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Performance Assessment of Distributed Tuned Mass Dampers for Wind Response Control of Tall Buildings Using CFD and Structural Dynamic Analysis

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Abstract-*Wind-induced vibrations significantly influence the serviceability and performance of tall buildings due to their increasing height and flexibility. This study evaluates the effectiveness of Distributed Tuned Mass Dampers (d-TMDs) in controlling the dynamic response of G+20 and G+40 reinforced concrete buildings using an integrated Computational Fluid Dynamics (CFD) and structural dynamic analysis approach. Transient wind forces were obtained through CFD simulations in ANSYS Fluent using the Realizable k–ε turbulence model and were converted into floor-wise wind loads for application in ETABS. Comparative analyses were performed for buildings with and without d-TMDs under equivalent static and CFD-derived wind loading. The structural performance was assessed in terms of storey displacement, storey acceleration, storey drift, and base reaction. The results indicate that the distributed damper system effectively mitigates wind-induced responses, enhances energy dissipation, and improves the overall dynamic behaviour of tall buildings. The proposed CFD–structural analysis framework provides a practical methodology for the performance-based design of wind-resistant high-rise structures.*

Keywords: [Computational Fluid Dynamics, Distributed Tuned Mass Dampers, Tall Buildings, Wind-Induced Vibrations, Structural Dynamics, Wind Engineering, CFD-ETABS Coupling.]

1. INTRODUCTION

Rapid urbanization and the growing demand for high-rise infrastructure have resulted in the construction of increasingly tall and slender buildings. While advancements in construction materials and structural systems have enabled greater heights, they have also increased susceptibility to dynamic environmental loads, particularly wind. Unlike gravity loads, wind loads are highly variable and can induce significant lateral displacements, accelerations, and torsional responses. For modern tall buildings, serviceability criteria often govern design rather than strength requirements. Excessive building accelerations may cause occupant discomfort even when structural safety remains unaffected. Consequently, understanding wind–structure interaction and developing efficient vibration control systems have become essential aspects of structural engineering.

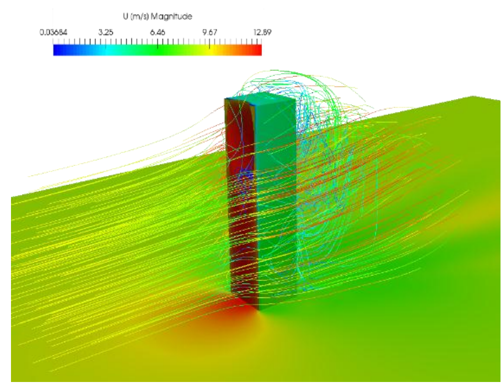


Fig 1. CFD Analysis**-** Flow around the building.

Traditionally, wind effects have been evaluated through wind tunnel testing and empirical codal procedures. Although these methods provide reliable estimates, they are often expensive, time-consuming, and limited in capturing detailed flow physics. Computational Fluid Dynamics (CFD) has emerged as a powerful alternative capable of simulating atmospheric boundary layer flow, vortex shedding, wake formation, and pressure distributions around complex geometries.

In parallel, structural vibration control systems have evolved significantly. Among passive control devices, Tuned Mass Dampers (TMDs) have demonstrated effectiveness in reducing dynamic responses. However, conventional single TMD systems are generally tuned to the fundamental mode and may become ineffective under multi-modal excitation. To address this limitation, researchers have developed Multiple Tuned Mass Dampers (MTMDs) and Distributed Tuned Mass Dampers (d-TMDs), which distribute damping capacity across several vibration modes.

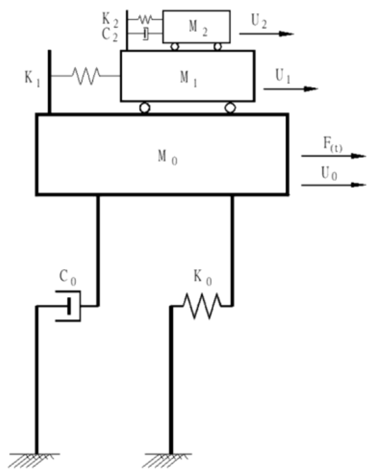


Fig 2. Analysis model of the d-TMD-structure system

The integration of CFD-generated wind loading with structural dynamic analysis provides an advanced methodology for evaluating d-TMD performance under realistic wind conditions. This paper examines previous developments in CFD-based wind analysis, vibration control technologies, and their combined application for improving the serviceability performance of tall buildings.

2. OBJECTIVES OF STUDY

1. To investigate wind flow characteristics around G+20 and G+40 tall buildings using CFD (ANSYS Fluent, Transient URANS with the Realizable k–ε model).
2. To generate realistic CFD-based aerodynamic force time histories and convert them into floor-wise wind loads for structural analysis.
3. To develop ETABS structural dynamic models of tall buildings with and without Distributed Tuned Mass Dampers (d-TMDs).
4. To design and optimise d-TMDs based on modal characteristics, including mass ratio, tuning frequency, damping ratio, and installation locations.
5. To evaluate structural performance using storey displacement, storey acceleration, inter-storey drift, and base reaction under CFD-derived wind loading.
6. To compare the performance of buildings with and without d-TMDs and assess the effectiveness of the integrated CFD–Structural Dynamic Analysis approach for wind response control.

3. METHODOLOGY

An integrated CFD–Structural Dynamic Analysis methodology was adopted to evaluate the effectiveness of Distributed Tuned Mass Dampers (d-TMDs) in reducing wind-induced responses of tall reinforced concrete buildings. The study was carried out in four stages: (i) CFD simulation using ANSYS Fluent to obtain transient aerodynamic forces, (ii) preparation of drag and lift force time histories, (iii) application of CFD-derived wind loads in ETABS, and (iv) dynamic response evaluation of buildings with and without d-TMDs. The structural performance was assessed in terms of displacement, acceleration, storey drift, and base reaction.

3.1 Modelling Process in ANSYS Workbench

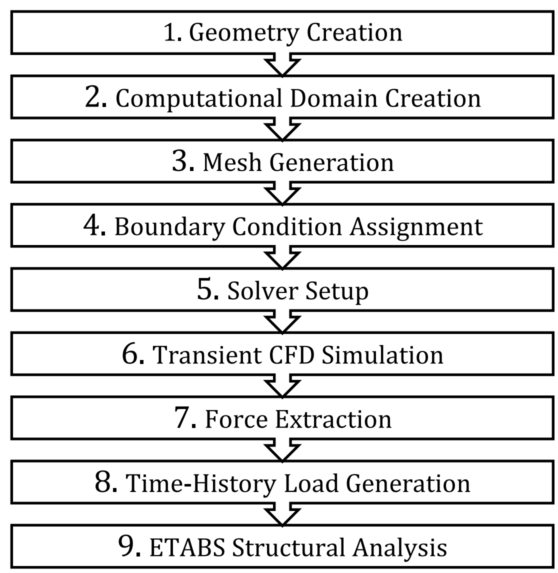


Fig 3. Ansys Workbench Steps Flowchart

Geometry(G+20 and G+40 Building)

Building plan-29m x 29m
Building height-71.2 m and 135.2 m
Building type- Rectangular bluff body

Computational Domain

Upstream distance-5H
Downstream distance-15H
Side distance-5H
Topdistance-5H

Mesh Details

Number of Cells- 115,504
Number of Faces- 236,250
Number of Nodes- 22,047
Element Type- Tetrahedral

The building geometry was developed in ANSYS Workbench and enclosed within a sufficiently large computational domain to accurately capture flow separation and wake formation while minimizing blockage effects. A tetrahedral mesh with local refinement near the building surfaces was generated for the transient CFD simulations.

CFD Model

Solver- Pressure-Based
Analysis-Transient URANS
Space- 3D
Turbulence Model- Realizable k–ε
Wall Treatment- Standard Wall Functions

Boundary Conditions

Inlet- Velocity Inlet (ABL Power-law Profile)
Wind Velocity- 44 m/s
Turbulence Intensity- 5%
Turbulent Viscosity Ratio- 10
Outlet- Pressure Outlet (0 Pa Gauge Pressure)
Side & Top- Symmetry
Building & Ground- Stationary No-Slip Wall

Solution Controls

Pressure-Velocity Coupling- SIMPLE
Pressure Discretization- Second Order
Momentum- Second Order Upwind
k & ε- Second Order Upwind

Transient Parameters

Time Step- 0.02 s
Number of Time Steps- 1000
Iterations per Step- 20
Total Simulation Time- 20 s

Transient URANS simulations were performed to capture vortex shedding and fluctuating aerodynamic loads acting on the buildings. The drag and lift force histories obtained from CFD were used for subsequent structural dynamic analysis.

3.2 Time-History Preparation for ETABS

The aerodynamic forces obtained from ANSYS Fluent were exported as transient drag (X-direction) and lift (Y-direction) force histories. The extracted forces were converted into floor-wise loading using the Atmospheric Boundary Layer (ABL) velocity profile.

Table 1. Time History Data of models.

Parameters	G+20	G+40
Simulation Duration	20 s	20 s
Time Step	0.02 s	0.02 s
Number of Data Points	1000	1000
Initial Peak Drag Force	1621.34 N	3005.96 N
Average Stable Drag Force	1240–1500 N	2711–2750 N
Initial Peak Lift Force	979.43 N	528.28 N
Average Stable Lift Force	474–506 N	254–350 N

The aerodynamic force histories were converted into ETABS-compatible time-history functions for dynamic structural analysis.

4. STRUCTURAL MODELLING

4.1 Modelling process in ETABS

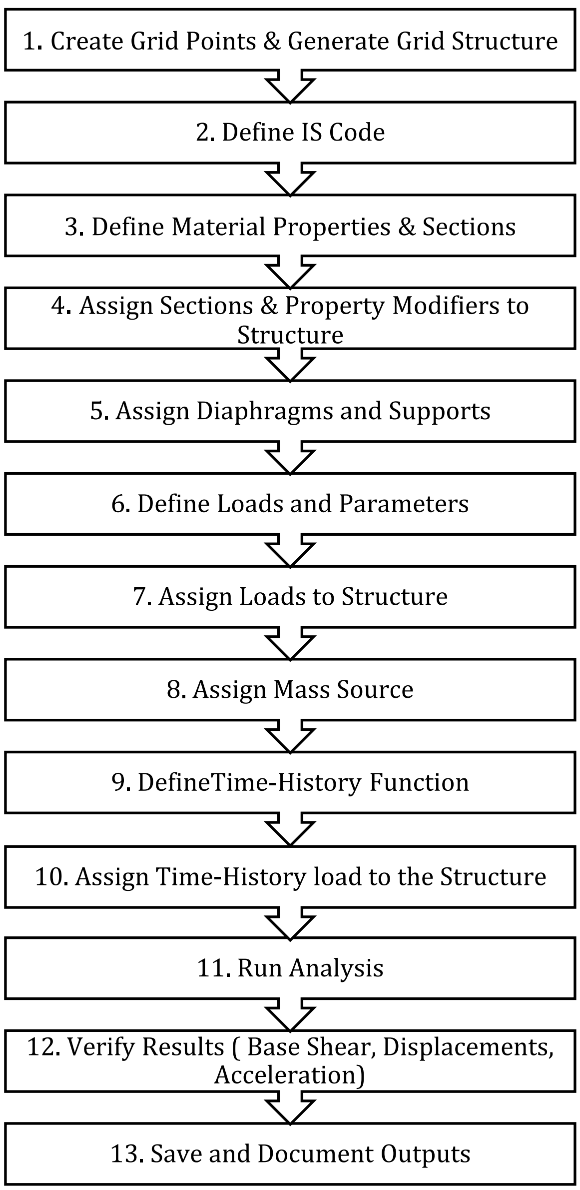


Fig 4. ETABS Steps Flowchart

4.2 Model Data

Materials Properties

i. Grade of Concrete: M35
ii. Grade of Steel: Fe550
iii. Density of RCC: 25 kN/m^3
iv. Density of Steel: 78.5 kN/m^3
v. Density of Light Weight Block Work: 10 kN/m^3

Storey Details:

G+20 Building:

1. Plan Size: As Per Plan
2. Height of Building: 71.2 m
3. Slab Thickness: 150 mm
4. Floor to Floor Height: 3.2 m
5. Shear Wall Thickness:
   i) From Storey Base to 10th: 350 mm
   ii) From Storey 11th to 17th: 300 mm
   iii) From Storey 18th to 20th: 230 mm
6. Beam Size: 230 mm x 550 mm (Sizes used as per structural framing requirements)

G+40 Building:

1. Plan Size: As Per Plan
2. Height of Building: 135.2 m
3. Slab Thickness: 150 mm
4. Floor to Floor Height: 3.2 m
5. Shear Wall Thickness:
   i) From Storey Base to 20th: 350 mm
   ii) From Storey 21st to 30th: 300 mm
   iii) From Storey 31st to 40th: 230 mm
6. Beam Size: 300 mm x 650 mm (Sizes used as per structural framing requirements)

Loading on Structure:

Live Load:

a) Floor: 2 kN/m^2
b) Terrace: 1.5 kN/m^2

Dead Load:

a) Floor: 3.75 kN/m^2
b) Terrace: 5.25 kN/m^2
c) Staircases: 3.75 kN/m^2

Wall Load:

a) Floors(exterior): 0.23 x (3.2 – 0.75) x 10 = 5.7 kN/m
b) Floors(interior): 0.115 x (3.2 – 0.75) x 10=2.9 kN/m
c) Terrace: 0.23 x 1.2 x 10 = 2.8 kN/m

4.3 Modal Analysis

Modal Participation Factor

Table 2 Modal Mass Participation Ratios of G+20 Building.

Case	Mode	UX	UY	RZ
Modal Ritz	1	0.6915	0	0
	2	0.0002	0	0
	3	0	0.6509	0

Table 3 Modal Mass Participation Ratios of G+40 Building.

Case	Mode	UX	UY	RZ
Modal Ritz	1	0.0011	0.4658	0
	2	0.7742	0.0013	0
	3	0.0003	0.2639	0

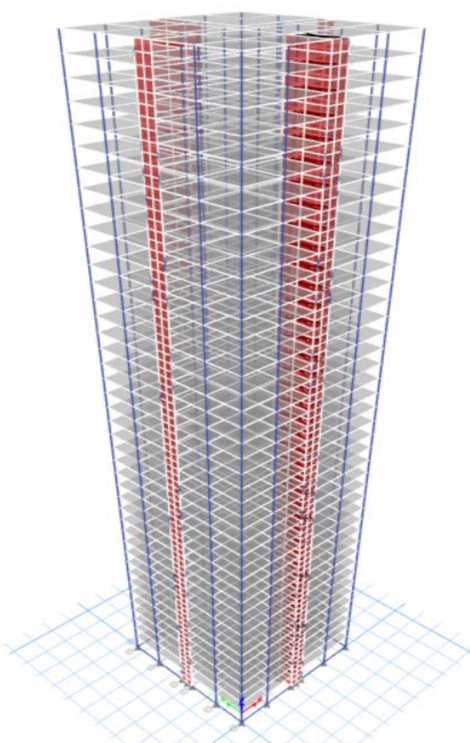


Fig 5. 3D View of G+40 Model

Natural Time Period

Table 4 Time Period of G+20 and G+40 Building.

Mode	G+20 71.2 m	G+40 135.2 m
1	4.373	3.327
2	3.271	3.133
3	2.999	2.749
4	1.15	1.046
5	0.813	1.029
6	0.63	0.878
7	0.535	0.599
8	0.368	0.546
9	0.328	0.472
10	0.259	0.408

4.4 Calculation of Stiffness and Damping Coefficients

The d-TMD parameters were calculated using the optimized mass ratio and frequency ratio.

Governing Equations

TMD Mass

$$m_{TMD} = \mu m_{modal}$$

Tuned Period

$$T_{TMD} = \beta T_n$$

Circular Frequency

$$\omega = \frac{2\pi}{T_{TMD}}$$

Stiffness

$$k = m_{TMD}\omega^2$$

Critical Damping

$$C_c = 2m_{TMD}\omega$$

Damping Coefficient

$$C = 2\zeta m_{TMD}\omega$$

where:

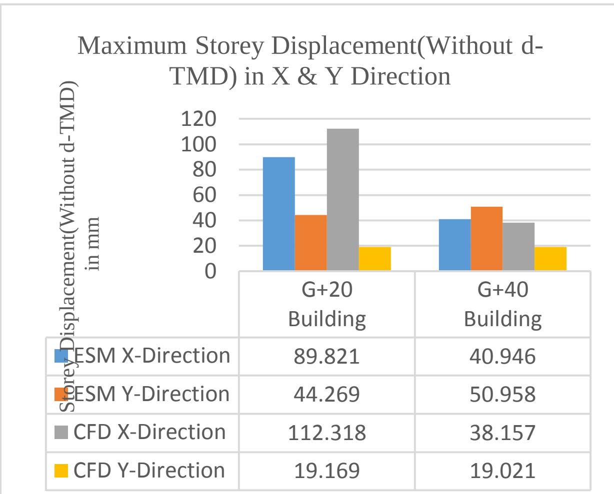
- μ= mass ratio
- β= frequency ratio
- ζ= damping ratio

- T_n= structural natural period
- ω= circular frequency

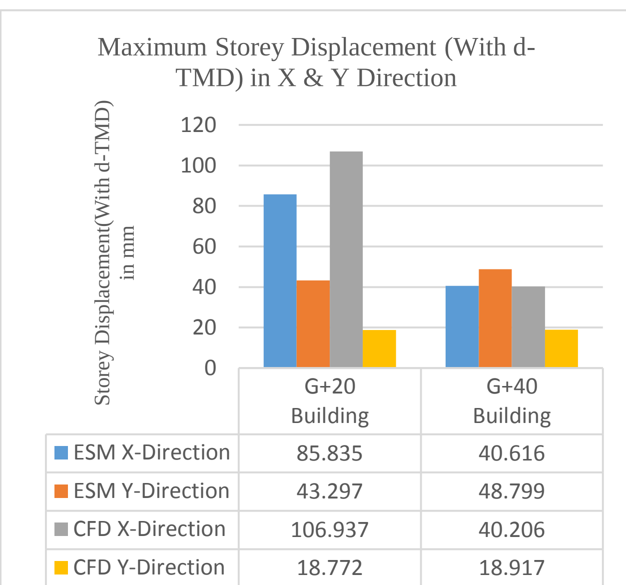
The calculated stiffness and damping coefficients were assigned to the spring-damper link elements representing the distributed tuned mass dampers in ETABS.

5. RESULTS AND DISCUSSION

5.1 Story Displacement

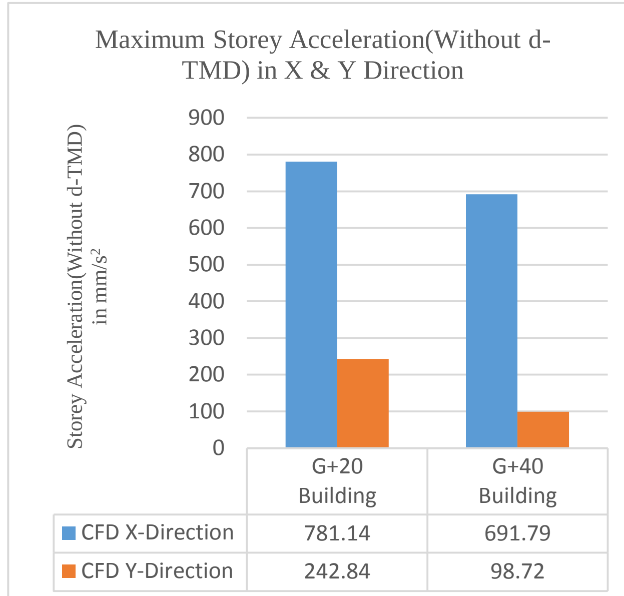


Graph 1. Maximum displacement for G+20 and G+40 Building Without d-TMD

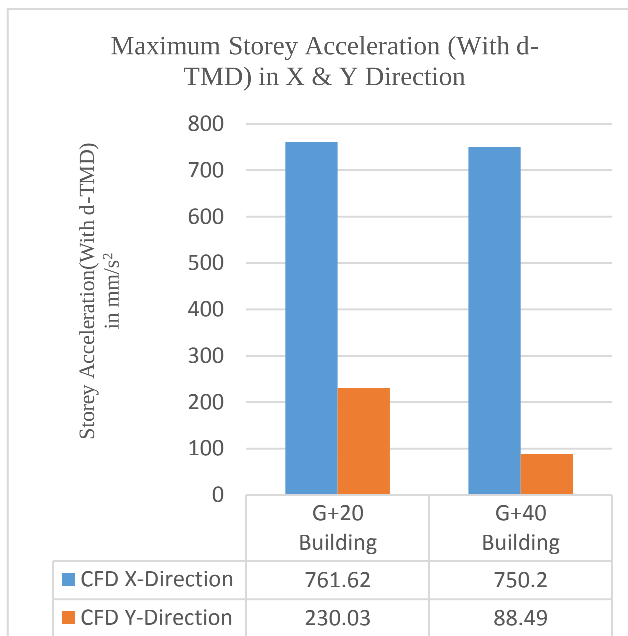


Graph 2. Maximum displacement for G+20 and G+40 Building Without d-TMD

5.2 Story Acceleration

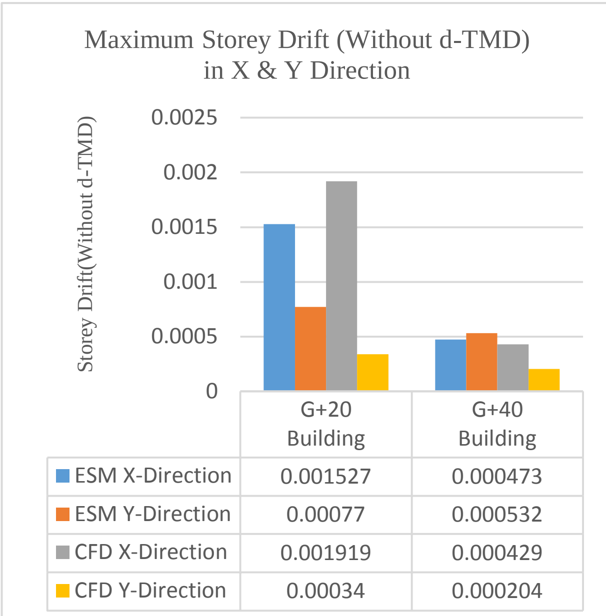


Graph 3. Maximum Acceleration for G+20 and G+40 Building Without d-TMD



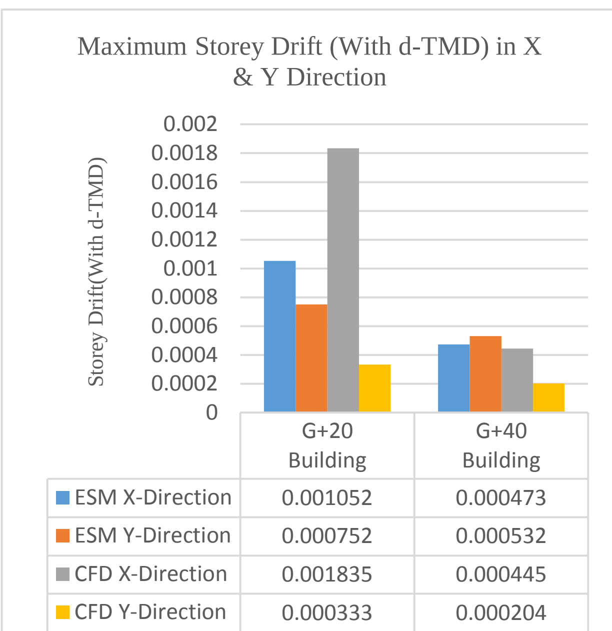
Graph 4. Maximum Acceleration for G+20 and G+40 Building With d-TMD

5.3 Story Drift



	G+20 Building	G+40 Building
ESM X-Direction	0.001527	0.000473
ESM Y-Direction	0.00077	0.000532
CFD X-Direction	0.001919	0.000429
CFD Y-Direction	0.00034	0.000204

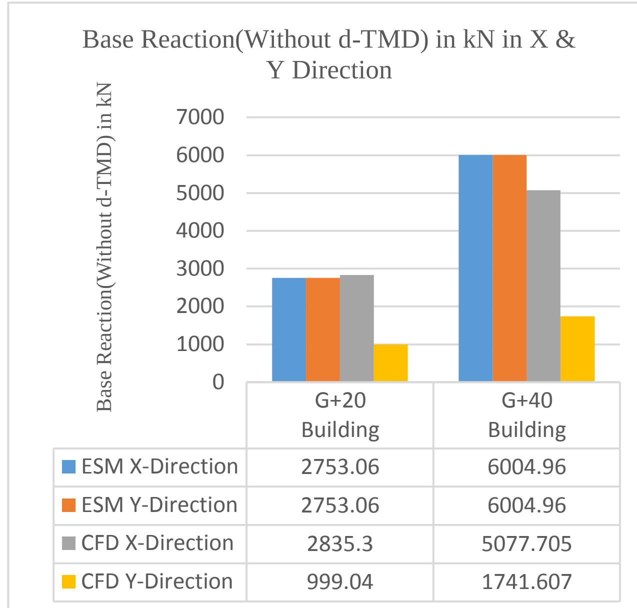
Graph 5. Maximum Story Drift for G+20 and G+40 Building Without d-TMD



	G+20 Building	G+40 Building
ESM X-Direction	0.001052	0.000473
ESM Y-Direction	0.000752	0.000532
CFD X-Direction	0.001835	0.000445
CFD Y-Direction	0.000333	0.000204

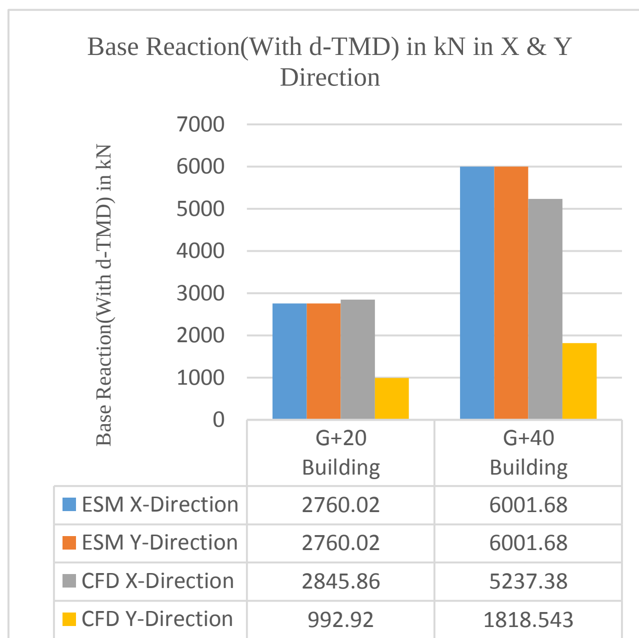
Graph 6. Maximum Story Drift for G+20 and G+40 Building With d-TMD

5.4 Base Reaction



	G+20 Building	G+40 Building
ESM X-Direction	2753.06	6004.96
ESM Y-Direction	2753.06	6004.96
CFD X-Direction	2835.3	5077.705
CFD Y-Direction	999.04	1741.607

Graph 7. Base reaction for G+20 and G+40 Building Without d-TMD



	G+20 Building	G+40 Building
ESM X-Direction	2760.02	6001.68
ESM Y-Direction	2760.02	6001.68
CFD X-Direction	2845.86	5237.38
CFD Y-Direction	992.92	1818.543

Graph 8. Base reaction for G+20 and G+40 Building With d-TMD

6. CONCLUSION

Following are the conclusions obtained from these studies:

1. The proposed integrated CFD–ETABS framework successfully evaluated the wind response of G+20 and G+40 reinforced concrete buildings using CFD-derived transient wind loads. Compared with the Equivalent Static Method (ESM), the CFD approach provided a more realistic representation of fluctuating aerodynamic forces, enabling accurate assessment of structural dynamic behaviour.
2. Distributed Tuned Mass Dampers (d-TMDs) effectively reduced storey displacement under both static and dynamic wind loading. For the G+20 building, displacement reductions ranged from 4.44–9.65% (ESM X), 2.20–5.32% (ESM Y), 4.79–23.61% (CFD X), and 2.07–5.35% (CFD Y). For the G+40 building, reductions ranged from 0.8–9.7% (ESM X), 4.2–17.5% (ESM Y), 2.45–3.21% (CFD X), with a maximum reduction of 38.32% under CFD Y loading.
3. The d-TMD system significantly controlled inter-storey drift, thereby improving lateral stability. Drift reductions for the G+20 building were 8.28% (ESM X), 2.97% (ESM Y), 4.43% (CFD X), and 2.06% (CFD Y), whereas the G+40 building achieved 0.21% (ESM X), 3.62% (ESM Y), 11–20% (CFD X), and up to 39.08% (CFD Y).
4. The greatest improvement was observed in storey acceleration, indicating enhanced vibration control and occupant comfort. Acceleration reductions reached 2.50–11.70% (CFD X) and 9.27–23.08% (CFD Y) for the G+20 building, while the G+40 building achieved 4–18% (CFD X) and 10–65% (CFD Y).
5. The effectiveness of d-TMDs increased with building height. The G+40 building consistently exhibited larger reductions in displacement, drift, and acceleration than the G+20 building, confirming that distributed damping systems are more effective for taller and more flexible structures subjected to dynamic wind loading.
6. Overall, the study demonstrates that distributed tuned mass dampers are an efficient passive vibration-control strategy for tall buildings. The coupled CFD–ETABS methodology provides a reliable framework for performance-based wind engineering, enabling significant reductions of up to 38.32% in displacement, 39.08% in storey drift, and 65% in storey acceleration under realistic CFD-derived wind loading conditions.

7. FUTURE SCOPE

This research area has vast scope for the future studies. Some are discussed below:

1. Higher-fidelity turbulence models such as LES, DES, and hybrid turbulence models may be adopted to improve the prediction of unsteady aerodynamic phenomena and vortex shedding characteristics.
2. Optimization techniques such as Genetic Algorithms, Particle Swarm Optimization, and Machine Learning approaches may be used to determine optimal d-TMD mass ratios, tuning frequencies, damping ratios, and installation locations.
3. Evaluation of d-TMD systems for buildings having different heights, aspect ratios, and structural configurations.
4. Optimization of damper mass ratios, stiffness values, damping coefficients, and placement locations using advanced optimization techniques.
5. Study of multi-directional wind effects and torsional responses using coupled CFD–structural interaction analysis.

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