A framework for fatigue damage estimate in single-axis solar trackers

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Abstract. Solar trackers are constructions consisting of a series of photovoltaic modules mounted on a motorized supporting structure; such systems are usually characterized by limited torsional stiffness and low number of torsional constraints, factors that lead to lower structural frequencies. At these frequencies, trackers are typically susceptible to turbulent wind, and when excited by it, the expected responses can lead to significant deformations and, with its cyclical load variation, also to fatigue damage. On this premise, the presented article proposes a methodology for estimating fatigue damage caused by dynamic wind effects in single-axis solar trackers. As observed in full-scale scenarios, it is assumed that the fatigue damage accumulates in correspondence of the elements connecting the photovoltaic modules to the underlying structure. To this end, a transfer function that relates the pressure acting on the panel to the stress state in a specific point is evaluated with a FE model and then experimentally validated with a cyclical load test. Time histories acting forces, derived by wind tunnel measurements, are used with the transfer function to infer the evolution of the stresses acting in the regions of interest. Finally, the rainflow cycle count is used in conjunction with the Wöhler curve of the investigated structural detail to analyze the stress history and derive a fatigue damage estimate. It is expected that the proposed approach can aid designers in the damage estimation and verification procedures.

1. Introduction

Solar energy is one of the most known sources of renewable energy, and it has the potential to make a significant contribution to transition towards sustainable energy systems. Among the different technologies used to harness solar energy, photovoltaic (PV) systems have been growing in popularity over the past decades. To increase the energy output of PV modules, tracker systems have become commonly used in large-scale installations, as this can significantly increase the surface exposed to sunlight and energy output. In such scenario however, the absence of barriers, either natural or man-made, shielding the PV park, makes relevant the wind loads perceived by solar tracker systems.

Single-axis solar trackers are the most common kind of this type of structures and consist of a series of PV modules mounted on a motorized supporting system that, by rotating about a longitudinal axis, allow the panel surfaces to be orientated and track the sun during the day. To have competitive solutions, solar trackers need to be as cost effective as possible: designers therefore seek to minimize the amount of material used by reducing the cross-sectional area in the torsional shaft and other supporting elements, consequently leading to limited torsional stiffness. This aspect, combined with the low degree of torsional constraints that characterize the rotation mechanism of solar trackers, leads these PV systems to have low structural frequencies and to be particularly susceptible to the effects of dynamic wind, to the point of reaching significant overall torsional deformations. These deformations can compromise the structural integrity of the entire system or any part of it, especially when the system responds cyclically, and fatigue damage is accumulated in the elements connecting the different parts of the structure. Fatigue damage in these systems is actually a known problem in practice; some research in the existing literature aims at characterizing the response under cyclical wind loads; such examples can be found for the actual dimensioning of the PV modules [1] and for the supporting system as illustrated in [2] and [3] for the case of 2-GDL systems.

Pursuing the fatigue damage estimation, the main objective of the presented article concerns the definition of a predictive model for the estimation of the fatigue damage accumulated due to cyclical dynamic wind effects acting on the large tracker surfaces. The approach proposed is developed on the premise that experimental wind tunnel tests are available and can be used for the characterization of the forcings terms acting on the structural system. Then, by combining the pressure distribution time histories, and eventually information about the aeroelastic response of the tracker [4], both of which are acquired through wind tunnel testing, with the structural properties derived from a FE model -or technical specifications-, it is possible to define and numerically integrate the governing problem of the system. In such a way the inertial forces, related to structural accelerations, are easily derived by the displacements; this component, summed with the external forcing term, is needed to define a set of Equivalent Static Wind Loads (ESWL).

In accordance with evidence observed in full-scale scenarios, the fatigue damage is expected to accumulate in correspondence of the elements connecting photovoltaic modules to the underlying supporting structure. A function that relates the static equivalent pressure acting on the panel surface (that is the ESWLs) to the stress state in a specific point is reconstructed by performing a series of analysis on a local FE model reproducing a portion or a structural detail of the of the whole PV tracker. From the definition of the transfer function, the time history of the loading term, obtained for a specific cross section of the tracker by combining the pressure distribution and the inertial forces, is translated in the time history of the stress acting in the connections. The analysis of this last quantity, which is performed by means of a rainflow cycle count, combined with the SN, or Wöhler, curve of the structural detail and material investigated [5], provide useful information for the fatigue damage evaluation. Finally, in order to validate the transfer function, a series of cyclical-loads experimental tests are carried out on full-scale modules. From this analysis it is expected that, with minor calibration of the SN curve and transfer function, the developed procedure produces reliable results for the design. In conclusion, it is expected that the approach developed for calculating fatigue damage in PV trackers, specifically in connections, can enable designers of these structures to optimize the verification procedure.

2. Methodology

The methodology presented for estimating the fatigue damage of solar trackers is based on the development of numerical simulations that include information about the distribution of acting pressures, construction details of the structural assembly as well as knowledge of the adopted materials properties. One point that can generally be affected by problems related to cyclic loads concerns the connection system that constrains the PV module to the underlying support beam. Noting that the procedure can be easily extended to different types of connections, or even to completely different areas, for the case presented in the research, reference will be made to a portion of the PV module's aluminum frame, in proximity of the outermost connection element.

2.1. Wind induced structural response

PV trackers are slender structures and thus respond dynamically to wind actions. The first key information for fatigue damage assessment, and also for the characterization of the PV response, involves the identification of the actual wind forcing acting on the system. A typical approach for evaluating this quantity is to develop a wind tunnel test on a scaled rigid model of a given PV park portion with the aim of calculating the pressure distribution along the tracker surfaces. By repeating the tests for different parameters (such as inclination angle, wind exposure angle and inter-row distance) the photovoltaic power plant under consideration is fully characterized from the point of view of acting loads. When the coupling between wind flow and structure is expected to be relevant, another approach that can be used is shown in [4] which, in addition to the buffeting loads, also takes into account in the forcing term, of the self-excited component. The evaluation of this quantity can be performed, by means of wind tunnel free-motion measurements on a suspended sectional model.

The second information required to define the governing equilibrium equation are the mechanical properties of the system, that is: mass, stiffness and damping which typically, can be obtained from an FE model, such as the one depicted in Figure 1, or technical specifications of structural details. Once the quantities are defined the governing equation can be defined with the following:

$$\mathbf{M}\ddot{\boldsymbol{x}}(t) + \mathbf{C}\dot{\boldsymbol{x}}(t) + \mathbf{K}\boldsymbol{x}(t) = \boldsymbol{f}(t) \qquad (1)$$

In which the three matrices $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ represent respectively the structural mass, damping and stiffness, the vector $\boldsymbol{x}(t)$ is the physical displacement and $\boldsymbol{f}$(t) is the forcing term.

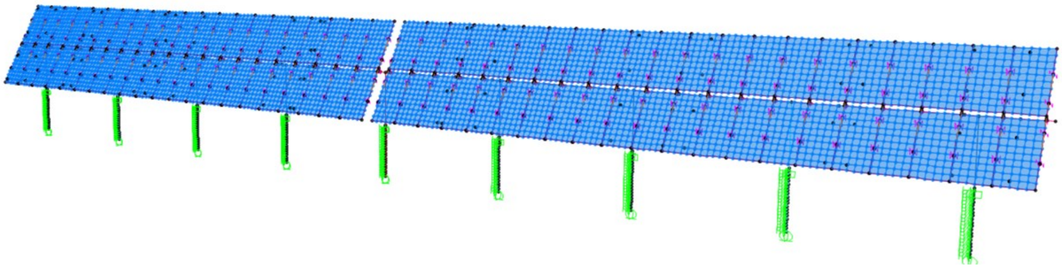

Figure 1 – Global FE model of a PV tracker

2.2. Evaluation of the equivalent static loads

The methodology presented involves, for the estimation of fatigue damage, the application of wind loads on a numerical static model; it follows that it is necessary to identify, instant by instant, the equivalent static wind loads (ESWL) associated to the specific configuration analyzed.

To address this objective, the dynamical system of equation (1) is solved numerically, ensuring that the integration step is small enough to have a smooth, convergent solution. The information about the structural displacement is necessary to derive the system accelerations and consequently the associated inertial forces. The term related to the structural damping can be typically neglected: in this way the resulting equivalent static force distribution at a given time t_1.can be written as:

$$\boldsymbol{f}_{\mathrm{ESWL},t_1} = \boldsymbol{f}(t_1) - \mathbf{M}\ddot{\boldsymbol{x}}(t_1) - \mathbf{C}\dot{\boldsymbol{x}}(t_1) \simeq \boldsymbol{f}(t_1) - \mathbf{M}\ddot{\boldsymbol{x}}(t_1) \qquad (2)$$

For convenience, exploiting the geometry of typical PV trackers, when applying loads to the numerical model, it is possible to simplify the problem formulation. At first, with reference to a generic cross-section, the sum of the acting contributions is collapsed into a normal force acting at mid-span and a torsional moment about the longitudinal axis of the tracker, as it is shown in Figure 2a.

$$\begin{cases} F_{N,t1} = \sum_{\boldsymbol{j}} f_{\mathrm{ESWL},t_1,j} \\ M_{t,t1} = \sum_{\boldsymbol{j}} f_{\mathrm{ESWL},t_1,j} \cdot b_j \end{cases} \qquad (3)$$

Where $f_{\mathrm{ESWL},t_1,j}$ and b_j are respectively the ESWL and the distance with respect to the mid-section of the j-th node along the tracker chord. $F_{N,t1}$ and $M_{t,t1}$ are the two resultants related to the instant $t1$.

Then, dividing by the surface area of one panel A_{PV} and the distance between the centroids of the two panels present on a same chord B_{PV}, the load acting on a single PV module is approximated in a uniform pressure distribution, as shown in Figure 2b, in accordance with the relation:

$$p_{\mathrm{ESWL},t_1} = F_{N,t1}/(2A_{PV}) \pm M_{t,t1}/(A_{PV}B_{PV}) \qquad (4)$$

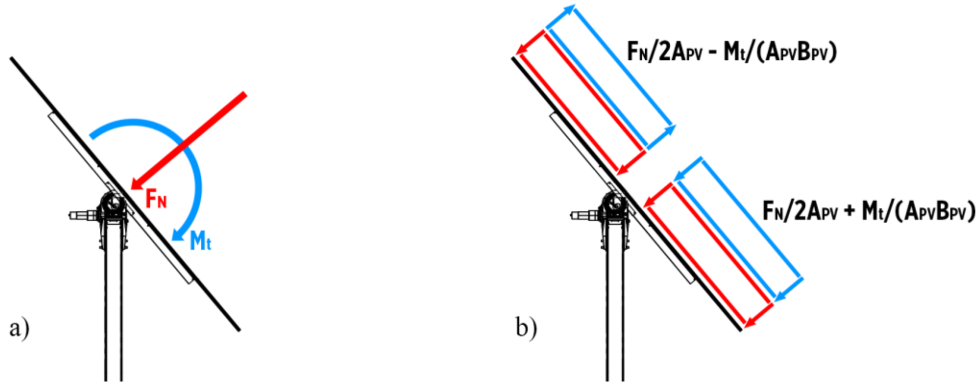

Figure 2 – Simplification of the acting loads into: a) concentrated forces b) and uniform distributions

2.3. Identification of the internal stresses

Given the forcing acting on the system under investigation, in order to estimate the damage state, it is necessary to identify the internal stress state in the given point of interest. Since the connecting elements between the two bodies (PV module and supporting beam) have geometric discontinuities and non-linear constraints, the development of an FE model of the structural detail, such as the one presented in Figure 3, is functional in the evaluation of internal responses for a given applied pressure. Regions characterized by linear geometries and constraints, however, could be well-characterized with relatively simpler numerical models.

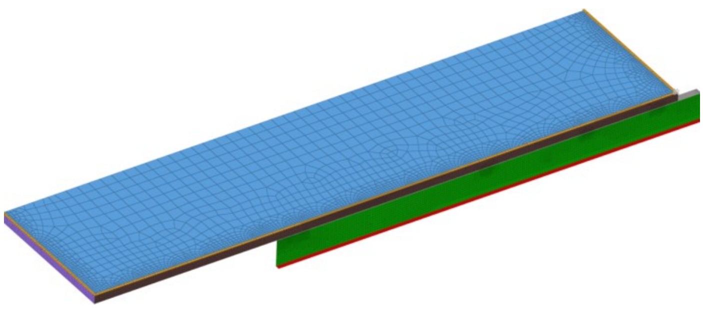

Figure 3 – Local FE model of the PV module and underlying support beam

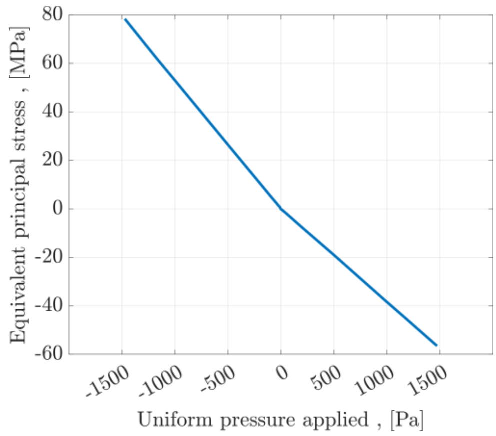

Figure 4 - Transfer function of the aluminium principal stress, derived from the FE model

2.3.1. Evaluation of the transfer function.

Starting from the finite element model, a series of nonlinear static analyses are performed. In each of these simulations the panel surface is uniformly loaded following a loading ramp until an equivalent pressure is reached. Since the one developed is a static model, while the actual situation is a dynamic one -as well known with the application of ESWLs- it is necessary to consider the inertial force component in addition to the external loads. By repeating the computations for different load values, the transfer functions that link internal structural responses to the acting forces can be identified by points. In the case of the present study, the principal stress observed in the bottom flange of the PV aluminum frame, in the neighborhood of the connection element, is taken as the reference: in Figure 4 the associated transfer function is reported.

2.3.2. Experimental verification of the response with a full scale-model.

In order to validate the numerical simulations, and more specifically the transfer function described in the previous section, an experimental test was developed for the present case study.

For this task, a real PV panel and its supporting beams were mounted on a frame to simulate the real operating setup. In this test, load application is carried out by an actuator placed below the system whose output force is transmitted, via a suspended frame mounted around the PV module, in an about-uniformly distributed load on the panel surfaces. In this way, the acting load results having a distribution comparable to the one of wind action, a photo of said experimental model can be observed in Figure 5.

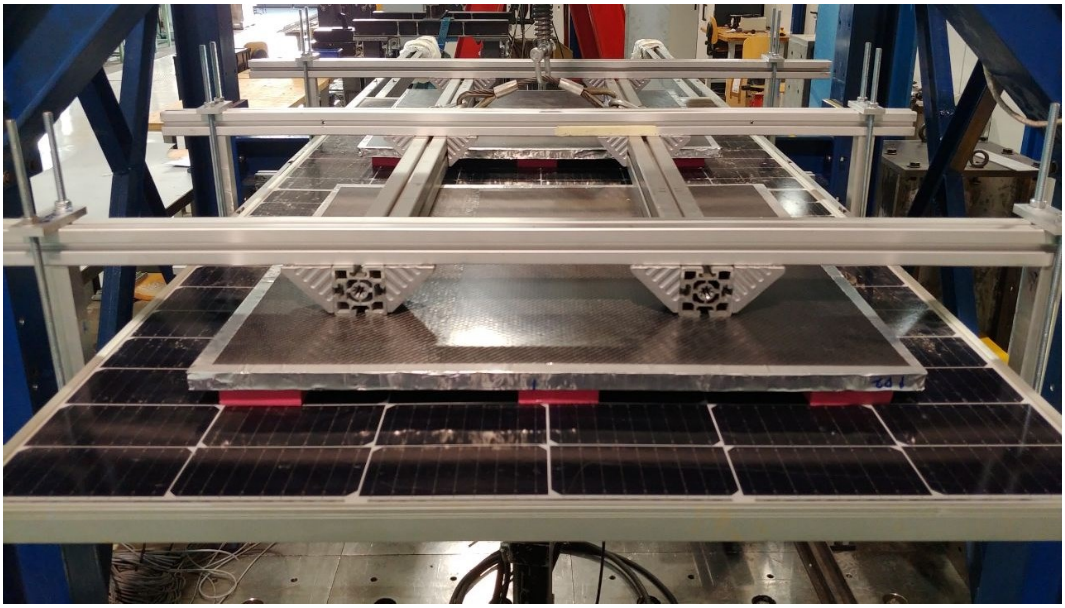

Figure 5 – Experimental setup for the evaluation of the structural responses

To compare the two results, the experimental setup was instrumented with a laser for the evaluation of the mid-span displacement and a strain gauge for strain evaluation in the reference point. The results of this validation can be observed in Figure 6, in which the experimental trend is plotted against the results of the numerical FE model, considering respectively in Figure 6a the strain in the principal direction of the monitored point and in Figure 6b the displacement in the mid-span point of the PV module. Since both measurements seem to provide consistent results, the numerical model can be assumed to be validated and representative of the actual response for the considered case study.

2.3.3. Evaluation of the internal stresses time history.

With all inputs to the problem known, the evaluation of the internal stresses turns out to be of immediate application. The external forcing term, added to the inertial contribution, provides the equivalent static load acting on the numerical model. By means of the transfer function the associated strain, or stress, at a given reference point is directly computed as:

$$r_i = T_i(p) \cdot p \qquad (5)$$

Where p is the equivalent static pressure distribution, r_i is the selected internal response and $T_i(p)$ is its associated transfer function expressed as dependent of the load parameter. The procedure can also be generalized and extended to evaluate an entire load time history; the output for this case will clearly be the time history of the monitored internal response:

$$r_i(t) = T_i\big(p(t)\big) \cdot p(t) \qquad (6)$$

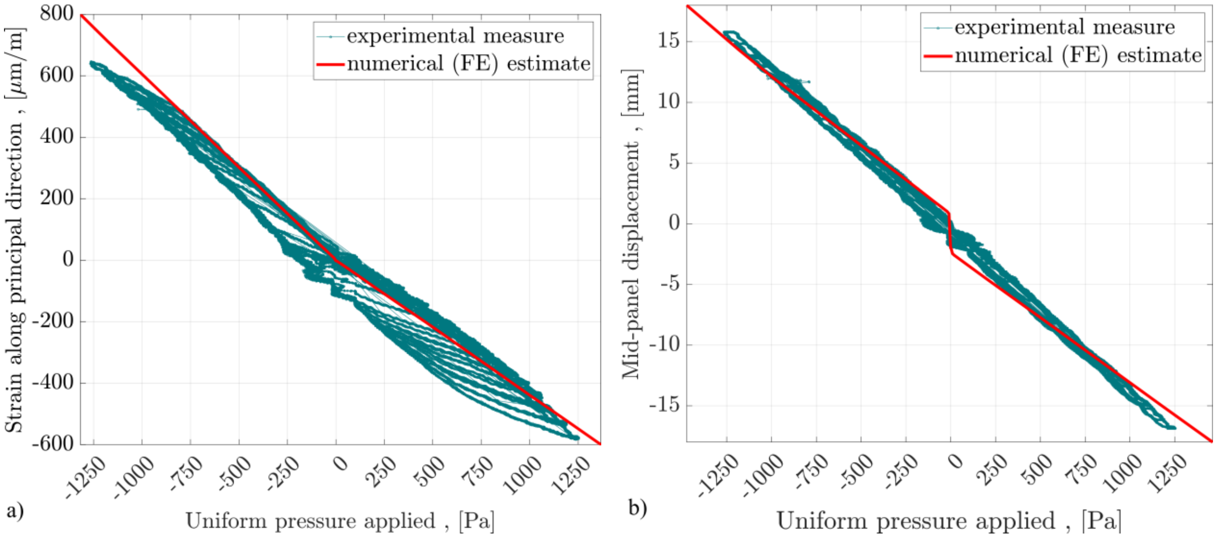

Figure 6 – Comparison of the PV panel response between numerical and experimental simulations for different load values: a) Strain in the monitored point, b) Mid-span vertical displacement

As an example, in Figure 7, the different steps of the quantities presented in equation (6) are graphically depicted, Figure 7a and Figure 7b, depict respectively at the right hand side of the equation, a slice of the equivalent pressure distribution time history, and the transfer function T_i. In Figure 7c is reported, for the same time interval of $p(t)$, the time history of the resulting internal response $r_i(t)$, given by the multiplication of the two other quantities. In the figures, the range of variation observed for the $p(t)$ history, and the associated range of the response $r_i(t)$, are reported with dashed lines.

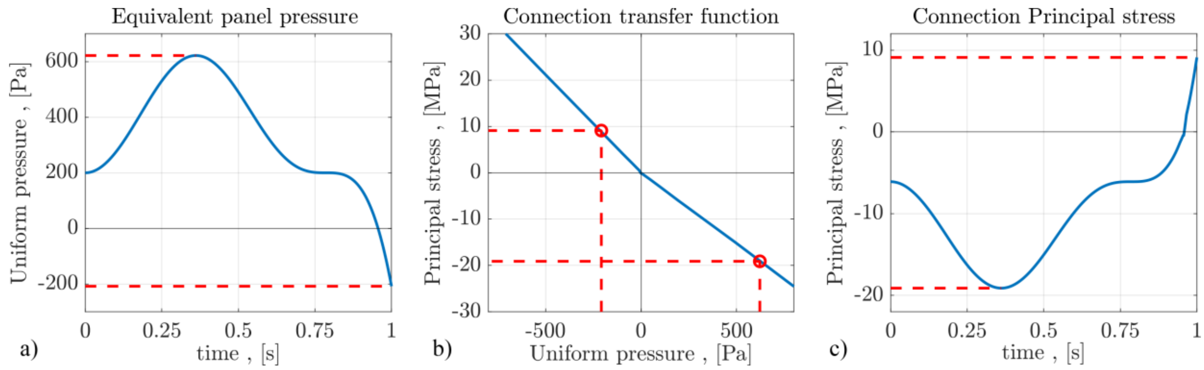

Figure 7 – Example of transformation from pressure to internal stress
a) acting pressure $p(t)$, b) Transfer function $T_i\big(p(t)\big)$, c) internal response $r_i(t)$

2.4. Damage estimation

As mentioned in previous section 2.3.1. the main stress in the flange of the aluminum frame, will be taken as the sole internal response considered with regard to the development of the methodology that is the subject of this paper. Furthermore, since the damage estimate is performed with respect to the tracker system, the stress computation should in principle be repeated for all the j-nth cross-sections of interest. For simplicity, the examples below refer to the analysis of a single cross-section; however, it remains understood that the procedure can be easily extended to the whole tracker length.

The time history of the stress under consideration is reprocessed in order to have a usable measure for fatigue damage assessment. More specifically, at the monitored point the stress is essentially uniaxial, it follows that the rainflow method is sufficient for the identification of a sequence of equivalent constant amplitude (or range) stress reversals. The number of cycles evaluated from the stress time history is reported in Figure 8a while, if neglecting the average of each cycle the previous rainflow, the results read as the histogram depicted in Figure 8b.

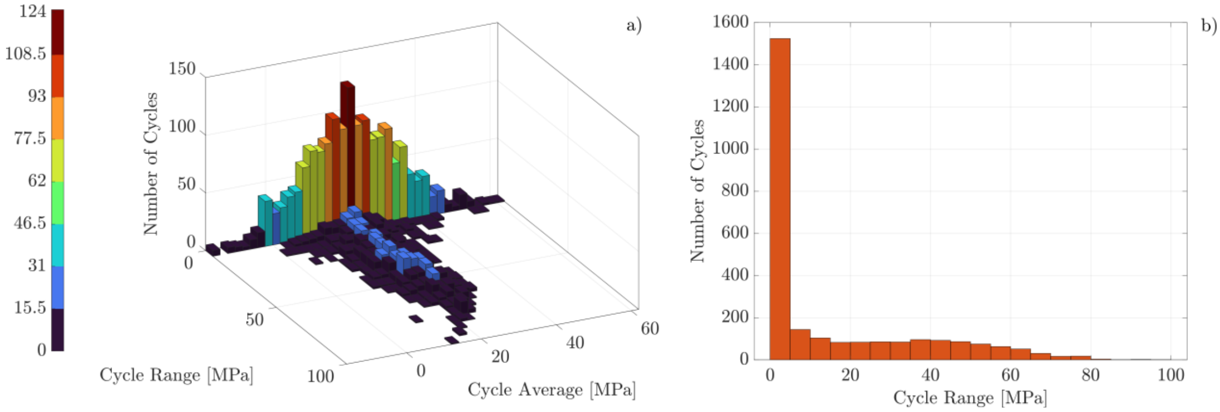

Figure 8 – Rainflow cycle counting of the numerically simulated internal stresses time history
a) number of stress reversal accounting the amplitude and average of each cycle
b) number of stress reversal accounting only the amplitude of each cycle

Given the sequence of cyclical loads from the rainflow method, and remarking on the uniaxiality of the monitored stress, the damage for the analyzed situation can be estimated directly with Miner's rule.

$$d = \sum_{k}^{\mathrm{n}\Delta\sigma} \left(\frac{n_k}{n_{\mathrm{lim}(\Delta\sigma_\mathrm{k})}} \right) \qquad (7)$$

In which $k = 1 \cdots \mathrm{n}\Delta\sigma$, is the number of unique amplitudes inferred by the rainflow algorithm, while n_k is the number of cycles counted for the specific stress range $\Delta\sigma_k$. The term $n_{lim}(\Delta\sigma_\mathrm{k})$ is the expected number of cycles leading to failure, assuming only one cyclic load is applied at constant amplitude $\Delta\sigma_\mathrm{k}$. Here, the curve defined by the $n_{lim}(\Delta\sigma)$ function can be evaluated experimentally or taken from literature considering the material and the specific geometry of the mechanical detail; for instance, in the depicted case, reference was made to [5]. In Figure 9 the results of previous equation (7) is shown: the blue line represents the limit cycle curve provided by $n_{lim}(\Delta\sigma)$, while the red circles represent for each unique amplitude, the associated number of cycles due to the selected wind tunnel pressure time history.

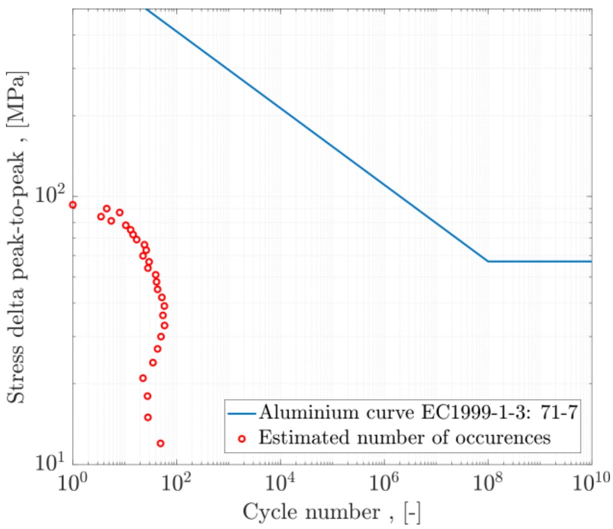

Figure 9 – Cycle occurrences counted by rainflow method plotted against the steel S-N curve

2.5. Extension of the procedure

The damage calculated in accordance with the previous equation (7), as already mentioned, is in principle referred to a specific structural response i and tracker cross-section j. By considering all the damage estimated for the structure investigated, the damage state of the tracker, D, can be assumed to be equal to the envelope of all the computed damages:

$$D = \max_{\{i,j\}}\left(d_{ij}\right) \qquad (8)$$

Another aspect to consider, concerns the association of the damage with the time history of loading used to infer the internal stresses. Since the time series of the acting forces is derived directly from an experimental wind tunnel measurement, characterized by a limited time duration, the damage index obtained in equations (7) and (8) is also linked to the same time duration simulated in the experiment. This could be problematic in the case of comparisons between different experimental inputs and in the estimation of measurements to full-scale structures. The issue can be overcome by considering a damage rate by dividing the damage index over the corresponding full-scale simulation time.

$$d_{\text{rate},ij} = d_{ij}/\Delta t_{exp} \qquad (9)$$
$$D_{\text{rate}} = D/\Delta t_{exp}$$

In Figure 10 a schematic of the experimental park modeled in wind tunnel is depicted: the topmost row and the column on the right are the perimetral elements in the full-scale PV park. It is expected that these are the elements most susceptible to dynamic wind action since they are directly exposed to wind action and shielding effect is absent. As an example of the generalization made in this section, focusing on the perimetral trackers, it is possible to see reported above each system the respective damage rate estimate, D_{rate}, computed as in equation (9). In addition, a colormap that represents the damage rate, $d_{\text{rate},ij}$, assessed for each tracker cross section and for each installed panel is reported for each of the trackers. As can be seen, the largest values in the whole distribution are found in the tracker of the second row, third column (R2 C3), for which a small portion of the tracker, near the external side, defines the most unfavorable design condition.

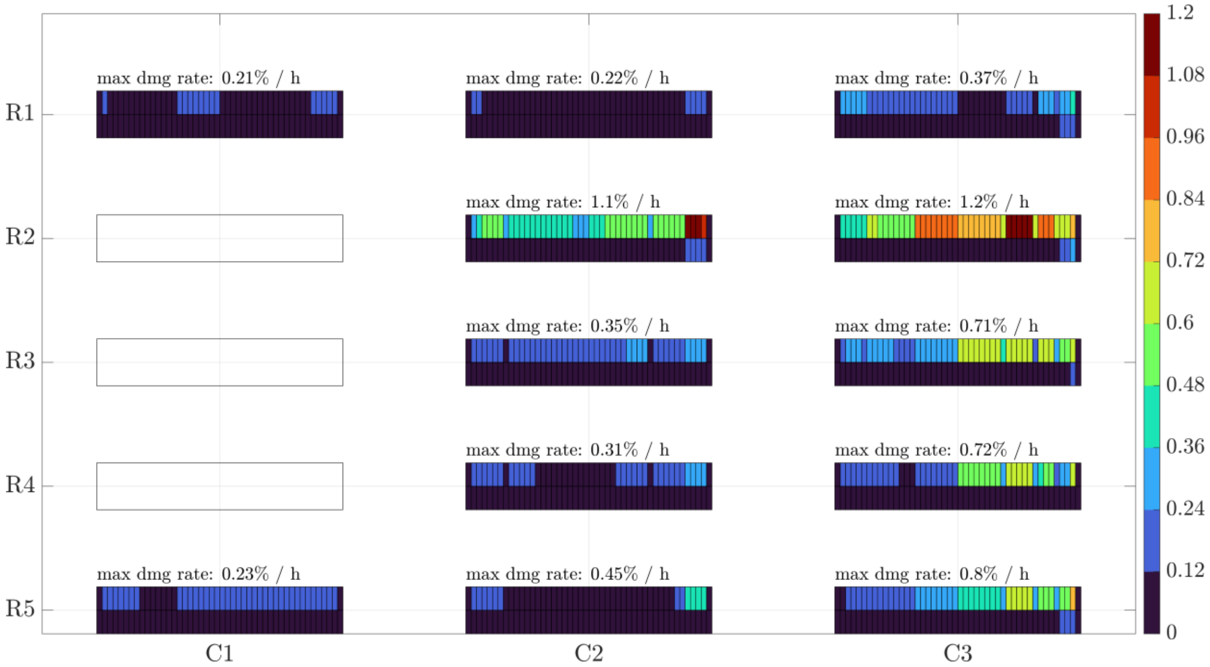

Figure 10 – Graphical representation of the distribution map of the damage rate estimate

3. Conclusions

The methodology shown in this paper develops, by combining theories already existing in the literature, a computational methodology for estimating fatigue damage on PV tracker arrays.

Starting from experimental wind tunnel simulations, a numerical model was developed to simulate the response of the system to dynamic wind effects. From this initial set of data, the time history of the pressure distribution and the inertial forces are known and can be adopted for the definition of an equivalent static load distribution. Under this assumption, a second numerical finite-element model was developed to characterize, for different load values, the internal stresses acting in a local portion of the tracker.

Combining the equivalent pressure distribution obtained from the wind tunnel tests and the transfer functions inferred by the local numerical model, which links the forcing term to an internal response, the time history of a local stress has been computed. This time series is then processed by means of a rainflow cycle counting algorithm in order to evaluate the amplitude and the number of stress reversals associated to the monitored points, and consequently estimate the fatigue damage, for example with the adoption of the Miner's rule.

The advantage of the proposed procedure is that, with only the knowledge of experimental wind tunnel acquisitions, it is possible to estimate a fatigue damage distribution map for a portion of a PV park. This tool, from the designer's point of view, is certainly of useful application as it allows the identification of the elements most susceptible to the investigated phenomenon. Furthermore, accounting for the probability distribution of wind direction and wind speed, time-normalized damage maps are ideally suited to be combined with statistical data, and provide a better insight about the estimated fatigue damage not only for the specific structure but also a given plant in specific installation site.

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