category condition, then it would appear there are approx. 250 test cycles and just over 400 test cycles respectively, for Cat1-2 and Cat3-4 groupings, in a 1-hour design wind storm. A simplified testing procedure that can be extracted from Table 4 is summarised in Table 5. This table suggests the testing strategy to be substantially similar except that double the number of test cycles for the 0 to 60% design ultimate, (400 instead of 200) are suggested for Cat3-4 compared to Cat1-2. A further simplification is to treat all Terrain Category conditions using the test cycle regime of Cat1-2.

<table>
<thead>
<tr>
<th>Terrain Category</th>
<th>100 %Ult</th>
<th>90 %Ult</th>
<th>80 %Ult</th>
<th>70 %Ult</th>
<th>60 %Ult</th>
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</thead>
<tbody>
<tr>
<td>1 or 2</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>3 or 4</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>30</td>
<td>400</td>
</tr>
</tbody>
</table>

### 6 CONCLUDING REMARKS

This paper has detailed simulation techniques, based upon random phase spectral modelling, that can be used to model the wind loading of tilt-up or precast panels depending on geometry of the panel being considered. The models proposed are an IFFT procedure and an equal amplitude wavelet approach that can use as few as 6 wavelets (1-hour design wind storm for Terrain Category 1 or 2 with wind traces simulated directly at 3-sec intervals for 1200 points). When the wind loading condition corresponds to ultimate (100 YRP wind), the method can be used to provide a time history over one-hour at 1-sec intervals of the wind speed, which is then 3-sec block averaged to provide 3-sec gusts. This trace can then be translated to a non-linear prop force time-history for the purposes of investigating and comparing the performance of various prop fixtures in terms of a prequalification test for such fixtures.

Cycle-counting using rainflow analysis can be exercised on the modelled wind force time traces to obtain a block cycle testing regime alternative to direct signal testing. The cycle-counting method however, loses information on frequency content as the trace is reduced to a number of cycles with associated Mean-Range characteristics. A much simplified method, labelled here as the dynamic Simplified Testing Procedure, or STP, uses 1000 cycles at 1-2 Hz ranging from 0 to 60% of Ultimate prop force on the prop-fixture test assembly as the prequalification test of anchor systems in panel propping applications. This procedure can be compared to a more rational test strategy suggested following cycle counting via a rainflow investigation of simulated non-linear ultimate wind loading conditions for a 1-hour storm. This strategy is based upon only 460 total test cycles, 400 of which are now in the 0-60% ultimate condition, and the remainder divided up into cycles from 0 to a percentage ranging from 70% to 100% ultimate, as detailed in Table 4.

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### REFERENCES:


