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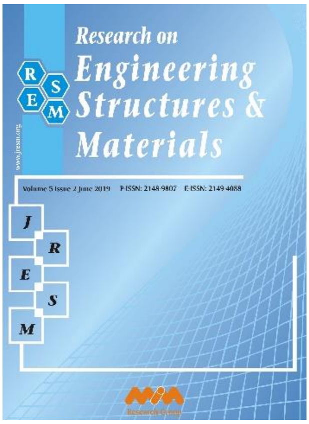

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Research Article

London the Shard analysis in the context of parametric and sustainable skyscraper design

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Abstract

In this study, London The Shard skyscraper structure was examined under the concepts of sustainability and wind engineering dynamics. The aerodynamic examination of the building in accordance with the wind dynamics principles and the relevant CFD simulations as proof, created. In the simulations carried out in the Matlab CFD environment, the Navier Stokes equation principles with k-omega turbulance model were followed. The skyscraper model 1-1 was created in its original form and simulated under real wind data at its location in London. In the results obtained after the simulations, the velocity increased by V-3V in the first 600-800 meters distance range, in the x direction of the model, created a vortex around the structure. While the speed-vortex effects mechanisms were examined on the model by V-3V, the pressure load P within the first 25 meters in the z direction (structure height) of the model was reached to 5P, up to the limit of 280-300 meters. When it is reached to 300 meters height, a 5-fold increase in pressure was detected. In the x-direction, pressure change of the model tested. The variation of the pressure load at the rate of P - 2P was determined in the first 800-1000 meters of the model in the x-direction, and the pressure exerts a double effect in the first 800-1000 meters of the model. In addition to the norms and regulations of supertall design principles, all risk scenarios of wind, under the effect of velocity and pressure need to be simulated before safe construction.

1. Introduction

In this study, the concept of skyscraper construction systems will be discussed through two basic principles. The first of these will be to examine the sustainable energy efficient parameters of the building, which proves that skyscraper structures are also important as being sustainable. The concepts of how much effect it can have on the surrounding structures, and to what extent the vortex power and turbulence created by the structure itself classified, including the center. In the context of this study, both features were examined on the same prototype structure: London The Shard Skyscraper, has been analyzed in detail. The reason for this choice is that "London The Shard" structure is the most qualified skyscraper structure in the Western European building group, as well as the parametric construction systems in its design were placed on a plan base close to the conical by Renzo Piano and the tendency to taper upwards was completed into a high upright pyramid crystal, with tapering [1]. It is an effective and very dynamic plan scheme and is an important feature that distinguishes it from other structures that are both sustainable and parametric. In addition, "London the Shard" structure differs from other structures in terms of the progress of the construction technique during the construction process, the differences in the construction phase, especially in the establishment of its foundations, and the special solutions developed by WSP group. These differences are

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techniques that have been examined so that the structure gains strength by showing effective quality against wind dynamics and is less affected by vortex current intensities.

The differences in the construction system, as well as the different architectural iconic design, which has a crystalline quality in the cross-section process that evolves from a conical base to a high vertical pyramid, [2] and the fact that it is the most qualified skyscraper structure in Western Europe, enabled the analysis of the shard structure to be chosen in this study.

The study was examined in two main sub-headings, in terms of sustainability and wind engineering principles. Considering the sustainability, it has been proven with 5 qualified parameters that, high energy efficiency could be possible even also for a high-tech skyscraper structure, when it is designed with the right decisions & principles.

To focus on the importance of energy efficient principles of skyscraper structures, one of the sustainable architectural solution methods could be choosing the right decisions in terms of aerodynamics concept of design, to build with a lighter construction load bearing-system. To achieve this aerodynamic design envelope, the structure has been handled entirely with the principles of wind engineering dynamics and fluid mechanics simulations.

Evaluations need to be considered for the functions of the changes on the wind speed, vortex measurements, pressure and velocity vectors over the fluid system dynamics of the structure, depending on the distance (x) and height in z direction of the coordinate system.

The effect of physical environmental conditions on the change of velocity and pressure needs to be analyzed. Calculations and measurements have to be created by calculating on the basis of Navier Stokes equations over Matlab CFD Computational Fluid Dynamics systems for safe and aerodynamic high rise building envelope design.

As a result, a high-rise structure over 300+ meters, such as The Shard structure, in focus for this research, has high influence on the wind dynamics and pressure of its own structural load system and also for its surrounding in terms of physical environment conditions on ground and upper-level human comfort and reliability for safe environment.

The ratios and the coefficients of change need to be calculated and pre-estimated before the construction of real design such as the ratios for pressure: P-2P, and velocity of V-3V coefficients in terms of The Shard design simulations, calculated by Computational Fluid Dynamics (CFD), before and after the vortex effect of structure. It has been interpreted and analyzed through the CFD simulations and obtained the correct risk scenarios with the velocity and pressure ratios for safe and sustainable design principles.

The main purpose here is to clearly observe the difference in the distance through the coefficient of variation, and, since the change will still depend on the increase in the coefficient ratio, even if the wind speed changes throughout the year, the distribution and variation can be examined clearly. The simulation data are based on the actual wind speed data for the year and are explained in detail in the methods and methodology. The Shard structure has also been modeled 1-1 in 3D by using the Rhino 3D model system, in a way that would exactly match the real original.

2. Sustainable Building Design Evaluation of "London the Shard" Structure

2.1. Difference of Shard in terms of Sustainable High-Tech Design

When it comes to the design of sustainable building subsystems, it is not only an energy efficient building, but also the design parameters that should be considered in essence. Keeping the sustainability of a building limited to the articulated units such as solar active solar collectors or wind turbines placed in the structure of the building will actually tie the whole load to the foreign units added after the main structure design. The creative design of the form, by inhibiting the rational design decisions that should be made at the beginning.

As a matter of fact, the changing perception of architecture after 1960, and since Archigram, founded in 1961 by a group of pioneer architects like Peter Cook and Dennis Cropmton, who adopted the futuristic design approach, Plug-in City [3], [4] and Instant City [5] concepts, the use of high technology in architectural design had been futuristicly changed. Starting from the first design stages of the building, going to the most suitable structural solutions possible, and the appropriate function, function-form and typology parameters of the building being compatible with the concept, provided with the design had been re-considered after all.

In this study, the structure of London The Shard skyscraper will be analyzed as a pilot application and the unique qualities of the iconic Renzo Piano design and its contribution to sustainability will be examined in the context of sustainable building subsystems.

In the design of The Shard structure, Italian Architect Renzo Piano collaborated with WSP Global in terms of structural solutions. The Technical Director of the Shard, John Parker, defines this meeting with these words, “In general, in every building design, the architect deals with color and aesthetic concerns, and the engineer deals with numerical concerns, and the structure cannot show the desired performance at the point where they cannot communicate. This was not the case at The Shard, Renzo Piano and WSP. He (Renzo Piano) worked in a very good communication, with indefinite and countless meetings. The architect told us about his aesthetic concerns and we, as the engineer, our structural concerns for our architecture, and this communication turned The Shard into reality.”[6]

2.2. Parameters of the Sustainable Concept of Shard

The Shard contained 5 very qualified parameters in a sustainable context at the same time.

2.2.1. To Decrease the Traffic Load of the City in Terms of CO Emissions

The first of these is that the structure is located just above the London Main Line Central Station structure and alleviates the traffic load of the city. This approach focused on minimizing the use of private vehicles among home office life in daily routine. Shard design unit, both for those working on their own office floors and the critical Port area and its surroundings, where it is located, the regulation of the traffic routine on behalf of the London Bridge area and the internal solutions established by the ground floor solutions with the London Main Line Station structure bear the burden at the highest level in a sustainable context. To reduce the CO carbon monoxide gas emission of the city, by the way, to provide a positive effect on air quality. (see figure 1, figure 4)

The region where the Shard is built is exactly the definition of the concept of regeneration. The structure has directly affected the general character of the region and has ensured the full integration of the main switchboard station with the economy and finance center of the city. It has inhibited transportation and traffic problems.

2.2.2 Steel Spire to Eliminate the 3 Million Pound Damper System

Secondly, in the creation of the main structural system of the Shard, the main load bearing structure forming the core with the cooperation of the “mace” group and “WSP”, with an application that was tried for the first time in the world, was primarily raised.

The form made of glass and steel on it was raised like a tapering mesh made of layers and layers, and the facade design was integrated. The building reached its apex between the 72nd and 95th floors with a steel structure spire placed on it like a crown.

The building, which looks like an olympic torch here, was imagined to be completed just before the London Olympic Games and this spire was designed. With the designed load bearing structure, the apartment and residence floors, reinforced concrete office floors and the viewing terrace were formed as a steel structure.

All these rational design parameters saved the structure from the need to put a 3 million pound damper in the structure and provide aerodynamic resistance. Once again, commitment was a prerequisite, name obtained "Renzo Piano Design". [6]

2.2.3. Triple Glazed Blue Panel Systems

Thirdly, the building has "triple glazed blue glass panels" designed by ARUP and solar active energy conversion systems, which are described as expensive efficiency. (see figure 1, fig2) This triple glazed system is cost-effective, on the other hand, obtained by using 75 million dollars of the 375 million dollars full budget of the building only on the facade, it is an application. [7]

2.2.4. Tapering Against the Wind Aerodynamic

The fourth parameter, in fact, should be made at the very beginning of the design decisions, especially in high structures and skyscraper structures of 300 meters and above. Due to the extra load that the active wind speed puts on the building structure, it is necessary to make the aerodynamic resistance decisions of the structure very accurately. Tapering upwards from cube to cone also fully meets the sustainability criteria in terms of inhibiting the wind load on the Shard design, in which the "Tapering" system is actively used, and thus reducing the initial construction costs of the structure. (see figure 5)

2.2.5. Reuse of Recycled Materials in Terms of Constrcution

Finally, the fifth parameter is the following, the fact that the material used as the building structural material is obtained from 95% recycled material shows that it is suitable for the sustainable design criteria of the Shard in all possible dimensions at the time it was made, according to The Guardian. [8]

Fig. 1 The Shard Facade View[7]

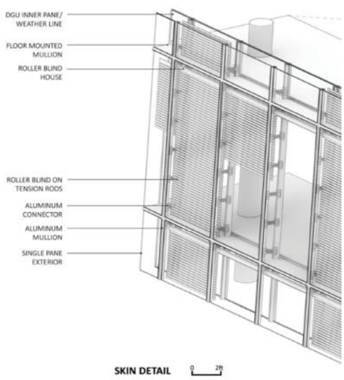

Fig 2 Triple Glazed Detail [7]

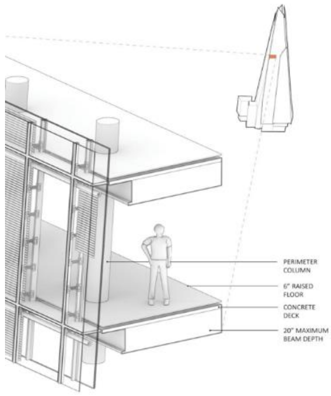

Fig. 3 The Shard Facade, Triple Glazed Detail [7]

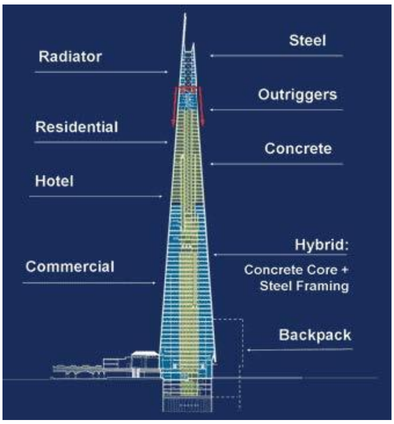

Fig. 4 Construction Technique and Usage Functions According to Shard Floors, Cambridge [9]

Fig. 5 Shard Parametric Facade Design System, a Street View [2]

3. The Shard London Analysis in The Context of Parametric Design

3.1. Understanding the Key for CFD Simulations to Evaluate High Rise Structures

Within the scope of this study, London The Shard skyscraper project, which is one of the high-rise building studies designed and implemented with parametric design principles, firstly over the Rhino 3D modeling system, which will enable CFD (Computational Fluid Dynamics) analyzes to be performed, followed by simplification and mass analysis studies, and the data of the wind structure is abundant. Based on basic data such as direction, the structure was modeled in its real condition and subjected to wind tunnel tests.

In this study, which is based on CFD applications, the main purpose and aim to be examined are, built on the basis of parametric design principles, to what extent a 300 meter or more high structure affects the building physics parameters in the surrounding area, how many meters distance, how dense it is in the wind load affects. Turbulence models are the calculation of how much it affects other structures and what the distance of the impact area is.

In the analyzes made, the results of how much the structure is affected by wind load in the context of structural load analyzes on itself will also be examined on the basis of both P wind load pressure, wind speed and vorticity, and effective vortex distributions.

Fig. 6 Building Physics in The Shard London Structure and Its Metropolitan Concept, Its Situation in Environmental Relations, Its Relations with Transportation Networks and Its Relation with Other High Building Stock [10]

4. Methodology and Method for Simulations

4.1. Modelling the Simulation Environment & Procedures

The study proceeded through 2 basic methods, in the first of which, Navier-Stokes flow equations were used with the exact and instantaneous solution method used in "stationary model" static loads - wind turbulence factor analysis. In the second, Time Dependent analyzes were performed and time dependent time-based oscillations were measured in a certain Δt interval.

In the Shard model, where the wind turbulence is tried to be inhibited to design for 300 meters above, tapering upwards technique has been adapted. In terms of CFD simulations, in the time dependent based solution technique, the effect of turbulence on the physical environment of the structure has been analyzed, for the wind vorticity problems, up to how many meters can be calculated mathematically in the model on the coordinate system.

As it is observed in some literature, the structural analysis is based on not only the pressure load, but also "ρ", the density of the flow on the structure, "μ", the viscosity shown against this flow, the creative velocity of the flow and the pressure. In this study, the Navier Stokes equation-based analysis have been examined using the 300 meters and above algebraic and k-omega turbulence models.

Peter Irwin from RWDI Canada group stated that the 300 meter boundary is a critical threshold value in the context of measuring the wind character and the loads on the structure [11] Calculations and standards of high structures depending on the regulations can be used in practice and in a primary sense, but in structures of 300 meters and below [12], [13].

4.2. Necessity for Simulations to Risk Scenario, Losing the Reliability of Norms and Standards above 300 meters

The main point of this theory is the view that when the high structure is designed higher than the 300-meter limit, Irwin supports that norms and standards lose their applicability and reliability. [12] Turbulent flow of 300 meters high and Eddy Vortexes make the effect of the wind on the structure from being measurable and predictable, to the point of unmeasurable and unpredictable. At this point, the two safest methods available are CFD computer simulations and real wind tunnel testing.

With the simulations made in the context of CFD, wind tunnel designs that make it possible to obtain physical qualifications and suitable wind turbulence models in real wind tunnels. Sensor mechanisms placed in the model (prototype) and instantaneous measurements based on differentials can provide the closest results to the reality and the appropriate risk analysis can be obtained. [14] This argument of Peter Irwin, in the relevant article [11], was also supported in the speech of Ender Ozkan. (a member of the same group, Head of RWDI London and RWDI Europe CEO, on May 29, 2021, in the context of Mimsa Workshop Conference Series.)

While the vortex effects make norms and standards far from safe in structures of 300 meters and above, real tests and simulations against every bad scenario make it necessary to calculate P wind pressure measurements, vorticity, and vortex loads, and oscillations on the basis of risk.

“The boundary layer models in many building codes and standards have served well for buildings less than about 300m but more realistic models need to be used above 300m. “ Peter Irwin – RWDI Canada [11]

5. Results and Discussions

Data analyzes were concluded in this context. As a result of experimental analysis and simulation studies carried out in Matlab environment, 23853 grid cells were assigned on 5039 grid points, data sensitivity should be considered in this context. (Fig.7)

5.1. Simulation Environment Model Factor and Mesh Condition

Simulations are provided over

- the minimum grid cell volume of 4.6758,
- 4.2603e+03 (m^3) mean grid cell volume
- and 1.1788e+04 maximum grid cell volume,
- 0.1695 minimum grid cell quality,
- 0.8532 average grid cell quality
- 6 limit value interfaces.

The 3D mass analysis of the structure has been modeled with real data in the Rhino environment, and it has been made measurable and adaptable to CFD for Matlab simulation.

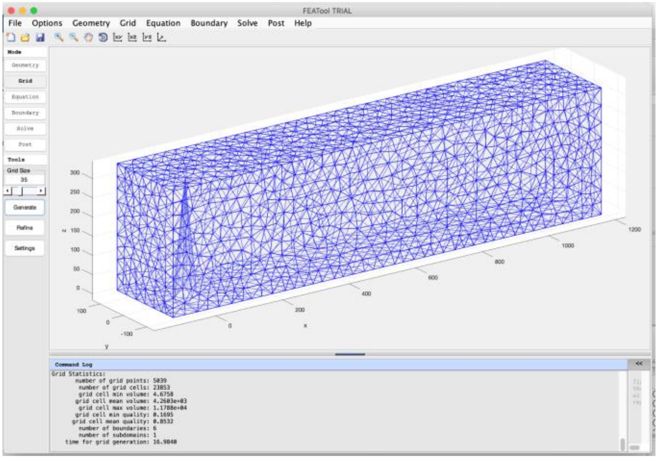

Fig. 7 Matlab Experimental Analysis And Simulation Data Analysis Precision Criteria

5.2. Simulation Model for the Velocity Change, k-omega Turbulence Model & Wind Vortex, Velocity Spectrum (x, z - directions)

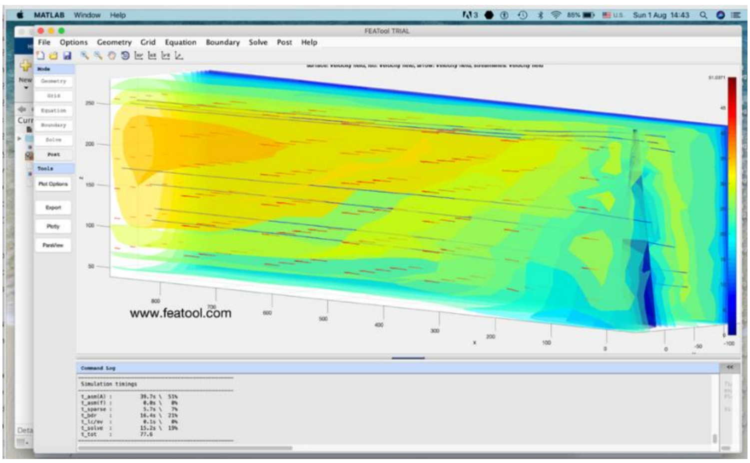

Fig. 8 The Effect of the Shard Structure Around 300 Meters In The Context of the V-3V Velocity

In the results obtained, it has been determined that the normal, ground story speed level influences the building physics and environmental conditions in the first 600-800 meters range after the building itself, 3 times as much, and it increases the current speed vector from V to 3V.

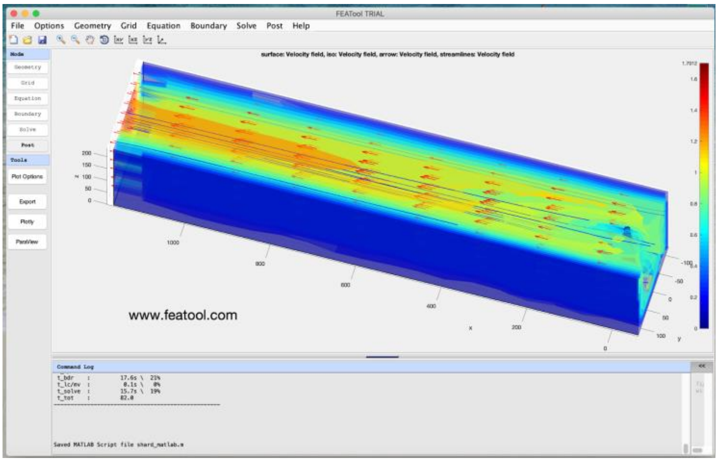

Fig. 9 Vortex And Wind Turbulence Effects of the Structure in the 600-800 Meter Range

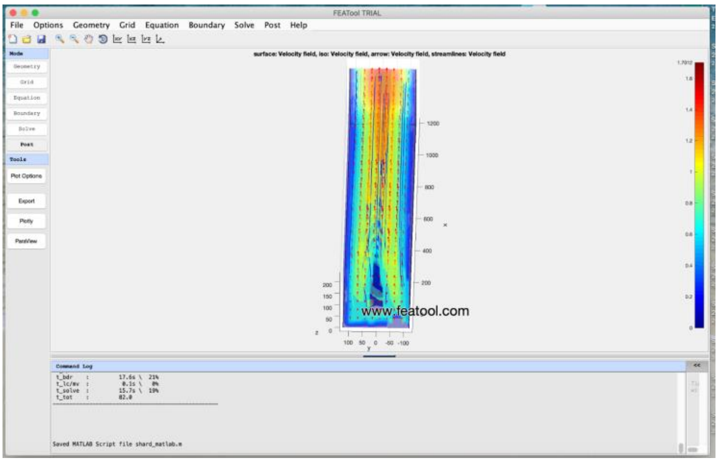

Fig. 10 Vortex and Wind Turbulence Effects of the Structure in the 600-800 Meter Range

Due to the wind turbulence and vortex effects created around the 300 meters above structure, it has been determined that the vortex effect persists in the 600-800 meter distance range closest to the structure. (Fig 9, Fig 10)

5.3. Simulation Model for the Time Dependent Scenario– Δt interval change & Wind Vortex (x, z -directions)

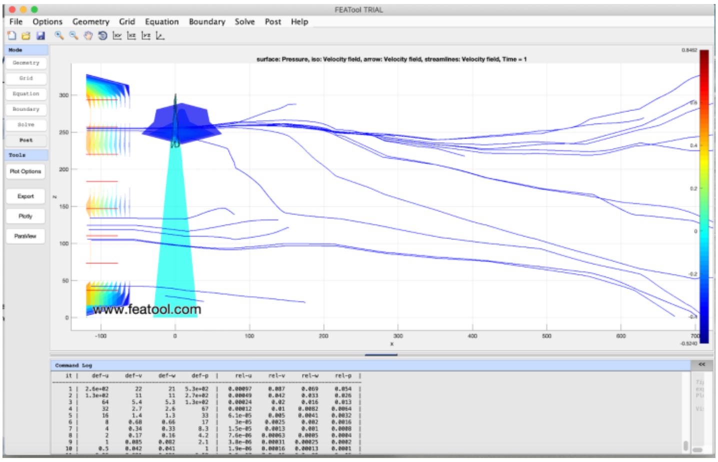

Fig. 11 Measurement of Vortex Effect Distance In The Solution of the Structure in the Simulation Range of Time Dependent Delta T

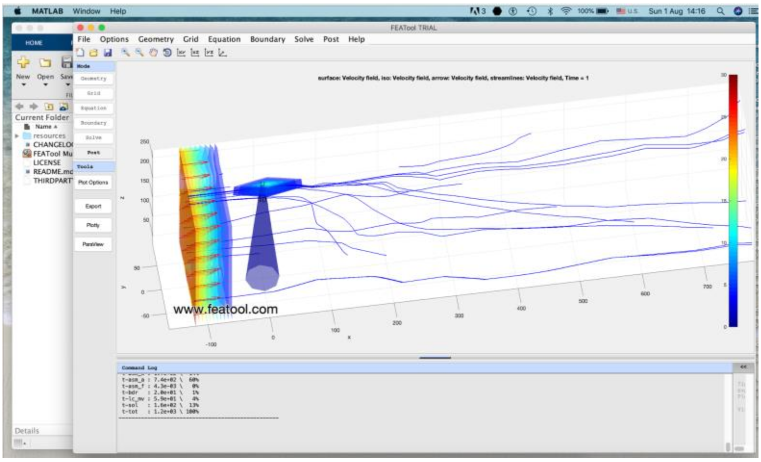

Fig. 12 Measurement of Vortex Effect Distance in the Solution of the Structure in the Simulation Range of Time Dependent Delta T

In the time dependent analyzes used as the second method, the change in the vortex and velocity vector in a certain Δt interval, have been examined. This method supported the first obtained Navier Stokes instantaneous and clear solution data. It has been proven that the effect creates on top of the structure, that is, the highest point, continues until the first 600-800 meters after the flood.

5.4. Simulation Model for the k-omega Turbulence Model Scenario– & Wind Vortex and Pressure Spectrum (x, z-direction)

After the analysis of the structure on the velocity and vortex effect mechanisms, the relationship of the structure with the pressure has been examined, and it has been concluded in this analysis that the pressure load on the structure in the range of 280-300 meters have an effect in the context of P-5P pressure change in spectrum.

The pressure load, which is P in the first 25 meters of the structure, reaches a pressure of 5P in the range of approximately 280-300 meters height of the structure. (z direction) (Fig 13)

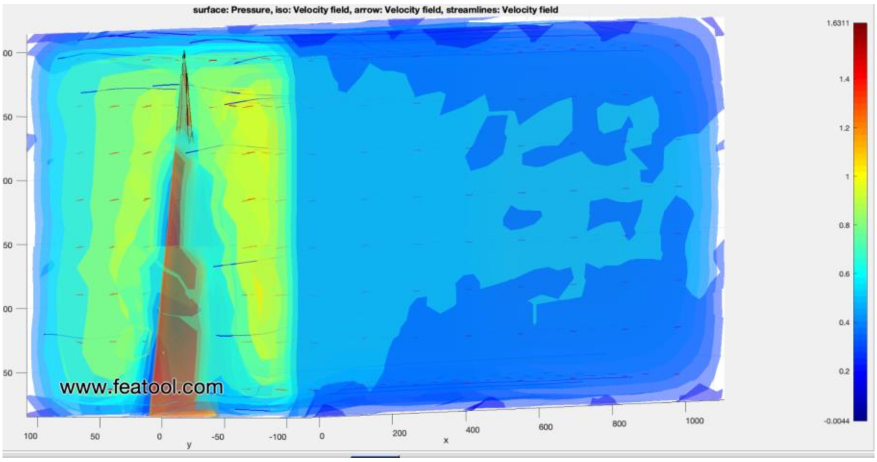

Fig. 13 Analysis of the Pressure Factor, Change Between the First 25 Meters of the Structure and 280-300 Meters Thereafter

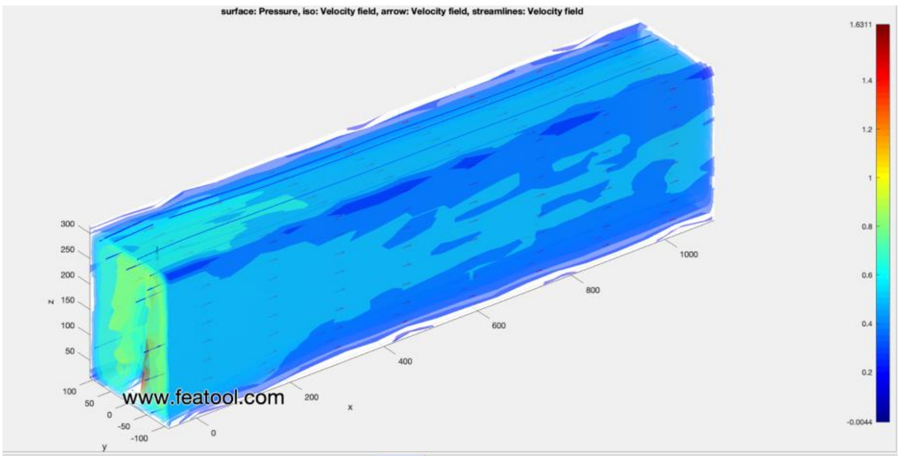

Fig. 14 Analysis of the First 800-1000 Meters Environment Interaction of the Structure and P-2P Pressure Changes (X-Direction)

In addition, when the building physics and safety comfort conditions on the surrounding of the structure are analyzed, it has been determined that the pressure effect on the P-2P scale continues in the first 800-1000 meters after the structure, based on the prevailing wind direction (Fig 14).

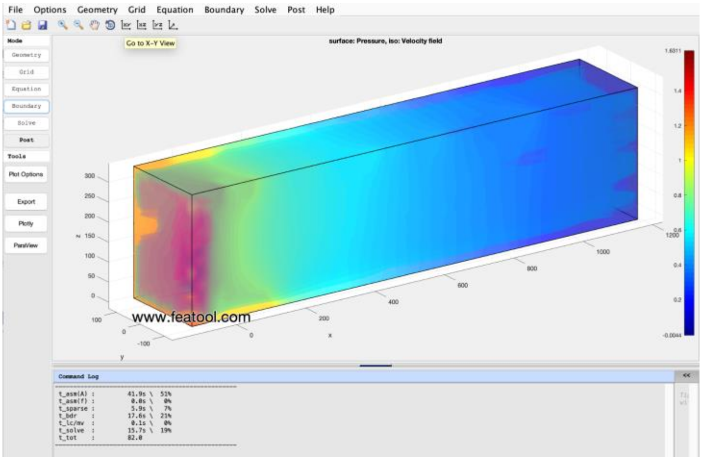

Fig. 15 The Risks of Separation of the Facade from the Structure with the Vortex Effect of the Building Facade Cladding System and the Density Indicators for the First 150 Meters

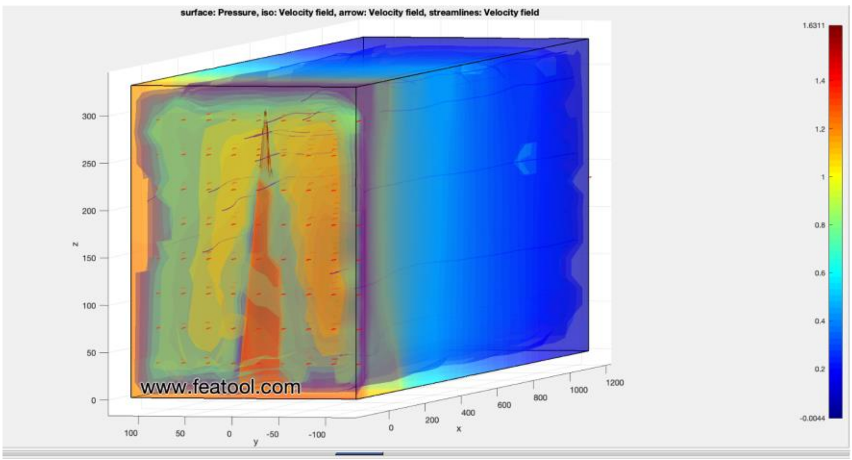

Fig. 16 The Risks of Separation of the Facade from the Structure with the Vortex Effect of the Building Facade Cladding System and the Density Indicators for the First 150 Meters

Based on the structural load, the pressure on the building and especially the risk of separation of the facade from the structure with speed vortices and turbulence on the glass facade system, it is concluded that the wind load on the facade primarily affects the building environment in the first 100-150 meters.

As a result, in the part of what is called “the skyscraper” structures, take their place in the literature as "supertall buildings and skyscrapers" at 300 meters and above, have essential and critic design points to be safe and sustainable. 300 meters and above heights need to be examined differently from the norms and standards. Finding a topic in the world literature as “high-rise design and wind engineering” – “tall building design and wind engineering” is an extreme critical point needs to be simulated in detail both for speed vortex and pressure affects. A serious research area that requires special design principles with both simulations and effective CFD analysis, in turbulent and laminar flow assumptions, also considering the risks it contains. To mention such as the the risk of facade fall under turbulent flow, could be possible in a negative risk scenario. Unfortunately, became reality in HSBC Headquarter in London. (info on 29 may 2021, conversation with Ender Ozkan, RWDI) Writer's research continues effectively with their original design & models, methods and analyzes for Ph.D. doctorate, in the context of MSGSU Mimar Sinan University - Construction Physics Doctorate Program.

6. Conclusions

In this study, a comprehensive review of the shard skyscraper structure, which is known as the best example of western Europe, was made under the topics of sustainability and wind aerodynamics, to be safe and provide sustainable design. Wind dynamics and fluid mechanics proncliples have been taken into account in detail. All the calculations performed under the reliability of matlab systems with the Navier Stokes equation on k-omega turbulance model.

6.1. Risks and Essentials of Supertall Structures Design

Skyscrapers are structures that need to be built and tested as prototypes in wind tunnel tests [14] because they are exposed to extra wind load that do not comply with the norms and standards in force during their construction, especially when skyscrapers over 300 meters are considered.

In this context, it is a structure group that is difficult to construct, whose structural calculations must be specially designed for

- both their facade strength and their individual load-bearing systems,
- by pre-determining the risk on them,
- such as the risk of overturning,
- collapse risk,
- damage from the wind,
- or the measurement of the oscillation coefficient.

They are structures that can be constructed by the simultaneous work of architecture and engineering disciplines and producing solutions together.

6.2. Success of The Shard London in Terms of Sustainability

The success of "London The Shard" skyscraper structure, which is one of the best known examples of western Europe, and studied as a prototype in this study, in terms of energy efficient transformation mechanisms and energy efficiency in its initial design, is analyzed. In this concept, with the data obtained from the literature studied on the Shard [8], the recyclable materials used at the rate of 95% in the construction of the structure. Moreover, the use of a 3-million-dollar damper has been waived thanks to the steel crown positioned on top of the structure itself. In aethetics aspects, it has been also considered to be the flame of the Olympic Games. [6]

Moreover, the location and having the role to be an icon of the the business life of city centre by its location is highly essential. In terms of being the transit point of the city and the relation with the building & office aspects need to be taken into consideration. It has been seen that the building exhibits a successful example in terms of sustainable architecture due to reasons such as being a pioneer-designed high-rise building. With all the explanations and proven cases above, it has been determined that a high-rise building or a skyscraper structure can also be energy efficient with a creative design.

6.3. Success of The Shard London in Terms of Aerodynamic Structure Design

The Shard skyscraper structure is modeled in Rhino computer environment, in accordance with the 1-1 architectural features and the original, with the relevant proportions, dimensions and this created model is analyzed with CFD Computational Fluid Dynamics simulations in the Matlab environment.

The technique applied is similar to the techniques studied in skyscraper construction systems, which are built in the real sense, by modeling skyscraper prototype models as models and testing them in wind tunnels, making it possible how this analysis can be done during a Ph.D. doctoral study at the university, academic level.

Model simulations were created by creating appropriate environmental data in a matlab computer environment, processing the relevant scenarios into the model, and the Shard skyscraper structure in real terms and at the location in London, taking into account the characteristics such as wind speed, wind load, pressure factors, and 300 meters above - high structure, with its environmental models were created.

Since the structure over 300 meters is exposed to the vortex effect within the scope of super-high structures, the turbulent flow is solved by using the Navier Stokes equations. Here, in the interface of the matlab program, the data related to the solution are provided as input to the Navier Stokes equation.

In the data obtained from the simulation, the graphs obtained as matlab CFD simulation outputs, vortex diagrams, pressure and velocity controls enable the structure to be evaluated. The difference between the pressure and velocity distributions on and behind the structure observed in 800-1000 meters range, and in this sense, the velocity change of V-3V spectrum, or the pressure change of P-2P spectrum, obtained in x -direction. For z-direction, the pressure change detected with the scope from P to 5P, from first 25 meters to 280 – 300 meters limit, under the effect of height and wind.

Table 1 .Pressure and Velocity Differences on X and X coordinates (Fig 8, 9, 13, 14)

Coordinate	Mean	Dimensions (meters)	P(initial)	P(final)	V(initial)	V (final)
			(in ratio and coefficient)			
X	distance	800-1000	P	2P	V	3V
Z	height	280-300	P	5P	Increase regularly by height of the floors	

Finally, as it is, the change of the environmental conditions on the front of the facade and behind the facade of The Shard structure is determined in accordance with the real data, and essentially, by obtaining the necessary ratios in the context of the coefficient. In case, by this way, the total risk scenario can be calculated actively, even during the wind speed and fluctuations throughout the year occur.

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