Critical review of turbulence models for CFD for fatigue analisys in large steel structures

Alberto Lorenzona,\* – Marco Antonelloa - Filippo Bertob

aDepartment of Engineering and Management, University of Padova, Stradella San Nicola 3, 36100 Vicenza, Italy

bNTNU, Department of Engineering Design and Materials, Richard Birkelands vei 2b, 7491, Trondheim, Norway

\*Corresponding author. Tel.: +39 0444 998711; fax: +39 0444 998888; E-mail address: alberto.lorenzon.3@phd.unipd.it

# Abstract

The determination of wind-induced fatigue load in large structures and buildings with complex geometries, which do not fall in typical cases of building codes and standards, represents a consuming task and it is usually evaluated through the aid of wind tunnel tests, while computational approaches do not yet have a large application.

The practical use of Computational Fluid Dynamics (CFD) techniques in civil engineering applications has in fact been rare outside the framework of steady-state analyses, because of the limitations of RANS approaches and of the higher cost of LES, but with the increase in computing resources and with the introduction of new and more efficient turbulence models, the practical use of CFD to evaluate fluctuating features of wind flow is much more feasible now. With it, it is possible to foresee the possibility for the evaluation of wind-induced fatigue loads in steel structures by using CFD. This paper has the purpose to discuss the feasibility of a procedure that uses CFD as the first step in a chain of numerical simulations that leads to the fatigue calculation of a large, complex structure.

The state of the art of turbulence models for CFD is here shown by performing literature review, with particular attention to their application to case studies related to large steel structures. A special focus in this paper lies in the use of PANS models, which reduce computational cost and grid sensitivity compared to LES, while providing comparable accuracy.

# Keywords:

Computational fluid dynamics; wind-induced fatigue; turbulence models, wind engineering, large steel structures.

# Nomenclature

*p* pressure

*v* velocity vector

*Ui* time-averaged velocity

*ui’* fluctuating velocity

 mean velocity vector

*µ* molecular viscosity

 kinematic viscosity

 eddy viscosity

ρ specific weight

*Sij* deformation tensor

 Reynolds stress tensor

*K* turbulent kinetic energy

*ε* turbulent dissipation rate

ω specific dissipation rate

ζ velocity cale ratio

*Pk* production term

*δij* Dirac delta

*Cij* cross-term stress tensor

*Rij*, *Qij* sub-grid scales (SGS) Reynolds stress tensor

*fk, f* *ε* PANS filter-width control parameters

*ku,εu* PANS unresolved total dissipation

# Introduction

The comprehension of fluctuating, time-dependent wind loads acting on large steel structures is necessary for the assessment of a time-dependent structural response to wind action. This has been a long due request which arised parallel to the increase in building sizes and to the optimization in weights. In fact, as buildings and bridges become larger and more weight-optimized, they become also more sensitive to the dynamic effects of wind.

High-cycle wind-induced fatigue collapse is a well-documented phenomenon in case of structurally simple structures, for which it is possible to define aprioristically the characteristics of the relevant dynamic wind excitation. Also, the wind-induced fatigue assessment is a necessary design requirement for wind turbines 1–3.

In case of large and complex civil structures, this type of phenomenon is usually not easily recognizable and accountable. This paper considers the latter type of structures as they represent a typical case in which, as of today, regulations require to take into account the phenomenon of wind-induced fatigue. International standards such as EN 1993-1-1:2005+A1:2014, Annex C have recently reinforced the request to consider the fatigue phenomenon for the design of large steel structures. The size of the structure is implicitly part of the concept of Consequence Class and the large size almost automatically leads to fatigue calculations.

In general, the prediction of wind-induced fatigue life requires the description of wind loading first and, secondly, the estimation of damage. Hobbacher reported in 4 that the exact knowledge of the actions is one of the most relevant issues and a source of many uncertainties in fatigue calculations, and that only evaluations of the stress history can be made for many applications: this is particularly true for the of wind excitation. A typical approach for the description of wind loading is the generation of time series of pressure fluctuations by adopting semi-analytical approaches, together with the assumption of Gaussian random fluctuations. As shown in 5, the hypothesis of Gaussian loads can result in non-conservative fatigue life estimates. Moreover, the characteristics of wind pressures depend on the geometry, on the location and on the wind direction and semi-analytical models find a difficult application when the geometry of the structure becomes complex. In such cases, evaluation of wind loading is performed with the aid of wind tunnel tests. In wind tunnels, the spectral features of the natural wind can be reproduced and it is possible to provide simultaneous measurements of instantaneous pressures at various locations 6. A series of wind-induced fatigue analyses that involved wind tunnels are further reported in chapter 2. Wind tunnel tests are frequently performed for complex, large structures, but execution times and costs of these tests are often not compatible with the design process, in particular with early design stages. This gives rise to the interest and the research for a practical instrument capable of providing fluctuating wind loads with a sufficient level of reliability. As Computational Fluid Dynamics (CFD) over the last decades has been successfully used to determine static wind loads on practical applications such as buildings and structures, an extension of its use for this purpose is desireable. Compared to mass-producted structures such as light poles, tanks, wind turbines, etc., large civil structures are almost always one-of-a-kind products, and cannot be designed using trial-and-error approaches, hence numerical simulation has become a fundamental part of the design.

Until recently, the numerical simulation of wind could not be considered feasible, because of the high computational cost of advanced turbulence models, which are required in order to obtain accurate enough time-dependent series of instantaneous pressures, the difficulty to model natural wind and the fact that CFD is still a relatively recent tool. Many of these problems were outlined where peak-type values needed to be predicted in order to allow for a wind-resistant design and gust evaluation7,8. Now, many of these drawbacks have been (or are being) overcome: the computational power is constantly growing allowing to execute more advanced simulations; a new generation of turbulence models is being developed and validated and allows to provide high quality results with lower computational effort 9,10 and inflow generators have been developed11 and validated which are able to introduce and sustain the correct profiles of mean velocity and turbulence spectrum.

Unfortunately, there is at the moment no literature that correlates the two topics of CFD and wind-induced fatigue and there are still many issues which need to be outlined before a seamless connection is realized. With the aim of shortening the gap between these two vast topics and enabling future developments in this regard, the recent advances of CFD are further reviewed with a practical attention to its potential use for the determination of wind-fatigue loads on buildings and large structures. The choice of turbulence models which are able to correctly represent the complexity of real flow structures on buildings is fundamental in this evaluation and still represents an open issue for industrial CFD 12, hence a review of studies that involve various turbulence models is presented in chapter 3 with the aim of addressing the most efficient turbulence models for this application.

If, on the one hand, the determination of the fluctuating wind loads is a major issue today, on the other hand the massive fatigue calculation of a complex structure is not yet a completely solved problem when FE models are involved. Hobbacher 4 noted that in almost every modern structural project, the use of FE models is at the center of design workflow. Therefore, even if the stress cycles due to wind are supposed to be know and loaded in the FE model, it is necessary to carefully treat the information provided by the models, as FE analysis determines notch stresses and not nominal stress. This treatment requires a particular attention and expertise as no common code guides the designer in the determination of nominal stress from FE results.

Therefore, in light of the requirements of the standards on the study of wind-induced fatigue in the design of large structures and observing that many of the topics involved are not easily accessible to designers, a search for a practical numerical tool for the determination of dynamic wind loads appears to be fundamental.

In order to perform a complete numerical simulation of wind induced fatigue in a complex structure, the chain that connects the dynamic wind evaluation on the structure to the fatigue verification on the single weld or structural element must be developed in its entirety. The purpose of this paper is to discuss the feasibility of such a procedure.

# Treatment of wind loading for wind-induced fatigue damage assessment

The determination of the statistical distribution of fatigue cycles still represents one of the most important problems in fatigue analyses as wind is a random loading and, especially in case of complex structures, the load spectrum varies with the position. The process for the determination of wind-induced fatigue is dependent on the characteristics of the available wind data. In fact, the necessity to introduce stochastic assumptions about the characteristics of the wind excitation depends on the disposability of experimental data or test data.

Of the many studies of wind-induced fatigue which are available in literature, a series of studies are here referred and described with the aim of identifying how the wind loading is treated with different approaches, with the purpose of evaluating a possible role of CFD.

## Wind loading from on-site measurements

Ideally, assuming that the transient wind loading is known for the complete lifetime of a structure, and that the complete time history of stresses is available at every location, an appropriate cycle counting method such as the rainflow cycle counting can be applied and the fatigue damage can be evaluated using Palmgren-Miner rule. This could be the case of a full-scale structure built on site with the availability of data from a structural health monitoring system. Such a situation is not practically realizable and, even if time series obtained from full scale measurements are available, usually they cover only a limited period compared to the life of the structure and it is necessary to perform a statistical analysis in order to obtain a complete joint probability density function that takes into account mean wind speed and direction.

As a practical application, Xu et al. 13 performed fatigue calculation due to buffeting of a long suspension bridge, based on data measured on site, where the distribution of the complete population of wind speed at the bridge site is built by using Weibull distribution.

## Wind loading from test measurements

The availability of wind test data obtained from a wind tunnel represents a typical case for the evaluation of wind-induced fatigue in complex structures.

In case time series of pressures are available, time domain-based methods are applicable. A series of instantaneous pressure fields on a whole building for different wind speeds and for different wind directions are measured in a boundary layer wind tunnel, on a fixed (not flexible) scaled model of the structure. The instantaneous stress is calculated with the aid of a FE model including, if necessary, the resonant part of the wind load. The application of deterministic counting method such as the rain-flow counting algorithm to time series of stresses, provides the total fatigue damage by using the Miner’s law. In order to predict the fatigue life of the structure, statistical property of the wind on site are considered. As underlined in 14, rain-flow cycles counting of long time series is the approach that is most widely used in different fields and standard codes and is part of the framework of classical fatigue theory. The study performed by Flamand et al.15 falls in this category. The authors performed fatigue analyses for the design of a large steel stadium exposed to wind, and boundary layer wind tunnel provided the time series of the pressures on a 1:200 scaled fixed model of a stadium. Using a FE model, the calculation of stress time series due to quasi-static and resonant wind components was then performed. A rain-flow counting method was then used to build the fatigue load spectrum and the total damage was evaluated using Palmgren-Miner rule. In order to calculate the number of cycles for each stress group, the authors used site wind data measured over 30 years to calculate the probability of occurrence of every wind speed.

Although experimentally onerous, this type of approach allows the identification of wind flow characteristics without the introduction of aprioristic assumptions about the relevant spectral components for the structural response. It is noted that the availability of the time series of the pressures in all positions of the structure fits well with the use of FE models.

## Wind loading from stochastic approach

On the contrary, often only mean or peak pressure coefficient are provided by wind tunnel tests or literature and the fluctuating wind action must be modelled by applying principles of random dynamics as first shown by Davenport 16, or by generating synthetic time histories using Monte Carlo algorithms.

The first approach, which is performed in frequency domain, requires a comprehension of the characteristics of the wind loading on the structure or on the structural component. Two different types of stationary random processes can be distinguished: narrow band and wide band 17. In narrow band processes it is possible to identify a predominant frequency response, such as in case of along-wind response of structures with low natural frequencies or cross-wind vortex shedding of circular cylindrical structures. In wide band processes, the PSD has relevant values over a broad interval of frequencies, with a large background response peak. In case of complex structures, the wide-band component is usually dominant. As pointed out in 18 these methods are able to provide elegant solutions but are difficult to use in practical applications; moreover, the link between the stochastic characteristics of excitations and those of the structural response is easily determinable only when the structural model is linear (see 19).

Many closed form formulations (see 17,18,20,21) to assess the wind-induced fatigue damage in narrow band and wide band hypothesis has been proposed.

Repetto and Solari extensively analyzed the fatigue behavior of slender steel structures in 18,22 and formulated a mathematical model in frequency domain in order to obtain the accumulated fatigue damage in closed form for slender vertical structures subjected to alongwind, crosswind and directional gust-excited vibrations. This is done by taking into account the probability distribution of in-site mean velocity and determining the histogram of the stress cycles by applying a probabilistic counting method of the cycles to an analytical solution of the dynamic response.

In 23, Petrov executed the calculation of the fatigue life of a tower-shaped steel monument with height of 64.8 m. The wind load was applied by applying statistically independent exciting wind load approach, which means that stress fluctuations of the static, resonant and quasi-static stresses in the structure are assumed to be statistically independent processes.

# Turbulence models for CFD

In the previous paragraphs, many examples of fatigue analyses of steel structures subject to wind action have been shown. In real, complex cases, the effect of wind-induced fatigue is usually evaluated with the aid of a wind tunnel test, while simplier geometries can be approached analytically. While wind tunnel tests can be used to determine wind-induced fatigue loads, CFD simulations have not yet been used for this purpose. Extensive literature is available on CFD analyses of civil structures subject to wind, or more generally on the study of the bluff body invested by highly separated external flow so it is possible to infer about their usability for fatigue scope.

A brief theoretical introduction about turbulence models for CFD is reported below, together with a series of corresponding practical applications from literature regarding wind flow around bluff bodies of practical interest.

The following is a selection of turbulence models for which relevant applications are available in literature. For an extensive review of turbulence approaches the interested reader is directed to papers such as, for example, Argyropoulos and Markatos 24.

## Theoretical framework

Navier-Stokes equations provide every information about all the features of a turbulent flow.

In general, Navier-Stokes equations for homogeneous incompressible fluids of constant viscosity can be expressed as:

 (1)

 (2)

As shown by many 24–26, limitations in computational power make it impossible for now and the foreseeable future to provide a complete solution to the equations in complex turbulent flows of practical interest.

This is due to the fact that turbulence is by nature an irregular condition of flow, with strong nonlinearity and large width in the scales of length, time and velocity.

The use of mathematical models that simulate the physics of turbulence without analytically resolving Navier-Stokes equations is thus necessary, and in practice this affects the ability of the computational method of describing wind spectral components that potentially have effects on the building. The different approaches to turbulence modeling differ fundamentally in this ability, by changing the portion of turbulence which is described by solving Navier-Stokes equations against the portion that is instead modeled.

The three major classes of models are:

* DNS (Direct Numerical Simulation): Navier-Stokes equations are numerically simulated at all length and at all scales and therefore no turbulence model is used. Its computational requirements are far too high for any practical application.
* LES (Large Eddy Simulation): the major vortices are analytically solved while sub-grid eddies are described with sub-grid models.
* RANS (Reynolds Averaged Navier-Stokes): the entire flow is averaged and the turbulence is modeled using various approaches, reducing the physical complexity of turbulent flow and, thus, accuracy.

Between these classes are also present many other models that aim to realize improvements in the description of the physics while obtaining reduction in computational cost. An ample review of hybrid RANS-LES models has been provided in the paper of Fröhlich and von Terzi9. Some of the most successful hybrid approaches are:

* VLES (Very Large Eddy Simulation) 27;
* DES (Detached Eddy Simulation) 28;
* PANS (Partially-Averaged Navier-Stokes) 10.

In recent years, *Partially Averaged Navier-Stokes* methods proposed by Girimaji et al. 10 have gained appreciation for their ability to improve the evaluation of fluctuating components of the flow at reasonable computational cost and for its easy implementation into existing RANS solvers 9 and many researchers are foreseeing its adoption for industrial purposes 29.

## Reynolds-averaged Naver-Stokes (RANS) models

RANS models have been for many years the only tool available to calculate the features of a turbulent flow in relevant, complex applications 30. The fundamental concept of RANS methods lies in Reynolds decomposition of Navier-Stokes equations: turbulent flow is described as a random variation around a mean value.

The Reynolds-averaged Navier-Stokes equations can be written as 31:

 (3)

while time-averaged mass-conservation is identical to the instantaneous:

 (4)

In RANS equation the quantity  is known as the Reynolds Stress tensor, .

The unknowns are 10: one pressure, three velocity components, six Reynolds stress tensor components, while the equations are four. In order to solve the problem, it is necessary to introduce more equations. This is called the “closure problem” and the system is resolved with the aid of turbulence models*.*

Hanjalic26 defines the major requirements and expectation over a turbulence model such that the model should be able to mimic faithfully the flow and turbulence physics in a broad range of flow situations, to satisfy mathematical rigor and physical constrains, to be manageable with relatively simple numerical methods and to serve as a computational tool for predicting new complex flows. Most critical physical effects are typically flow separation and recirculation, unsteadiness, wall proximity, three-dimensionality, swirl, rotation, streamline curvature, extra strain rate and buoyancy. In case of buildings and large structures the focus should be on the flow phenomena of separation, unsteadiness, wall proximity and three-dimensionality.

At the moment there is no turbulence model which is able to accomplish perfectly all these features, but many have proven to be reliable and effective in complex flows.

## Standard k-ε model

### Theoretical framework

The most popular two-equation model is the Standard  model and is based to the physical hypothesis that the production of dissipation should be proportional to the production of turbulent kinetic energy. The following equations define a Standard  model:

 (5)

 (6)

 (7)

 (8)

The constants assume the following approximate values of , , , , .

### Practical applications

*Standard k-ε* is one of the most widely adopted turbulence models and thus a very large literature of test cases for this turbulence model is available, also in relation to buildings and large structures. Despite its popularity this model is also known for its defects, which have been highlighted by many relevant authors. Among them, in AIJ guide for numerical prediction of wind loads on buildings 8 and in 32, the model has been reviewed for the case study of a steady wind flow over a cubic low-rise building: for a wind angle normal to windward face, the model greatly overestimates turbulent kinetic energy *k*, and consequently the surface pressure distribution, in the impinging region around the frontal corner of the roof; it also shows limited ability to reproduce correct flow physics as the flow separation from the frontal corner of the roof is not reproduced. For a wind direction 45°, the model cannot reproduce the conical vortices, which can be observed in wind tunnel.

In 33 the model was used to calculate the time dependent wind load on the Commonwealth Advisory Aeronautical Council (CAARC) standard tall building, which is a relevant validation case. The authors reported that this turbulence model led to a drag coefficient 20% lower than reference results, with an over-prediction of pressure distribution on the front face and an under-prediction of pressure distribution on the back face. As expected, the model proved to be unsuitable for evaluating the fluctuating features of the flow.

Because of these deficiencies, relevant guideline papers such as Franke et al.34 have discouraged the use of the *Standard* *k-ε* model in the simulation of wind engineering problems in favour of more advanced linear or non-linear eddy viscosity models.

## Modified k-ε models

### Theoretical framework

The coefficients for the standard *k-ε* model were devised specifically to predict certain low-Reynolds-number phenomena in boundary layer and duct flows35. Since the first introduction of the model, many of its weaknesses in more complex flows have been outlined, such as excessive production of turbulent shear stress and excessive levels of turbulence in stagnation and impingement regions.

The *standard* *k-ε* model is therefore generally considered unsuitable for wind engineering studies of buildings especially for cases with high separation8,34, which are very frequent in case of large steel structures exposed to wind.

However the large CPU time requirements of more sophisticated CFD approaches such as DNS and LES make them unfit for an application to many wind engineering problems of practical interest. In order to stay in RANS framework, various authors have proposed improved versions of the *standard k-ε* model to overcome the deficiencies of the original model without compromising its simplicity: other closure models differ essentially by the choice of the modeled equations along with the equation of turbulent kinetic energy.

- *Realizable* *k-ε* model 36 uses a different eddy-viscosity formulation based on the realizability constraints, the positivity of normal Reynolds stresses and Schwarz’s inequality for turbulent shear stresses. In fact, it can be shown that in *standard k-ε* if the strain is large enough, the normal stress, which is a positive quantity by definition, becomes negative and the Schwarz inequality for shear stresses can be violated. In order to fix this, the coefficient *Cµ* is variable, in opposition to *standard* *k-ε*. This model improved the performance of the standard *k-ε* model in various flows including jets, mixing layers, channels, boundary layers, separated flows, and completely removed the spreading rate anomaly of planar and round jets.

- *Renormalization Group (RNG) k-ε* 37model is a modification of the *standard k-ε* model, which uses the same equation of original model but uses a variable definition of the *Cε2* coefficient. This model allows to improve the prediction of the recirculation length in separating flows.

- *MMK (Murakami-Mochida-Kondo) k-ε* 32model was developed on the basis of Launder-Karma (LK) modification and aimed at the elimination of turbulence overproduction at the impinging region by correcting the production term where and is replaced with where , and

*- Durbin k-ε* 38: this modification addresses the stagnation anomaly with impinging flows by relating the eddy viscosity to the turbulence velocity scale: .

### Practical applications

*Realizable (Shih) k-ε* model was first validated in Shih’s paper 36 with a set of unified model coefficients in elementary flows such as rotating homogeneous shear flows, boundary-free shear flows, channel and flat boundary layer flows and backward facing step separated flows. In all these test cases the model has shown significant improvement over *Standard* *k-ε* model. The model was also used for modelling flow over more complex structures although much of the studies were steady state.

In 39, the authors compared the results of realizable model against *k-ε V2-f* and *Wilcox k-ω* for the case of a wall-mounted rectangular cylinder. The model provided the best results among the three, and the authors proved its ability to capture the mean flow of the complex flow patterns.

In 40 the model was used to calculate aerodynamic drag and lift force coefficients and their variations with angle of wind incidence in case of rectangular and H-sections. While the model provided a good prediction of slope of transverse force coefficient for rectangular and H sections, deviations have been observed for increasing values of B/D and for increasing values of angle of wind incidence. The authors explained these deviations as probably due to limitations even in improved RANS based models.

The model was also used in 41 for the assessment of the aerodynamic behavior of two self-oscillating bridge sections. The authors observed that the model is able to accurately predict aerodynamic behavior in a weak irregular turbulent flow, but in strong irregular turbulent flows the accuracy decreases.

The *Realizable k-ε* model were used in many other studies and its adoption for wind engineering applications is suggested in Franke’s paper 34.

The *MMK k-ε* model improves the prediction of turbulent kinetic energy and eddy viscosity for a bluff body field. Huang 42 uses this model to calculate the flow around the standard tall building CAARC obtaining a good estimate of mean pressure coefficients and of rms of lift. The results for the mean values of force coefficients have been proven consistent with the experiment, but the reproduction of the spectrum is not complete due to the basic hypothesis of RANS approach (Fig.2). This can be clearly observed also in time histories of drag forces obtained with different turbulence models (Fig. 3).

The use of *MMK* is also suggested in AIJ paper 43 although it underestimates the experimental result in case of low-rise buildings.

In 44 *MMK k-ε* and *Durbin’s revised k-ε* models were compared for the case of the flow around a high-rise building. In this cross comparison, the model proposed by Durbin showed the closest agreement with the experiment.

## Standard k-ω model

The *k-ω* model 31 utilizes the equations of turbulent kinetic energy and specific dissipation rate for the closure of RANS equations. The advantages of this model over the *standard k-ε* are above all higher accuracy in both separated flows and free shear flows and it is therefore more applicable for use in complex flow. The equations of kinematic eddy viscosity, turbulence kinetic energy and specific dissipation rate are:

(9)

(10)

(11)

For the closure coefficient and auxiliary relations, the interested reader is directed to the original paper.

The major drawback of this model is its sensibility to flows with free-stream boundaries.

## Eddy viscosity models

Non-linear eddy viscosity models have been developed and implemented in commercial CFD software with the aim of improving the near-wall turbulence description.

Durbin’s model 35 is based on the elliptic relaxation concepts and introduces two equations, additional to and . model 45 is very similar to Durbin’s model, as it solves for the velocity scale ratio making the model more robust and less sensitive to grid nonuniformities.

## Large eddy simulation (LES)

### Theoretical framework

In LES, the large eddies are fully resolved and the smallest, subgrid-scale eddies are modeled. Instead of time-averaging, the resolved (large-eddy) field is separated from the small-eddy (sub-grid) field by using a spatial filtering and providing the following governing equations:

 (12)

where

 (13)

 (14)

 (15)

Smagorinsky developed a model for the SGS stresses assuming that they follow a gradient-diffusion process similar to molecular motion, whose governing equations are:

 (16)

 (17)

where the Smagorinsky eddy viscosity:

 (18)

and *Cs* is the Smagorinsky coefficient.

The accuracy of LES is much dependent on the use of an accurate SGS stress model and in the correct representation of boundary conditions.

### Practical applications

LES has been proven to be capable of providing accurate predictions of wind effects on structures in atmospheric boundary layers which are comparable to wind tunnel experimental data 7. In fact, one of the most relevant advantages of LES over RANS consists in the fact that LES is able to resolve both energy containing spectral subrange and a large part of inertial subrange, while dissipation subrange is modeled, and this allows the introduction of inflow turbulence which follows the von Karman model, the same way it is done in wind tunnels. This is crucial, as wind speed fluctuations in atmospheric boundary layer obeys the von Karman model and this spectrum is used by major wind Standards.

Two examples of development of general inflow turbulence generators are in 46,47.

Many applications of LES are present in literature:

* In 7 the use of LES on many wind engineering problems was reviewed, showing its ability in providing accurate predictive values which well match wind tunnel experimental data.
* In 33,48–50 the flow around standard tall building (CAARC) with/without flow generation models and with/without surrounding buildings was studied using LES and compared against other CFD approaches and wind tunnels. The results of these studies indicated the ability of LES to evaluate steady and unsteady features of the flow, including an accurate description of wind load spectra (Fig. 4). In particular, in Zhang et al. 49 paper, the analysis of wind-induced vibrations were performed by coupling CFD and structural modal analysis proving good agreement with maximum displacements of the wind-excited structure.
* Other successful application include 51,52, where LES analyses of flow around bridge section were performed proving good agreement with the experimental results both on steady and unsteady characteristics, and 53, where the flow field around a large roof was studied and mean and rms pressure coefficients was correctly evaluated.

The ability of LES methods to predict stationary and unstable flow characteristics is now well established in literature. However, their applicability in industrial CFD and, in general, to the outside of the research field remains a topic of discussion. In fact, while on the one hand papers such 7 about a decade ago envisioned a broad use of LES as a tool with reasonable computational cost, other, more recent works 12 observe that even though LES has been more frequently used in the last years, its use is still for benchmarks or visibility studies because of high computational costs and that LES have to be carefully analyzed in order to accept the results, which could represent an obstacle for everyday use in industry.

**Partially Averaged Navier-Stokes (PANS) models**

*Theoretical framework*

Partially Averaged Navier-Stokes is a bridging method that allows for a seamless and smooth transition from RANS to DNS, depending on the values of the filter-width control parameters 10. The filter-width control parameters represent the ratio between unresolved to total kinetic energy and dissipation (in case of PANS *k-ε*). When the filter-width control parameter are equal to unity, the results of the parent RANS model are recovered; when it is equal to zero, Navier-Stokes equations are entirely resolved. As the PANS model is developed on the basis of a parent RANS closure, its performance are affected by the goodness of the parent RANS.

Starting from a *standard* *k-ε* as in original paper by Girimaji, which is expressed by:

(19)

(20)

(21)

Where and are the RANS production and dissipation. The constants are those shown above for the *standard* *k-ε* closure model*.*

The filter-width control parameters are defined as:

 (22)

(23)

where  is the ratio of the unresolved () to total () kinetic energy and is the ratio of unresolved () to total () dissipation.

Applying PANS approach, the equation of the total kinetic energy becomes:

(24)

Where the production term is defined as:

(25)

And the transport term is defined as:

(26)

And the unresolved kinetic energy Prandtl number .

Since the original development of Girimaji, other PANS models have been developed starting from different turbulence models, among which PANS 54 and PANS 55.

### Practical applications

These models have shown good results over the last decade, with results comparable to even the most computationally demanding LES models and have been widely tested on test cases.

In 56 a two-stage RANS-PANS simulations was performed to simulate the flow past a square cylinder. First, a RANS simulation allowed for the determination of the initial value of control parameter *fk* in each cell by calculating the distribution of turbulence length scale and Kolmogorov length scale. Then PANS simulation is started and the control parameter is constantly updated over time. The results of the simulation, including time series and rms of fluctuating velocities, are generally in good agreement with experiments and they show a low grid-dependency.

In 57 a PANS simulation is perfomed for the flow around a two bluff bodies. The PANS model is developed on the basis of a *k-ε-ζ-f* model and the control parameter *fk* is dynamic, being updated at the end of every time step for each point. In the first simulation the flow around a surface mounted cube is computed. The results of PANS using a coarse grid are similar to Unsteady RANS while as the grid is refined the PANS flow structures become similar to those provided by LES.  
The use of PANS for computational wind engineering purpose has also been reviewed in 50, where the authors remarked the need to provide further insight on its cost effectiveness and prediction accuracy.

# Fatigue assessment on complex structures

Global approaches, and in particular nominal stress, or sometimes hot spot stress, are, to date, the most commonly used methods for the fatigue design of welded joints, together with a series of classified structural details and related S-N curves, as discussed by Hobbacher 58,59. Nominal stress is the basis of most codes (IIW recommendations 60, Eurocode 3 61) and has been accepted by major industries. Despite this, even though it is conceptually easy to define by the classical principles of beam theory, there is no clear definition of nominal stress, nor recommendation on how to derive this value from the finite element stress plot, which provides local stresses 58,59. Hobbacher observed that the lack of any local concept in several new fatigue design codes leaving the determination of the nominal stress from FEA results to the engineering assessment of the designer.

As hot spot stress based approaches are known to require complex conditions on mesh generation as shown in 62 (Fig. 1) and are not as widely accepted as the nominal stress, many local approaches have been developed in the last two decades. Some of the most relevant methods are the effective notch stress method, as formulated by Radaj63, the notch stress intensity approach 64 and the strain energy density (SED) approach has been formulated by Lazzarin and Zambardi 65. Compared to other methods, SED approach does not require extremely refined meshes while maintaining its robustness.

# Discussion and conclusions

## CFD as a tool to evaluate wind-induced fatigue cycles

The approach to the study of wind-induced fatigue in large and complex structures appears to be fragmented both from the scientific and the regulatory point of view and such topics are not entirely covered by standards, in particular when numerical simulations are involved. In the case of complex structures, the only tool currently available for the evaluation of loads is the wind tunnel, but due to the time and costs it is difficult to frame this type of study in design activities, especially at the initial stages. Until now, CFD has not found an industrial application with regard to the assessment of wind-fluctuating loads to conduct this type of analysis. In fact, in order to evaluate a correct structural response, it is necessary to describe all relevant spectral subrange and only advanced CFD models can be employed.

This review has shown that computational methods are beginning to respond to the needs of wind engineering: there are many studies in literature that have shown good adherence between the structural dynamic response obtained with CFD models and the one obtained experimentally. In literature, many LES models have been coupled with custom inflow turbulence generators which were able to introduce in computational wind field a natural wind which well describes von Karman spectrum and which provides appropriate spatial correlation (Fig. 5). The ability of these models to correctly describe the turbulent eddies in the inertial subrange is of great significance as turbulent eddies in the inertial subrange have relevant effect on wind-induced fluctuating loads on buildings and structures. Although its use has increased in recent years, LES remains difficult to apply in industrial context due to the high cost and the need to analyze its results carefully.

While in LES only the small, isotropic turbulent scales are modelled, RANS models the entire spectrum. Although RANS models have been the only computational tool available for assessing mean wind forces for many years, they do not find direct applicability in evaluating complex fluctuating phenomena.

As an alternative to LES, bridging models such as PANS are obtaining more and more approval. PANS models resolve analytically only a predefined part of the fluctuating scales by tuning the parameters of the unresolved-to-total kinetic energy and dissipation (or specific dissipation, in case of *k-ω* PANS models) and they reduce computational efforts while providing good results in time-dependent analyses. As PANS models can be developed on the basis of particular RANS turbulence models, multiple choices could be made about the choice of used turbulence model for the development of a PANS model suitable for an application in large steel structures. The adoption of *standard* *k-ε* as a basis for a PANS model is not recommendable; as modified *k-ε* models such as *Durbin’s* *v2-f,* *MMK*, *Realizable*, or *k-ω* are able to provide generally good results in cases of interest for external separated flows, they represent a better choice and, in fact, some analyses have already been carried out with such improved models showing positive results. Further research must be performed for PANS models regarding the description of natural wind and its utilization for wind engineering application.

For an industrial overview of CFD it is necessary to observe that almost all CFD studies in literature involve simple structural geometry such as, standard tall buildings with rectangular section, low-rise buildings modelled as cubes, cylinders. Most of the studies related to fatigue are also relative to relatively simple cases in terms of geometry and dynamic response.

The introduction of complex geometries of engineering interest does not only require a larger operative effort, but also causes a rise in the complexity of the flow phenomena and, consequently, the need to perform wind tunnel tests or higher-resolution CFD studies.

In general, the use of CFD methods for the calculation of wind-induced fatigue loads in buildings with the methods currently available appears to be already potentially achievable, if advanced LES models with inflow turbulence generators are employed; in order to adopt it as an independent tool for industrial and complex applications as well, it will require further efforts for future development, focusing in particular on the development and validation of stable and accurate hybrid methods.

## The complete chain

On the basis of the current literature review, the key parts composing a complete chain that leads to a numerical evaluation of wind-induced fatigue starting from CFD are here briefly identified:

* The dynamic pressures on the structure must be evaluated using an adequate CFD modelling technique, in reference to multiple directions and at different wind speeds.
* Wind pressures should be applied to a FE model, evaluating the resonant component in addition.
* A rainflow cycle-counting algorithm must be applied to stress time histories.
* The result must be scaled integrating climatic measurements to extend the number of cycles given by the tests to the total number of cycles that the structure undergoes throughout its life.
* Finally, fatigue check can be performed.

The application of cycle counting algorithms to stresses in the various locations of the structure, such as weldings and connections, requires adequate computational power and, possibly, the use of submodeling techniques.

Many methods for calculating fatigue usually require FE models with very refined meshes, are difficult to combine with large and complex structures. The adoption of fatigue methods that allow to use coarser meshes is therefore advisable. Even so, it remains a difficult challenge to apply these criteria on massive fatigue investigations in large structures with thousands of welds. It is also the view of the authors that in a structure characterized by thousands of elements that must be tested against fatigue, workflow for fatigue calculation should be ideally as automatic as possible.

It is possible to observe that, as of today, no major breakthroughs are necessary to actually develop a complete procedure, both from CFD side and from fatigue side; still, significant development is needed in order to keep the numerical burdensome acceptable.

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