Turbulent wind flow through permeable claddings mounted on elevated scaffold using CFD simulation

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Abstract
An extensive numerical study was carried out to evaluate the turbulent wind effects on permeable nets and impermeable film claddings mounted on elevated access scaffolding using computational fluid dynamics techniques. Debris net/sheet scaffold cladding was placed at a distance 1.5 m ahead of the cubical building. Permeable nets of various porosities and aerodynamic coefficients were simulated, and the effects of aerodynamic coefficients on the pressure coefficients were studied on the scaffolding. The airflow behavior around and through the claddings and the cubical building, were also investigated. Permeable claddings have been modeled as porous media following the Forchheimer equation. The renormalization group $k$–$\varepsilon$ turbulence model using Reynolds averaged Navier–Stokes equations (RANS) was used to simulate turbulent wind through/around the scaffold cladding. Commercially available software ANSYS FLUENT 6.3 was used for simulation and analysis. Results showed that the force/pressure coefficients on permeable/debris net claddings are proportional to the aerodynamic coefficient.

KEYWORDS
debris nets, impermeable film, permeable nets, RANS, scaffolds

1 | INTRODUCTION

When wind passes through the permeable barrier, pressure rises on the windward side, and on the leeward side, it declines, thus retards the wind flow approaching the permeable barrier. The permeable barrier is called a windbreak as it considerably decreases approaching wind velocity.\(^1\)

The use of permeable net (as a debris net) and impermeable film (as windproofing) has been increased in the recent past as cladding material over scaffolding structures. The scaffolds are widely used globally to provide support and access for many permanent and temporary works during various construction phases. The cladding provides debris containment and protects both workers and passersby from falling debris, as well as shields from extreme weather to the structure and workers. Scaffold structures are vulnerable to damage or collapse due to high wind since cladding further raises the wind load on the scaffold. Several incidents of the collapse of scaffold due to wind have reported over the recent decades, one of which scaffold failure during restoration work of Uppark House in Surrey, which took a toll of two lives on 25 January 1990 (BBC News).\(^2\) High wind from typhoon Lan claimed a passerby’s life due to the collapse of scaffolding at the construction site in Fukuoka, southwestern Japan, on 22 October 2017 (Japan Times).\(^3\)
The U.K. Health and Safety Executive published a few reports of casualties and damage to both scaffolds and building structures during storms and high winds. Therefore, determining the forces induced by wind is essential for the safe design of scaffolds with claddings. Very little published research is available on the wind-induced loads on scaffolds. Most of the past researches aimed at understanding the behavior of scaffold under dead and live loads. Few experimental and numerical studies on aerodynamic behavior and distribution of wind pressure over the permeable net claddings mounted on scaffolds carried out in the past.

A conference on the wind-induced loads on the scaffold structure, was held by the U.K. Health and Safety Executive (HSE, 1994). Various research papers including wind damage by Blackmore, design of net clad structures by Williams full-scale tests by Hoxey, and wind-tunnel tests by Schnabel were presented in this conference. Methods to determine wind-induced loads on sheet clad scaffolds while considering it as permanent structure are included in British Codes BS EN 12810-2, BS EN 12811-1, and BS EN 12812.

To determine wind loads on temporary structures, a limited study using the computational fluid dynamics (CFD) technique has done so far. Yue et al conducted wind-tunnel tests to determine the pressure coefficients and wind-induced vibration effect on high-rise scaffold structures and concluded that the wind-induced effects are underestimated in Chinese code CNS-4750. Amoroso et al conducted the wind-tunnel experiments and reported wind effect on partially clad structures, whereas Giannoulis et al investigated the wind behavior around standalone elevated permeable panels using both the field study and numerical simulation.

However, wind-tunnel test for permeable nets is quite challenging to perform since it is hard to achieve scaled aeroelastic characteristics of the nets. A scale of 1:50 will lead to the thickness of the net almost negligible and the scaffold structure's width to be less than 1 mm and having almost no stiffness. Fixing pressure taps on scaled net/sheet cladding is also nearly impossible. CFD is, therefore, a desirable low-cost option. Despite that, Irtaza et al experimentally determined the pressure distribution over the clad scaffold around the cubical building at a modeled scale using an atmospheric boundary layer wind-tunnel experiment. A 6 m cubical building modeled at a 1:30 ratio with 1 mm thick plastic sheet as cladding, and 61 pressure taps used. A 33.33 mm elevated sheet clad at the modeled scale (1 m elevated at full scale) was also analyzed. The maximum net pressure coefficient was found to be 1.63 for a windward faced fully covered sheet clad scaffold, whereas the maximum net pressure coefficient was found to be 1.57 for windward faced elevated sheet clad scaffold. In another study, Irtaza et al performed CFD simulation for the two permeable net-type clad scaffolds around the Silso building cube. The models were verified using full-scale data from the Silsoe experimental site and wind-tunnel investigations of the permeability of scaffold nets. The study has observed that the Eurocode provisions for the net clad scaffolds are justifiable for the pressure coefficients on windward and side faces.

Higher computation technology developments have made it possible to solve the flow problem mathematically described by a set of coupled non-linear partial differential equations and the suitable boundary conditions in a comparatively short time with a low monetary cost.

The present study aims to determine the wind force coefficients/net pressure coefficients on the several raised permeable nets and impermeable film cladding on scaffolding provided at the front of the low-rise cubical building. The present work also analyzes the behavior of airflow around the elevated permeable and impermeable claddings. The methods used by Irtaza et al to simulate airflow through permeable net were utilized in the present study. In this study, nine different permeable nets of known porosity and aerodynamic coefficients have been used. 3-D numerical simulations were performed by incorporating CFD techniques using commercially available software ANSYS FLUENT 6.3 (Fluent). Reynolds averaged Navier–Stokes (RANS) Renormalization group (RNG) $k$–$\varepsilon$ turbulence model was used to determine the pressure coefficients on the outer and inner face of both net and sheet clad scaffolds. Porous jump boundary conditions were used to simulate permeable nets and were modeled as porous media.

In the present study, airflow behavior through clad scaffold on stand-alone low-rise building is taken into consideration. However, the effect of other buildings in surrounding can also influence wind flow behavior over the scaffold and the concerned building, increasing or decreasing the wind pressure over the concerned structure. The effect of surrounding structures on wind pressure intensity is significant in the urban settlement with high-rise buildings, whereas surrounding low-rise buildings in semi-urban regions impart the variation in pressure intensity over building in concern at low intensity.

The work here presented is part of the master's thesis by the corresponding author under the guidance of the co-author.
2 | MODELING AND SIMULATION

2.1 Method and materials

CFD model incorporated addition momentum source term based on Forchheimer’s equation in the flow equation to simulate flow through porous media. The momentum source term contributes to the pressure gradient in the porous region, inducing pressure drop, which is proportional to the flow velocity in the region. In the turbulent flow model, the momentum source term, consisting of viscous loss and inertial loss terms, is added in the momentum equation of Navier-Stoke’s equations (Fluent18).

Governing Navier-Stoke’s equations, comprising of momentum conservation equation, utilized by RANS model, consisting source term for the permeable region, is as follows:

\[
\frac{∂}{∂t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \left( \mu \left( \nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla (\vec{v} \cdot \vec{v}) \right) + \rho \vec{g} + \vec{S}
\] (1)

where source term,

\[
\vec{S} = -\left( \sum_{i=1}^{3} D_i \mu v_i + \sum_{i=1}^{3} \frac{1}{2} C_{2i} \rho |v| v_i \right)
\] (2)

Equation (2) represents the momentum source term in three-dimensional aerodynamic coefficient matrices \((D_i, C_{2i})\). For the case of a unidirectional airflow through thin homogeneous porous media, Equation (2) can be simplified as follows:

\[
S_i = -\left( \frac{\mu}{D} v_i + \frac{1}{2} C_{2i} \rho |v| v_i \right)
\] (3)

Equations (2) and (3) representing the Forchheimer equation,\(^{19}\) which can be further simplified in terms of pressure drop, \(\Delta p \text{ (N/m}^2\text{)},\) across \(\Delta x \text{ (m)}\) thick porous media and shown in the following equation.

\[
S = \frac{\Delta p}{\Delta x} = -\left( \frac{\mu}{D} v + \frac{1}{2} C_{2} \rho v^2 \right)
\] (4)

For a thin permeable panel

\[
\Delta p = -(\beta v + \alpha v^2)
\] (5)

where,

- \(S_i\) = Source term for the momentum equation,
- \(v\) = Velocity (m/s),
- \(D\) = Specific Permeability of material (m\(^2\)),
- \(C_{2}\) = Aerodynamic resistant coefficient (m\(^{-1}\)),
- \(\mu\) = Dynamic viscosity (kgm\(^{-1}\)s\(^{-1}\)),
- \(\rho\) = Fluid density (kg/m\(^3\)),
- \(\Delta p\) = Pressure drop (N/m\(^2\)),
- \(\Delta x\) = thickness of porous media (m),
- \(\alpha\) (Ns\(^2\)/m\(^4\)) and \(\beta\) (Ns/m\(^3\)) are the aerodynamic coefficients and can be determined by wind-tunnel measurements.

Specific permeability (\(D\)) and aerodynamic resistance coefficient (\(C_{2}\)) are inputs in CFD simulation and were determined using aerodynamic coefficients \(\alpha = \frac{1}{2} C_{2} \rho \Delta x\) and \(\beta = \frac{\mu}{D} \Delta x\).

The permeable nets were modeled as porous media in CFD simulation. Each permeable net types have different flow resistance parameters known as aerodynamic coefficients (inertial and viscous coefficient). Aerodynamic coefficients of individual net-type were empirically determined and reported by Hemming et al\(^{20}\) Nine commercially available nets were used as cladding materials in simulations and are specified in Table 1 with respective aerodynamic coefficients and porosity. The values of aerodynamic coefficients mentioned in Table 1 for the respective permeable nets were measured.
TABLE 1  Porosity and aerodynamic coefficients of various permeable nets

| Net type   | Porosity (%) | Aerodynamic coefficients |        |        |
|------------|--------------|--------------------------|--------|--------|
|            |              | α (Ns²/m⁴)               | β (Ns/m³) |       |
| OMBVRD70   | 22           | 7.3                      | 1.45    |        |
| WTAPE      | 38           | 3.02                     | 0.12    |        |
| SC75       | 38           | 0.76                     | 0.98    |        |
| LIBS50     | 46           | 0.79                     | 0.86    |        |
| OMBVRD50   | 54           | 0.94                     | 0.30    |        |
| SCMD       | 62           | 0.36                     | 0.50    |        |
| FR 25/26   | 82           | 0.12                     | 0.12    |        |
| Type A     | –            | 0.524                    | 1.082   |        |
| Type B     | –            | 1.238                    | 2.249   |        |

by Hemming et al. and Irtaza et al. using wind-tunnel experiments. These permeable nets were successfully used and simulated to analyze wind effects through elevated windbreaks by Agarwal et al. In the present study, the effect of different permeable and impermeable clad on pressure drop over the elevated clad scaffold and cubical building in the scaffold’s leeward side was studied using CFD simulations.

2.2 | Numerical simulation

Wind flow through the elevated scaffold structures was simulated by ANSYS FLUENT 6.2.16, and a 3D computational domain was modeled with an elevated scaffold (1.5 m raised above ground) of size 4.5 m in height and 9 m in length mounted 1.5 m ahead of 6 m cubical building.

The thickness of nets is in the range of 0.2–0.4 mm, which is computationally costly to model and mesh. While simulating porous material, the parameters $D$ and $C_2$ in Equation (4) are necessary inputs. We adjusted the $D$ and $C_2$ parameters to yield the experimental $\alpha$ and $\beta$ coefficients using the cladding thickness in our CFD model. As the aerodynamic coefficients ($\alpha$, $\beta$) are known parameters shown in Table 1, the permeable net thickness ($\Delta x$) can be selected arbitrarily, and $D$ and $C_2$ can also be determined using Equations (4) and (5), respectively. Since $\alpha$ and $\beta$ are invariant of permeable media thickness ($\Delta x$), choosing arbitrary thickness does not influence air permeability of the modeled net, but it may influence the aerodynamic behavior. Thus, the thickness of the permeable net should be small compared to the scaffold height so that the clad scaffold panel sustains its 2D behavior. 25 mm thick net cladding was modeled, which is having an aspect ratio (height/thickness) of 180.

The elevated clad scaffold with the cubical structure in its leeward side was simulated as an orthogonal barrier, which is normal to the wind flow within the 3D computational domain. Figure 1 represents the computational domain having the dimension of 120 m (in the X direction), 36 m (in the Y direction), and 45 m (in the Z direction). The scaffold frame
was placed 18 m apart from the domain inlet and was 1.5 m elevated above the ground surface. A cubical building of size 6 m was placed 1.5 m away on the scaffold’s leeward side.

Eight different cases with different nets and sheet clad scaffold panels were simulated. A Cubical building was also analyzed for turbulent wind, both with and without scaffold attached. The core of the domain consisting of scaffold and the cubical building was discretized in 3D tetrahedral elements, whereas hexahedral elements were provided outside the core in the computational domain. Hexahedral elements were also provided within the permeable net panel, whereas the impermeable film was modeled as an impermeable elevated wall with no element within the sheet clad panel. Hexahedral elements are recommended for improved refinement, convergence, and efficient simulation. Figure 2 shows the computational domain in different projections. The y–z faces of the scaffold have meshed uniformly, and the height and width of the panel were divided into 32 and 45 elements, respectively. Effective simulation of a permeable material requires a more refined meshing along with thickness porous media. Four elements were provided along with the thickness of the permeable net panel.

**FIGURE 2** Overall grid distribution of the computational domain in different views and mesh quality
For simulation, both the standard $k-\varepsilon$ and the RNG $k-\varepsilon$ turbulence models were used. Turbulent kinetic energy is overestimated while incorporating the standard $k-\varepsilon$ turbulence model. Overestimation of turbulent kinetic energy is intense in regions of higher velocity variation, like flow separation region, and in the present study occurs at the edges of impermeable panels and building edges. Turbulent kinetic energy dissipation more effectively treated using the RNG $k-\varepsilon$ turbulence model. Standard $k-\varepsilon$ turbulence model assumes a uniform dissipation rate for all eddies irrespective of size, whereas in the RNG $k-\varepsilon$ turbulence model, some eddies are filtered out.

Inputs for inlet velocity in the computing domain were taken as an atmospheric boundary layer (A.B.L.) with 10 m/s inlet velocity at 10 m gradient height with 10 mm aerodynamic roughness length representing open terrain. Data for simulated wind profile and turbulent intensity were drawn from Texas Technical University (T.T.U.) field data modified by Ahmad and Kumar\textsuperscript{22} for boundary-layer wind-tunnel tests on hip roof buildings in at I.I.T. Roorkee, India. To obtain the equilibrium Atmospheric Boundary Layer (A.B.L.), the calculated turbulent kinetic energy profile is matched with Shakeel's profile (Ahmad and Kumar\textsuperscript{22}) based on the T.T.U. velocity and turbulent intensity.

Power law coefficient, the longitudinal turbulence intensity, and integral length scale having values 0.15, 18\%, and 0.45 m, respectively, were used for the inlet boundary condition.\textsuperscript{22} A user-defined function was incorporated to provide the atmospheric boundary layer profile as an inlet velocity. No-slip wall condition was provided over impermeable film cladding surfaces, whereas; porous jump boundary condition was provided over the surfaces of permeable net clad panels. Pressure outflow boundary condition was provided at the outlet of the domain, which implies zero pressure to simulate an open wind-tunnel end. The symmetry condition was provided over the top and sides of the computational domain and was assumed to be a frictionless barrier.

\section{RESULTS}

The net pressure coefficient over the scaffold cladding, $C_{p_{\text{net}}}$, is the difference between the area-weighted average of pressure coefficient at the windward surface, $C_{p_{\text{windward face}}}$, and the area-weighted average of pressure coefficient at the leeward surface, $C_{p_{\text{leeward face}}}$.

$$C_{p_{\text{net}}} = C_{p_{\text{windward face}}} - C_{p_{\text{leeward face}}}$$

Area-weighted average of net pressure coefficients over the clad surface for both the standard and RNG $k-\varepsilon$ turbulence model are shown in Table 2. The net pressure coefficient for the impermeable film was found to be overestimated in Standard $k-\varepsilon$ turbulence model simulation on comparing with the RNG $k-\varepsilon$ turbulence modeling. Similar net pressure coefficients were obtained for the permeable nets in the Standard $k-\varepsilon$ and the RNG $k-\varepsilon$ turbulence model simulation. The standard $k-\varepsilon$ turbulence model provides a realistic outcome when flow does not create large vortices around the structure. Since permeable nets suppress vortices’ formation at the edges, the Standard $k-\varepsilon$ model does not overestimate the pressure over the leeward permeable net surface due to the absence of large eddies.

\begin{table}[h]
\centering
\caption{Net pressure coefficients for cladded on scaffold mounted ahead of cubical building}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{Cladding type} & \textbf{Porosity (\%)} & \textbf{Aerodynamic coefficients} & \textbf{Net coefficient of pressure $C_{p_{\text{net}}}$} \\
 & & $\alpha$ (Ns$^2$/m$^4$) & $\beta$ (Ns/m$^3$) & \textbf{Steady standard $k-\varepsilon$} & \textbf{Steady RNG $k-\varepsilon$} \\
\hline
Impermeable film & 0 & – & – & 1.62 & 1.24 \\
Permeable nets & OMVRD70 22 & 7.3 & 1.45 & 0.50 & 0.51 \\
 & WTAPE 38 & 3.02 & 0.12 & 0.41 & 0.40 \\
 & SC75 38 & 0.76 & 0.98 & 0.26 & 0.26 \\
 & LIBS50 46 & 0.79 & 0.86 & 0.259 & 0.26 \\
 & OMBVRD50 54 & 0.94 & 0.3 & 0.26 & 0.26 \\
 & SCMD 62 & 0.36 & 0.5 & 0.16 & 0.17 \\
 & FR 25/26 82 & 0.12 & 0.12 & 0.06 & 0.07 \\
 & Type A – & 0.524 & 1.082 & 0.348 & 0.354 \\
 & Type B – & 1.238 & 2.249 & 0.560 & 0.573 \\
\hline
\end{tabular}
\end{table}
Impermeable sheet clad, type A and type B permeable clad and cubical building without scaffold were experimentally analyzed by Irtaza et al.\textsuperscript{15} Simulated outcomes for these four cases were successfully validated with available experimental findings, which ensure that this study accurately predicted the wind flow through clad scaffolds and wind pressure distribution on panel surfaces. For an impermeable sheet clad scaffold, the coefficient of pressure having value 1.62 was found to be satisfactory compared to an ABL wind-tunnel analysis of an elevated sheet clad scaffoldings around a cubical building by Irtaza et al.\textsuperscript{15} with value 1.57.

The pressure coefficient contours over the windward face of the scaffold with each cladding type are shown in Figure 3. For all 10 cladding types, net pressure coefficient variation along the length, at mid-height, and 2/3 height of panel has

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Pressure coefficient contour over windward surface of scaffold having (A) impermeable film, (B) permeable net: OMVBRD70, (C) permeable net: WTAPE, (D) permeable net: SC75, (E) permeable net: LIBS50, (F) permeable net: OMVBRD50, (G) permeable net: SCMD, (H) permeable net: FR 25/26, (I) permeable net: Type A, (J) permeable net: Type B}
\end{figure}
been plotted for the RNG $k-\varepsilon$ turbulence model and shown in Figures 4 and 5, respectively. The net pressure coefficient at a 2/3 cladding panel height was found to be more than that at mid-height, for all cladding types. A sudden variation in net pressure coefficient is seen at edges, because of reverse flow over the cladding through the windward face of the cubical building, along the length (at mid-height and two-thirds height) of the cladding.

Pressure coefficient variation along the mid-height and two-thirds height was found to be overlapping for permeable net-type SC75, LIBS50, and OMVBRD50 having different porosities. The overall net average pressure coefficients for permeable net claddings SC75, LIBS50, and OMVBRD50 were also found to be the same, as shown in Table 2. Permeable nets WTAPE and SC75 had similar porosity (38%) results in different net average pressure coefficients, as shown in Table 2 since WTAPE and SC75 have different aerodynamic coefficients, which could be varied due to the weaving pattern and thread size of these nets. This confirms that the airflow behavior through permeable nets and pressure coefficients over the scaffold and building surface depends on aerodynamic coefficients of permeable nets instead of their respective porosities only.

Figure 6 shows the wind velocity variation at the leeward side of cladding (0.05 m away from the surface) along with height at mid-length is plotted for each cladding type. Figure 7 shows the velocity contours along the $xy$-plane of the domain at mid-length of scaffold type OMBVRD50.

The pressure coefficient contours the windward face of the building for each cladding type shown in Figure 8. Figures 9 and 10 show the variation of pressure coefficient over the windward face of cubical building along the mid-height and two-thirds height, respectively, for both clad scaffolds and without scaffold. Variation in the pressure coefficient over the
FIGURE 5  Pressure coefficient distribution at two-third height along section 2-2 on cladding surface (RNG $k$–$\varepsilon$ analysis)

FIGURE 6  Velocity distribution at mid-length along section 3-3 (RNG $k$–$\varepsilon$ analysis)
**FIGURE 7** Velocity contour at midsection for OMVBRD50 type cladding (RNG $k-\varepsilon$ analysis)

**FIGURE 8** Pressure coefficient contour over windward surface of cubical building with scaffolding having (A) impermeable film, (B) permeable net: OMVBRD70, (C) permeable net: WTAPE, (D) permeable net: SC75, (E) permeable net: LIBS50, (F) permeable net: OMVBRD50, (G) permeable net: SCMD, (H) permeable net: FR 25/26, (I) without scaffold, (J) 3D cubical building without scaffold, (K) permeable net: Type A
building’s windward surface shown in Figures 9 and 10 and pressure contours are shown in Figure 8 clearly shows the influence of cladding material type on the pressure distribution over the building surface.

4 | CONCLUSIONS

The wind flow behavior through permeable nets is highly complex and is aeroelastic in nature. Considerable wind load acts on scaffold structures. For the safe design of the scaffold structure, the wind load transferred from the covering materials to the scaffold is significant and mainly relies on the permeable net aerodynamic characteristics and air penetrability. Pressure coefficients were found to be proportional to the aerodynamic resistance of the permeable nets.

When no scaffolding is provided ahead of the building (isolated building), the maximum positive pressure coefficients found over the windward face of the building, whereas when impermeable sheet clad scaffold placed ahead the building, maximum negative pressure coefficient occur over the windward face of the building. The net pressure coefficient over the windward face of the building when net clad scaffold placed ahead of it, varies within the range of maximum positive (no scaffold) and maximum negative (sheet clad scaffold) values and followed the variation in the aerodynamic coefficients of the respective permeable net.

The present research work is limited to determine the effect of airflow through the clad scaffold over the stand-alone low-rise building. However, the effect of surrounding buildings on the airflow through the clad scaffolds can also be considered in future research work. Future work can also be undertaken for clad scaffolds on high rise buildings and buildings with different aspect ratios.
CONFLICT OF INTEREST
The authors declare no conflicts of interest.

PEER REVIEW INFORMATION
Engineering Reports thanks Nathaniel L. Jones and other anonymous reviewers for their contribution to the peer review of this work.

PEER REVIEW
The peer review history for this article is available at https://publons.com/publon/10.1002/eng2.12350.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Agarwal A, Irtaza H. Turbulent wind flow through permeable claddings mounted on elevated scaffold using CFD simulation. Engineering Reports. 2021;3:e12350. https://doi.org/10.1002/eng2.12350