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A Systematic Approach to Converting Lattice Models into Solid Models for LES-Based Aeroelastic Analysis of Flexible Tall Buildings

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Abstract

Performing precise aeroelastic analysis of tall buildings using computational fluid dynamics (CFD) and fluid-structure interaction (FSI) simulations requires structural models that accurately capture the prototype's dynamic characteristics. Traditional lattice-frame (SM) models are not ideal for direct CFD coupling because they do not provide a continuous representation of stiffness and mass. This study introduces a systematic framework for converting skeletal models into Equivalent Solid Models (ESMs) to facilitate Large-Eddy-Simulation (LES)-based CFD-FSI analyses. Orthotropic elastic parameters are calculated using Timoshenko beam theory. The benchmark CAARC building (45 m × 30 m × 180 m) is used to demonstrate the developed SM–ESM conversion framework. The ESM produced similar natural frequencies and achieved MAC > 0.9 for all modes, confirming the preservation of stiffness anisotropy and torsional coupling. This validated framework establishes a foundation for future LES-based aeroelastic and flexible-structure research.

Keywords: *Aeroelastic Analysis, Computational Wind Engineering, Skeletal Model, Equivalent Solid Model, Fluid-Structure Interaction (FSI), Flexible Building, CFD, Orthotropic Material, Modal Assurance Criterion (MAC).*

1. INTRODUCTION

Understanding wind-structure interaction is fundamental in wind engineering. Wind-tunnel studies have historically offered significant insights into aerodynamics and structural vibration, establishing the fundamental principles of design practice (Hou et al., 2023). Recent advances in Computational Wind Engineering (CWE) now enable comprehensive Large-Eddy Simulation (LES)-based aeroelastic analyses that complement, rather than replace, physical testing (Melaku & Bitsuamlak, 2024). Reliable FSI simulations require precise modeling of a structure's mass, stiffness, and damping. Frame-based structural models (LMs) generated by structural analysis software are not directly compatible with CFD solvers, which require a continuous, continuum representation. Improper conversion processes can lead to distortions in dynamic characteristics, including directional stiffness, torsional coupling, and mode shape hierarchies (Firouzbakhsh et al., 2024). Recent research has scrutinized simplified isotropic stiffness models; however, these frequently neglect the anisotropic properties inherent in tall buildings (Hussin, 2024; YAN et al., 2025). Building upon advances in structural dynamics and computational fluid dynamics (CFD) aeroelasticity, this study introduces a systematic methodology for transforming skeletal models into Equivalent Solid Models (ESMs). The proposed approach integrates structural and aerodynamic modeling to enable high-accuracy Large Eddy Simulation (LES)-based Fluid-Structure Interaction (FSI) studies, using the CAARC benchmark to demonstrate that calibrated orthotropic materials can accurately replicate modal behavior. This effort aims to unify experimental, analytical, and computational techniques to advance wind engineering research.

2. METHODOLOGY

The dynamics of tall buildings involve bending, shear, and torsion, which are crucial for converting lattice models into solid ones. Dynamic equivalence ensures the ESM matches natural frequencies, directional stiffness, and modal interactions. The equivalent stiffness for LM-ESM calibration, based on Timoshenko beam theory, accounts for bending and shear in a uniform beam of height H, with transverse displacement $w(x,t)$and rotation $\phi(x,t)$. The coupled governing equation is given below in Eq.(1) (Rao, 2006) .

$$\rho A\, \ddot{w} = \frac{\partial}{\partial x}[\kappa AG\,(\varphi - w')];\ \text{and}\ \rho I\, \ddot{\varphi} = (EI\,\varphi')' + \kappa AG\,(w' - \varphi) \tag{1}$$

Assume harmonic motion (Rao, 2006)(Sharpe & Bentley, 1977), $w(x,t) = W(x)e^{(i\omega t)}$ and $\varphi(x,t) = \Phi(x)e^{(i\omega t)}$ and the harmonic motions follow the sinusoidal shapes(Rao, 2006; Timoshenko, 1985), $W=W_0 \sin(kx)$ and $\Phi=\Phi_0 \cos(kx)$ we get,

$$\rho A\rho I\omega^4 - [\rho AEIk^2 + \kappa AG\rho Ik^2 + \rho A\kappa AG]\,\omega^2 + \kappa AGEIk^4 = 0 \tag{2}$$

For a Slender/tall building/beam, the Fundamental frequency (mode-1, mode-2) is very low, so the contribution of ρI (rotary inertia) is very low. So, we can ignore the ρI-term from Eq. (2) (Rao, 2006). Furthermore, finally, we get Eq.(3).

$$\omega^2 = \frac{EI}{\rho A} * [\frac{k^4}{(1 + (EI/(\kappa AG))\,k^2)}]$$

$$\omega^2 = \frac{EI}{\rho A} * [\frac{(\frac{\beta_n}{L})^4}{(1 + (EI/(\kappa AG))\,(\frac{\beta_n}{L})^2)}] \tag{3}$$

where, $k_n=\beta_n/L$ for a cantilever beam as β_n: $\cosh\beta \cos\beta + 1 = 0$ (Rao, 2006; Timoshenko, 1985).

The bending stiffness factor, $k = \frac{EI}{\rho AL^4}$ (unit s^{-2}) ; And, $E = \frac{K\rho AH^4}{I}$ (4)

and the shear parameter, $q = \frac{EI}{\kappa AGL^2}$ (dimensionless); And, $G = \frac{EI}{\kappa AqH^2}$ (5)

So, the final equation for the circular frequency is, $\omega_n^2 = \frac{\beta_n^4 . k}{1 + \beta_n^2 . q}$ (6)

For two-mode swaying in the same direction, we can evaluate the q formula. Suppose for modes 1 and 2 in the same direction, we will get,

$$q = \frac{\beta_i^4\omega_j^2 - \beta_j^4\omega_i^2}{\beta_i^2\beta_j^2 - (\beta_j^2\omega_i^2 - \beta_i^2\omega_j^2)} \tag{7}$$

$$K = \frac{\omega_i^2(1 + \beta_i^2 . q)}{\beta_i^4} = \frac{\omega_j^2(1 + \beta_j^2 . q)}{\beta_j^4} \tag{8}$$

The first torsion frequency for a fixed-free bar is defined as (Rao, 2006), $\omega_\theta = \frac{\pi}{2H}\sqrt{\frac{G*J}{\rho . Ip}}$ (9)

Rearranging Eq.(9) for shear modulus, $G = \frac{4H^2}{\pi^2} * \omega_\theta^2 * \frac{\rho . Ip}{J}$ (10)

where, $J \approx bh^3(\frac{1}{3} - 0.21\frac{h}{b}(1 - \frac{h^4}{12.b^4}))$ is the torsion constant.

MAC quantifies the correlation between two mode shapes, helping us determine whether they exhibit the same vibration pattern (Gentile & Saisi, 2007; Pastor et al., 2012), which is defined by the Eq.(11).

$$\text{MAC}\ (\Phi_i,\Psi_j) = \frac{|\Phi_i^T\Psi_j|^2}{(\Phi_i^T\Phi_i)(\Psi_j^T\Psi_j)} \quad (11)$$

Where, ϕ_i and ψ_j, are the mode shape vectors from the lattice model (LM) and the equivalent solid model (ESM), with MAC values ranging from 0 to 1 (Gentile & Saisi, 2007).

Extracting modal data from the ETABS lattice model enables the determination of natural frequencies, mode shapes, and effective mass. We then calibrate the equivalent orthotropic material using Eq. (4)-(10) to match these modal frequencies. Next, a solid model is generated in CFD using this calibrated material. Finally, we verify modal results via frequency and MAC comparisons with Eq. (11), ensuring model accuracy. It is noted that no external damping is added to the structures, as damping does not affect modal frequencies.

3. RESULTS

The CAARC tall building (45 × 30 × 180 m) is modeled as a 40-story reinforced concrete frame with an interstory height of 4.5 m, beams of 0.8 × 0.4 m, and columns of 0.8 × 0.8 m. The solid model replicates the envelope and uses a tetrahedral mesh. Calibrated orthotropic material properties are shown in *Table 1* and the natural frequency comparison in *Table 2*.

Table 1: Calibrated orthotropic material properties for CAARC ESM

Parameters	E_1	E_2	E_3	G_{12}	G_{23}	G_{13}
MPa	174	332	332	3.61	2.47	2.44

Table 2: Comparison of SM and ESM modal parameters

Mode Number	f_{SM}	f_{ESM}	MAC
1	0.131	0.123	0.9995
2	0.135	0.136	0.9998
3	0.164	0.164	0.9984

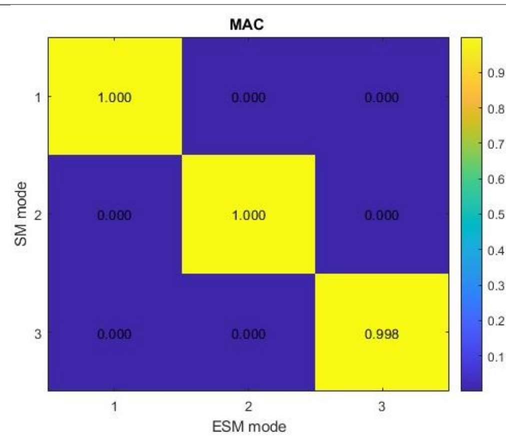

Figure 1: MAC plot for the CAARC building showing high correlation

4. DISCUSSION

The workflow links structural dynamics modeling to CFD without manual tuning. The first three modes of the Equivalent Solid Model closely match those of the skeletal model, with MAC values over 0.9 (Figure 1), indicating excellent modal correlation and accuracy. This confirms the framework's precision, efficiency, and robustness in maintaining modal identity and stiffness anisotropy. Removing trial-and-error tuning shortens setup time for LES-based FSI simulations and ensures consistent structural modeling across platforms. While only the CAARC case is shown, future studies on aspect ratio and damping calibration will be detailed in an upcoming journal article. It is also notable that the study only focuses on structural conversion, with no LES-based simulation.

5. CONCLUSIONS

A systematic and dynamically consistent SM-ESM conversion framework has been developed for the aeroelastic analysis of flexible tall buildings. By calibrating orthotropic materials, the Equivalent Solid Model accurately reproduces the modal characteristics of the skeletal model, with frequencies and MAC values that closely align. This validated framework seamlessly integrates with LES-based CFD solvers, forming a unified platform for high-fidelity FSI simulations and advancing future morphing structures. Ongoing research is extending this methodology to include aspect-ratio parametric studies and wind-induced morphing systems, with the goal of enhancing aerodynamic performance prediction.

REFERENCES

Dynamics of Structures eBook: Chopra, Anil: Amazon.ca: Kindle Store. (2023.). https://www.amazon.ca/Dynamics-Structures-Anil-K-Chopra-ebook/dp/B09V53KJCW

Firouzbakhsh, J., Malekinejad, M., & Rahgozar, R. (2024). Reducing the cost of calculations for stability analysis of tall buildings using a new approach. *Latin American Journal of Solids and Structures*, *21*(8), e558. https://doi.org/10.1590/1679-78258003

Gentile, C., & Saisi, A. (2007). Ambient vibration testing of historic masonry towers for structural identification and damage assessment. *Construction and Building Materials*, *21*(6), 1311–1321. https://doi.org/10.1016/J.CONBUILDMAT.2006.01.007

Hou, F., Sarkar, P. P., & Alipour, A. (2023). A novel mechanism—smart morphing façade system—to mitigate wind-induced vibration in tall buildings. *Engineering Structures*, *275*, 115152. https://doi.org/10.1016/J.ENGSTRUCT.2022.115152

Hussin, A. M. (2024). Numerical Simulation of Fluid-Structure Interactions on Super-Tall Slender Structures Using Two-Way Coupling Techniques. *Applied Mathematics and Information Sciences*, *18*(5), 1125–1140. https://doi.org/10.18576/amis/180518

Melaku, A. F., & Bitsuamlak, G. T. (2024). Prospect of LES for predicting wind loads and responses of tall buildings: A validation study. *Journal of Wind Engineering and Industrial Aerodynamics*, *244*, 105613. https://doi.org/10.1016/J.JWEIA.2023.105613

Pastor, M., Binda, M., & Harčarik, T. (2012). Modal assurance criterion. *Procedia Engineering*, *48*, 543–548. https://doi.org/10.1016/J.PROENG.2012.09.551

Rao, S. S. (2006). Frontmatter. *Vibration of Continuous Systems*, i–xxi. https://doi.org/10.1002/9780470117866.fmatter

Sharpe, R. D., & Bentley, R. J. (1977). Dynamics of Structures by Ray W. Clough and Joseph Penzien. McGraw-Hill 1975. 634 pp. illus. *Bulletin of the New Zealand Society for Earthquake Engineering*, *10*(2), 109–110. https://doi.org/10.5459/bnzsee.10.2.109-110

Timoshenko. (1985). *Theory of Elastic Stability - Stephen P. Timoshenko, James M. Gere - Google Books*. https://books.google.ca/books?id=98B6JOW2HiUC&printsec=frontcover&redir_esc=y#v=onepage&q&f=fals

YAN, B., Ran, Q., Yuan, Y., Ren, H., Li, X., Zhou, X., Yang, Q., & Liu, Q. (2025). Numerical investigation on the twisted wind-induced aeroelastic response of a square supertall building. *Journal of Fluids and Structures*, *137*. https://doi.org/10.1016/j.jfluidstructs.2025.104350