Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

Optimizing Mass Concrete Foundations for Low-Frequency Rotary Machines: Role of Rubberized Concrete and Geometric Modifications

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***Abstract* - Mass concrete foundations are widely used to support low-frequency rotary machines due to their high inertia and stiffness, which help in controlling vibration amplitudes and avoiding resonance. However, conventional mass concrete relies primarily on weight and stiffness, offering limited inherent damping. This study numerically investigates the dynamic performance of mass concrete machine foundations by incorporating material modification through rubberized concrete and geometric optimization through trapezoidal foundation shapes. Four foundation configurations are analyzed using three-dimensional finite element analysis of rectangular conventional concrete, rectangular rubberized concrete (10% coarse aggregate replacement), trapezoidal conventional concrete, and trapezoidal rubberized concrete. Static structural, modal, and steady-state harmonic response analyses are performed to evaluate stresses, deformations, natural frequencies, and vibration amplitudes under machine-induced dynamic loads from a low-frequency centrifugal pump. The results demonstrate that rubberized concrete significantly enhances damping and reduces vibration amplitudes, while trapezoidal geometry improves stiffness distribution and stress transfer to soil. The combined use of rubberized concrete and trapezoidal geometry provides the most effective vibration control, indicating a viable and sustainable alternative for foundations supporting low-frequency rotary machinery.**

Keywords - Mass concrete foundation; Rubberized concrete; Low-frequency rotary machine; Vibration control; Finite element analysis; Cuboid foundation; Trapezoidal foundation

I. INTRODUCTION

Low-frequency rotary machines such as pumps, compressors, and generators generate continuous dynamic forces due to imbalance, fluid interaction, and rotational motion. These forces are transmitted to the supporting foundation and soil, potentially causing excessive vibrations, resonance, and long-term structural degradation. Mass concrete foundations are commonly adopted for such machines because their large mass and stiffness help suppress vibration amplitudes and shift natural frequencies away from machine operating frequencies.

Despite their advantages, conventional mass concrete foundations exhibit relatively low inherent damping, making them sensitive to resonance when operating frequencies approach system natural frequencies. Recent research has shown that modifing concrete materials by incorporating rubber particles can significantly enhance damping characteristics. Additionally, foundation geometry plays a crucial role in stiffness distribution, stress transfer, and vibration response. Trapezoidal foundations, with wider bases and sloping sides, have been shown to improve load distribution and dynamic stability compared to conventional rectangular blocks.

This paper presents a numerical investigation into the combined effects of material modification (rubberized concrete) and geometric optimization (trapezoidal shape) on the dynamic performance of mass concrete foundations supporting low-frequency rotary machines.

II. LITERATURE REVIEW

A. *Review of Machine foundation dynamics and Rubberized Concrete*

Madhusudhan et al. (2024) investigated sand–rubber mixtures as vibration-dampening foundation materials using experimental and numerical methods. Their results showed that a 10% rubber content significantly improves damping characteristics, making such mixtures suitable for vibration-sensitive foundations.

Zhang et al. (2024) studied the multiaxial plastic deformation behavior of rubberized concrete and reported enhanced dilatancy and volumetric expansion under shear loading. The flexible rubber particles promoted improved energy dissipation and nonlinear deformation capacity.

Niu et al. (2021) experimentally examined the biaxial compressive behavior of rubberized concrete and observed improved deformation capacity and ductility compared to normal concrete. Rubberized specimens exhibited delayed failure and more distributed cracking under biaxial stress states.

Therese et al. (2020) reviewed vibration isolation techniques using sand–rubber mixtures and modified concrete materials. Their findings emphasized that structural incorporation of rubber-based materials provides more effective vibration control than surface treatments.

Wang et al. (2020) investigated the tensile behavior of rubberized concrete and reported reduced tensile strength but enhanced post-cracking deformability. The study highlighted

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improved ductility and vibration tolerance despite strength reduction.

Bhattacharya et al. (2019) emphasized the importance of dynamic analysis and soil–structure interaction in machine foundation design. Their work highlighted that proper frequency tuning and embedment depth reduce vibration amplitudes and resonance risks.

Belovolova et al. (2019) presented a comprehensive framework for designing foundations of pumps and compressors under dynamic loads. The study demonstrated that optimized foundation dimensions and vibration isolation materials improve operational stability.

Gerges et al. (2018) studied rubberized concrete with varying rubber content and found that 10% rubber replacement provides a balance between acceptable strength and enhanced damping. The material showed improved toughness and impact resistance.

Patel et al. (2017) analyzed machine foundations considering soil interaction and concluded that harder soils improve stiffness and reduce displacement. The study recommended an over-tuned design approach to avoid resonance in low-frequency machines.

Huang et al. (2017) experimentally evaluated rubberized concrete beams and reported increased ductility and strain capacity despite reduced compressive strength. Rubber inclusion enhanced deformability under cyclic loading.

Najim et al. (2016) investigated rubberized concrete under vibration loading and reported a significant increase in damping ratio at 10% rubber replacement. The reduction in stiffness contributed to lower natural frequencies and improved vibration attenuation.

Raffoul et al. (2016) studied the compressive behavior of rubberized concrete and observed reduced strength but increased ductility and energy absorption. The stress–strain response showed improved post-peak behavior compared to conventional concrete.

Patel et al. (2015) highlighted the influence of foundation geometry on vibration control in rotary machine foundations. Their results showed that stiffer geometric configurations reduce displacement and resonance effects.

Warudkar et al. (2015) demonstrated that rubber aggregate replacement up to 10% improves impact resistance and ductility. The study supported the use of rubberized concrete for vibration-sensitive and sustainable construction applications.

Gupta et al. (2014) conducted a parametric study on rubber content and concluded that 10% replacement provides optimal damping enhancement with manageable strength loss. The study provides practical guidance for vibration-controlled foundations.

Xue et al. (2013) reported significant increases in damping ratio and reductions in peak acceleration for rubberized concrete. The reduced natural frequency was found beneficial for avoiding resonance in low-frequency systems.

Xiong et al. (2011) reviewed vibration isolation techniques including sand–rubber mixtures and periodic foundations. Their findings confirmed the effectiveness of composite materials in reducing seismic and machine-induced vibrations.

Najim et al. (2010) studied rubber–cement bond behavior and identified weak interfacial bonding as the main cause of strength reduction. The study emphasized careful mix design for structural applications.

Skripkiūnas et al. (2009) reported reduced stiffness and increased deformability in rubberized concrete, contributing to improved vibration isolation. These properties were found suitable for low-frequency machine foundations.

Bhatia et al. (2008) emphasized the necessity of dynamic analysis and finite element modeling in modern machine foundation design. The study highlighted soil–structure interaction and damping effects as critical factors.

Zheng et al. (2008) observed significant improvement in damping ratios and reduction in natural frequency with rubber inclusion. Low rubber contents provided effective vibration control without excessive strength loss.

Turatsinze et al. (2008) characterized rubberized concrete and reported reduced density and stiffness with improved deformability. These properties enhance vibration isolation capability.

Wolf et al. (2004) demonstrated that optimized foundation geometry can reduce vibration response without excessive material use. Their work supports geometric refinement in vibration-sensitive foundations.

Li et al. (2004) reported improved damping and post-cracking behavior in waste-tire-modified concrete. The study confirmed its suitability for dynamic structural applications.

Yan et al. (2000) showed that fibre-reinforced concrete exhibits higher damping ratios due to interfacial friction mechanisms. Enhanced energy dissipation was observed under cyclic vibration.

Lee and Fenves (1998) developed a plastic-damage model capturing stiffness degradation and cyclic damage in concrete. The model provides a basis for nonlinear numerical analysis.

Kramer et al. (1996) provided fundamental concepts of dynamic soil behavior applicable to machine foundation vibration analysis. Their work is widely used for defining soil damping parameters.

Topcu et al. (1995) experimentally confirmed increased damping and ductility in rubberized concrete. The study emphasized controlled rubber content for structural applications.

Menetrey and Willam (1995) proposed a triaxial failure model for concrete incorporating dilatancy and biaxial strength enhancement. The model is widely used in nonlinear concrete analysis.

Eldin et al. (1993) demonstrated enhanced energy absorption and crack resistance in rubberized concrete under cyclic loading. Their work established rubberized concrete as a damping-enhanced material.

Gazetas et al. (1991) highlighted the influence of foundation geometry and embedment on dynamic stiffness and damping. Their formulations remain fundamental in vibration analysis.

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Prakash and Puri (1988) developed a unified analytical framework for machine foundation design forming the basis of IS 2974. Their work emphasized mass-based vibration control and resonance avoidance.

Wolf (1985) presented advanced soil–structure interaction theories under dynamic loading. The formulations support validation of numerical machine foundation models.

Hillerborg et al. (1976) introduced the fictitious crack model explaining tensile softening and fracture behavior of concrete. The model remains fundamental in nonlinear concrete mechanics.

Novak et al. (1972) demonstrated that foundation embedment increases dynamic stiffness and damping, reducing vibration amplitudes. The findings are directly applicable to mass concrete foundations.

Richart et al. (1970) established fundamental concepts of vibration transmission through soil–foundation systems. Their work remains a benchmark reference in dynamic foundation analysis.

Lysmer et al. (1969) introduced absorbing boundary concepts for finite element modeling of infinite soil domains. This contribution is essential for realistic dynamic FEA simulations.

Kupfer et al. (1969) experimentally demonstrated biaxial strength enhancement in concrete. Their results form the basis for multiaxial concrete constitutive models.

Barkan et al. (1962) provided one of the earliest analytical treatments of machine foundation vibrations. Their principles on mass ratio and frequency separation continue to influence modern design codes.

B. Material Properties adopted from Literature

Table: Material Properties for M40 Normal Concrete grade

Material Property	Values	References
Density	2451 kg/m³	IS 456:2000 – Plain and Reinforced Concrete
Young's Modulus	3.044×10^{10} Pa	IS 456:2000; Najim & Hall (2016)
Poisson's Ratio	0.2	IS 456:2000
Bulk Modulus	1.6911×10^{10} Pa	Derived from E & ν (elasticity theory – Timoshenko & Goodier)
Shear Modulus	1.2683×10^{10} Pa	Derived from E & ν (elasticity theory – Timoshenko & Goodier)
Uniaxial Compressive Strength	4.1369×10^{7} Pa	Najim & Hall (2016); IS 456:2000
Uniaxial Tensile Strength	3.999×10^{6} Pa	IS 456:2000 (Cl. 6.2.2)
Biaxial Compressive Strength	4.7919×10^{7} Pa	Kupfer et al. (1969); Menetrey & Willam (1995)
Dilatancy Angle	30 degrees	Menetrey & Willam (1995)
Softening	Linear	ANSYS Concrete Material Model Documentation
Plastic Strain at Uniaxial Compressive Strength	0.001	Menetrey & Willam (1995); ANSYS User Guide
Ultimate Effective Plastic Strain in Compression	0.01	Lee & Fenves (1998)
Relative Stress at Start of Nonlinear Hardening	0.4	ANSYS Concrete Model Calibration
Residual Compressive Relative Stress	0.2	Lee & Fenves (1998)
Plastic Strain Limit in Tension	0.01	Hillerborg et al. (1976)
Residual Tensile Relative Stress	0.2	ANSYS Concrete Damage Model
Damping Ratio	0.03	Najim & Hall (2016); Xue & Shinozuka (2013)
Constant Structural Damping Coefficient	0.06	ANSYS Structural Damping Definition

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Table2: 10% Rubberized Concrete Properties

Material Properties	Values	Reference
Density	2100 kg/m³	Turatsinze, et al., 2008
Young's Modulus	2.2×10^{10} Pa	Turatsinzea, et. al., 2008
Poisson's Ratio	0.28	Turatsinze, et al., 2008
Bulk Modulus	1.6667×10^{10} Pa	Derived from E & ν (elasticity theory – Timoshenko & Goodier)
Shear Modulus	8.5938×10^{9} Pa	Derived from E & ν (elasticity theory – Timoshenko & Goodier)
Uniaxial Compressive Strength	3.3×10^{7} Pa	Raffoul, et al., 2016 [9]
Uniaxial Tensile Strength	2.16×10^{6} Pa	Wang, et. al., 2020 [4]
Biaxial Compressive Strength	4.7919×10^{7} Pa	Niu, et. al., 2021 [2]
Dilatancy Angle	30 degrees	Menetrey & Willam (1995), Zhang, et. al., 2024
Softening	Linear	Menetrey & Willam (1995)
Plastic Strain at Uniaxial Compressive Strength	0.001	Menetrey & Willam (1995)
Ultimate Effective Plastic Strain in Compression	0.01	Lee & Fenves (1998)
Relative Stress at Start of Nonlinear Hardening	0.4	Lee & Fenves (1998)
Residual Compressive Relative Stress	0.2	Lee & Fenves (1998)
Plastic Strain Limit in Tension	0.01	Hillerborg et al. (1976)
Residual Tensile Relative Stress	0.2	Hillerborg et al. (1976)
Damping Ratio	0.075	Turatsinze et al. (2008); Raffoul et al. (2016)
Constant Structural Damping Coefficient	0.15	Zhang et al. (2024)

III. METHODOLOGY

A. *System Description*

The study considers a centrifugal pump operating at 520 RPM (8.67 Hz) as a representative low-frequency rotary machine. The pump is mounted on a mass concrete foundation supported by dense sandy soil. Dynamic loads include self-weight, machine weight, thrust force, fluid pulsation forces, and radial pulsation forces arising from impeller–fluid interaction.

B. *Foundation Configurations*

- Rectangular conventional M40 mass concrete foundation (RCF–CC)
- Rectangular rubberized concrete foundation with 10% rubber replacement (RCF–CRC)
- Trapezoidal conventional M40 mass concrete foundation (TCF–CC)
- Trapezoidal rubberized concrete foundation with 10% rubber replacement (TCF–CRC)

C. *Material Properties*

Conventional M40 concrete properties are adopted as per IS 456 and established literature. Rubberized concrete properties correspond to 10% coarse aggregate replacement, incorporating reduced density and elastic modulus with enhanced damping ratio. Nonlinear material behaviour is represented using the Menetrey–Willam concrete model, while damping is introduced through modal and structural damping coefficients.

D. *Finite Element Modelling*

Three-dimensional finite element models are developed in ANSYS using SOLID185 elements. Soil–foundation interaction is modelled using appropriate boundary conditions and subgrade stiffness. The analysis sequence includes:

- Static structural analysis to evaluate stresses and deformations under gravity and machine loads.
- Modal analysis to determine natural frequencies and mode shapes.
- Steady-state harmonic response analysis to assess vibration amplitudes under harmonic excitation corresponding to machine operating frequency and vane-passing frequency.

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IV. LOADS CONSIDERED FOR MACHINE FOUNDATION DESIGN

The mass concrete foundation supporting the low-frequency rotary centrifugal pump is subjected to a combination of static and dynamic loads. In accordance with IS 2974 (Part IV):1992, all loads that influence the vibration response and structural safety of the machine–foundation system are explicitly considered. These loads are categorized as dead loads, static machine loads, and dynamic (operational) loads.

A. Dead Load (Self-Weight of Foundation)

The dead load consists of the self-weight of the mass concrete foundation block. This load is calculated based on the geometry of the foundation (rectangular or trapezoidal) and the material density of concrete. Density of M40 concrete = 2451 kg/m³. Density of 10% rubberized concrete ≈ 2100 kg/m³.

B. Machine Weight (Static Load)

Total machine weight is 544 kg (≈ 5.34 kN), this load is transferred to the foundation through anchor bolts and base plate contact. As recommended in IS 2974 (Part IV), the machine weight is treated as a constant vertical load acting at the center of gravity of the machine.

C. Dynamic Loads Due to Machine Operation

The thrust force is approximately 1790 N, acting in the negative Y-direction. This thrust is assumed to be equally distributed among the four anchor bolts, resulting in a thrust load of 447.5 N per bolt. This load is considered as a continuous operational force acting throughout machine operation.

Due to eccentricity between the line of action of thrust force and bolt locations, overturning moments are generated as Moment at near bolts (0.1524 m offset) ≈ 68.12 Nm and Moment at far bolts (0.254 m offset) ≈ 113.67 Nm. These moments act about the Z-axis and contribute to torsional excitation of the foundation block.

Fluid pulsation force arises due to pressure fluctuations caused by vane-passing action in the impeller. In accordance with conservative assumptions adopted in the document, the pulsation amplitude is taken as 2% of the steady thrust force, the Pulsation force amplitude ≈ 36 N. The pulsation force is modelled as a harmonic load acting at the excitation frequency of the pump.

As per IS 2974 (Part IV), the excitation frequency of rotary machines with repeating components is calculated as:

$$f = \frac{n \times N}{60}$$

where:

- $N = 520$ RPM (pump speed)
- $n = 5$(number of effective vanes)

The resulting excitation frequency is 43.3 Hz. This frequency governs harmonic response analysis and resonance checks.

The rotating fluid inside the impeller produces centripetal forces. Based on the estimated mass of fluid per vane (≈ 0.436 kg) and angular velocity, the centripetal force per vane is approximately 165 N. For conservative design, the worst-case radial pulsation force is assumed as 50% of the centripetal force, resulting in a dynamic radial load of about 82.5 N per vane acting periodically.

V. RESULTS AND DISCUSSIONS

The cuboid concrete (CC) foundation exhibits a nearly uniform stress distribution along its height, with maximum tensile and compressive stresses of approximately 0.67 MPa and –1.19 MPa, respectively. Peak stresses are concentrated near the top surface due to direct machine load transfer, reflecting the high stiffness and limited stress redistribution of conventional concrete.

In the cuboid rubberized concrete (CRC) foundation, tensile stress increases to about 0.95 MPa, while compressive stress remains comparable at –1.15 MPa. The stress contours are more diffused, indicating improved stress redistribution and energy absorption resulting from reduced stiffness and enhanced damping of rubberized concrete.

The trapezoidal concrete (TC) foundation shows a modified stress pattern due to geometric variation. Tensile stress is approximately 0.81 MPa, while compressive stress increases to about –1.54 MPa. Stress concentrations shift from the top surface to the transition region between vertical and sloping faces, demonstrating improved load dispersion toward the wider base.

The trapezoidal rubberized concrete (TRC) foundation exhibits the most favorable stress response, with tensile stress reduced to 0.43 MPa and compressive stress of approximately –1.66 MPa. Stress distribution is more uniform, with minimal concentration near the machine–foundation interface, due to the combined effects of enhanced damping and optimized geometry.

Overall, rubberized concrete improves stress diffusion, while trapezoidal geometry enhances load transfer efficiency. The TRC foundation provides the most effective combination of reduced tensile stress, stability, and damping for low-frequency rotary machine foundations.

The cuboid concrete (CC) foundation shows a relatively uniform strain distribution, with a maximum tensile strain of 2.26×10^{-5} and a compressive strain of -1.91×10^{-5}, concentrated near the machine–foundation interface due to direct load transfer and high stiffness.

In the cuboid rubberized concrete (CRC) foundation, elastic strain increases to 3.29×10^{-5} in tension and -2.99×10^{-5} in compression. The strain contours are more diffused, reflecting reduced stiffness and enhanced deformability, which contributes to improved energy dissipation.

The trapezoidal concrete (TC) foundation exhibits redistributed strain due to geometric modification, with tensile strain of 2.16×10^{-5} and compressive strain of -2.52×10^{-5}. Higher strains occur near the transition between vertical and sloping faces, indicating effective deformation transfer toward the wider base.

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The trapezoidal rubberized concrete (TRC) foundation demonstrates the most uniform strain distribution, with tensile strain of 2.39×10^{-5} and compressive strain reaching -6.55×10^{-5}. Although strain magnitudes are higher, the smoother distribution indicates controlled deformation and superior damping performance. Overall, the combined use of rubberized concrete and trapezoidal geometry provides favorable strain behaviour for low-frequency machine foundations.

The cuboid concrete (CC) foundation exhibits peak shear stresses of approximately $\pm 5.7 \times 10^5$ Pa, concentrated near the machine–foundation interface due to the rigid response of conventional concrete.

In the cuboid rubberized concrete (CRC) foundation, the maximum shear stress reduces to 4.26×10^5 Pa, with more diffused stress contours. This reduction highlights the role of rubber inclusion in enhancing stress redistribution and energy absorption.

The trapezoidal concrete (TC) foundation experiences increased shear demand at geometric transition zones, with maximum and minimum shear stresses of 5.37×10^5 Pa and -1.00×10^6 Pa, respectively. While the trapezoidal shape improves load transfer, it introduces localized shear concentration in normal concrete.

The trapezoidal rubberized concrete (TRC) foundation exhibits the lowest shear stress response, with peak values of 2.59×10^5 Pa and -6.42×10^5 Pa. The stress distribution is more uniform, indicating effective mitigation of shear concentration through combined geometric optimization and material damping.

Overall, rubberized concrete consistently reduces peak shear stresses, while trapezoidal geometry enhances load transfer efficiency. The TRC foundation provides the most favorable shear stress performance under combined vertical and lateral machine loading.

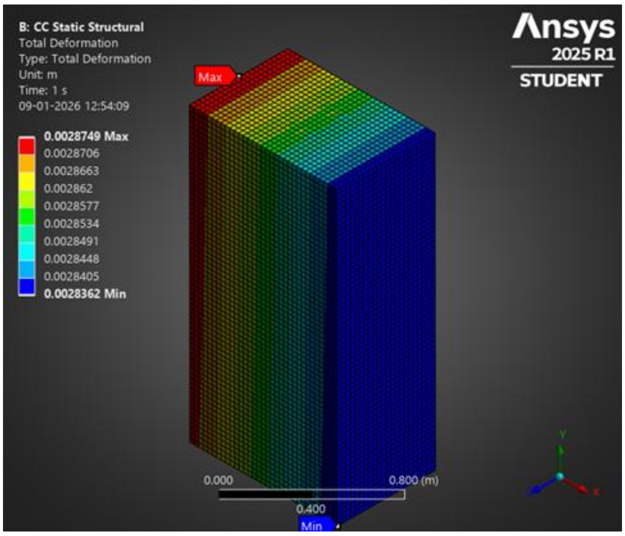
The static deformation results show a clear quantitative improvement with changes in material and geometry. The cuboidal concrete (CC) foundation exhibits the highest maximum total deformation of 0.002875 m. Replacing conventional concrete with rubberized concrete in the same cuboidal geometry (CRC) reduces the deformation to 0.002566 m, representing a reduction of about 10.8%, indicating the influence of material modification. A more significant reduction is observed with geometric optimization: the trapezoidal concrete (TC) foundation shows a maximum deformation of 0.001970 m, which is approximately 31.5% lower than that of CC. The trapezoidal rubberized concrete (TRC) foundation demonstrates the lowest deformation of 0.001775 m, achieving an overall reduction of about 38.3% compared to CC. These results indicate that foundation geometry has a dominant effect on static deformation control, while the use of rubberized concrete provides an additional but comparatively smaller reduction in deformation. Shown in figures1,2,3,4.

For the cuboid geometry, the CC foundation exhibited its first six natural frequencies between 10.64 Hz and 25.70 Hz, while the CRC foundation showed slightly higher values ranging from 11.48 Hz to 27.73 Hz. In both cases, the fundamental frequencies are well below the machine operating frequency of 43.33 Hz, ensuring adequate separation from resonance as per IS 2974 (Part IV). A significant difference is observed in damping characteristics: CRC exhibits a much higher modal damping ratio (≈0.074) in higher modes compared to ≈0.03 for CC, indicating superior vibration energy dissipation due to rubber inclusion.

Similarly, for trapezoidal foundations, TRC shows improved damping behavior compared to TC, confirming that rubberized concrete enhances vibration attenuation irrespective of geometry.

Comparing geometries, trapezoidal foundations (TC and TRC) show slightly higher fundamental frequencies than their cuboid counterparts due to improved stiffness and better mass distribution. The trapezoidal shape reduces stress concentration and promotes more uniform load transfer, resulting in improved dynamic stability. Higher modes for trapezoidal foundations also occur at lower frequencies than cuboid foundations, indicating reduced local stiffness effects.

The harmonic response analysis at an excitation frequency of 1000 Hz shows clear and consistent differences in total deformation among the four foundation configurations—Cuboid Concrete (CC), Cuboid Rubberized Concrete (CRC), Trapezoidal Concrete (TC), and Trapezoidal Rubberized Concrete (TRC). The CC foundation exhibits the highest total deformation, with a maximum value of approximately 1.40×10^{-6} m, indicating a comparatively higher dynamic response under harmonic loading for the plain cuboid geometry. When rubberized concrete is used in the same cuboid shape (CRC), the maximum deformation reduces to about 7.77×10^{-7} m, showing a significant decrease in vibration amplitude due to the improved damping characteristics of rubberized concrete. A much larger reduction in deformation is observed when the geometry is changed to trapezoidal: the TC foundation records a very low maximum deformation of about 2.59×10^{-8} m, demonstrating the effectiveness of trapezoidal geometry in enhancing stiffness and reducing dynamic response. The TRC foundation shows a slightly higher deformation than TC, around 3.02×10^{-8} m, which is attributable to the added flexibility of rubberized concrete, yet the response remains extremely small and well within acceptable limits. Overall, the results indicate that geometry has a dominant influence on harmonic deformation, while rubberized concrete further improves vibration control, with the trapezoidal foundations (TC and TRC) providing the best dynamic performance among all cases analyzed.



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ISSN: 2278-0181
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FIGURE 1: STATIC ANALYSIS OF CC – TOTAL DEFORMATION

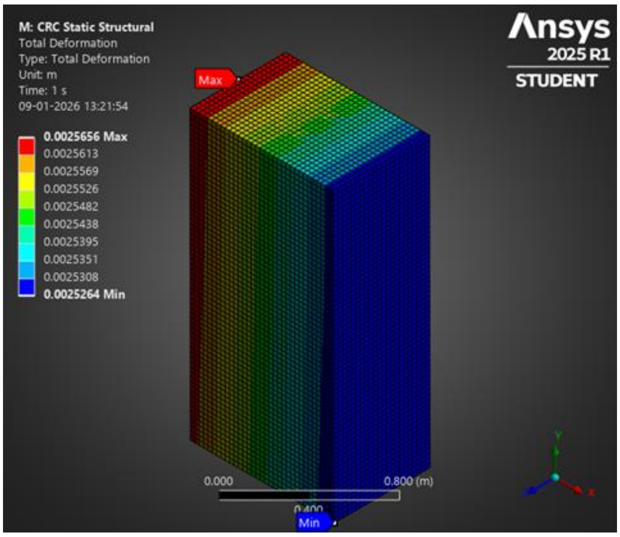

FIGURE 2: STATIC ANALYSIS OF CRC – TOTAL DEFORMATION

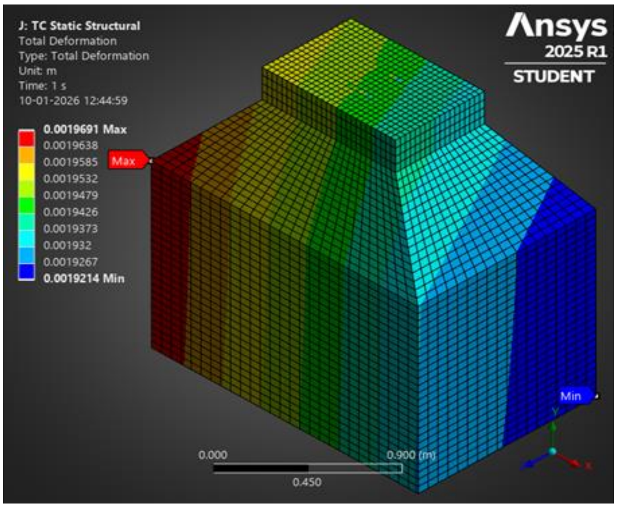

FIGURE 3: STATIC ANALYSIS OF TC – TOTAL DEFORMATION

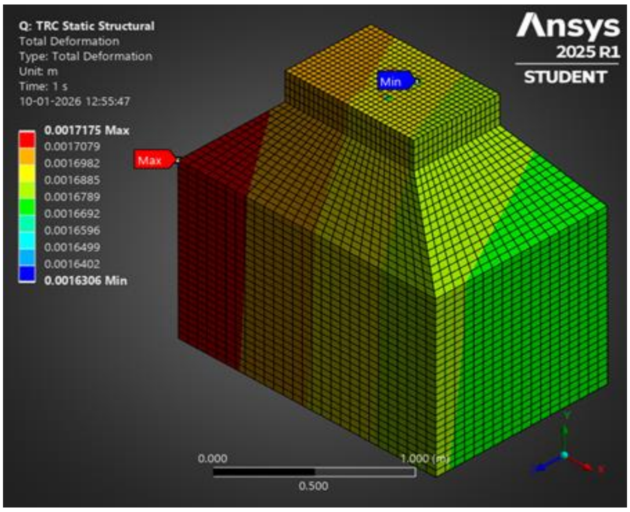

FIGURE 4: STATIC ANALYSIS OF TRC – TOTAL DEFORMATION

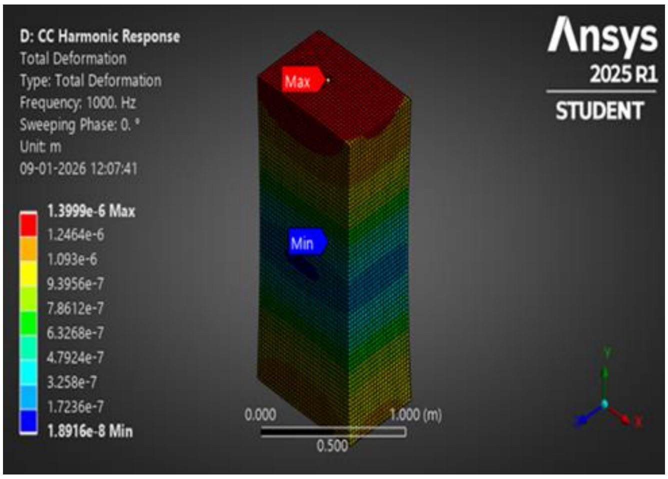

FIGURE 5: HARMONIC RESPONSE OF CUBOID CONCRETE - TOTAL DEFORMATION

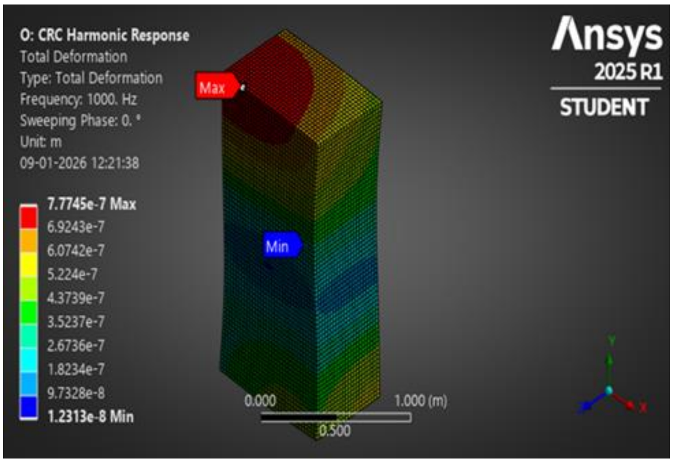

FIGURE 6: HARMONIC RESPONSE OF CUBOID RUBBERIZED CONCRETE – TOTAL DEFORMATION

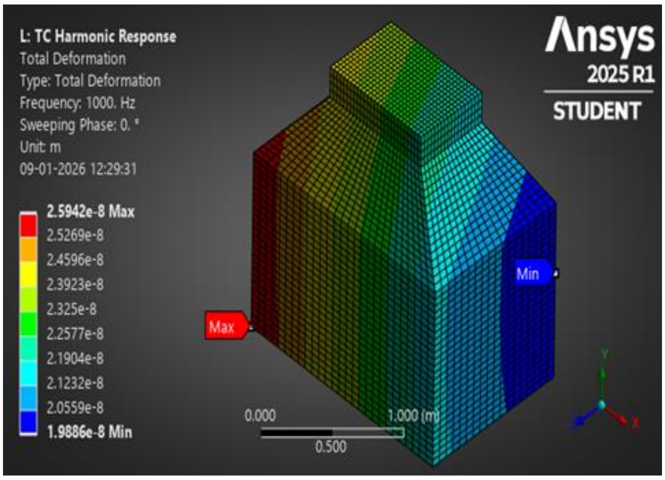

FIGURE 7: HARMONIC RESPONSE OF TRAPEZOIDAL CONCRETE – TOTAL DEFORMATION

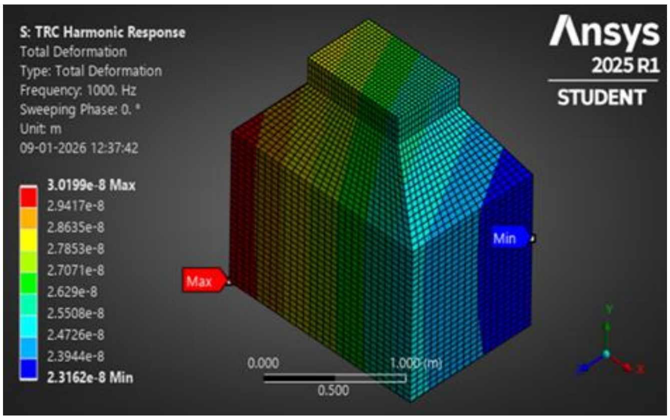

FIGURE 8: HARMONIC RESPONSE OF TRAPEZOIDAL RUBBERIZED CONCRETE – TOTAL DEFORMATION

a.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to my project supervisor Dinesh Pandit Assistant Professor, Department of Civil Engineering, CSMSS Chhatrapati Sambhajinagar, for his continuous guidance, valuable suggestions, and constant encouragement throughout the course of this research work. His technical expertise and constructive feedback played a vital role in the successful completion of this study.

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Vol. 15 Issue 01 , January - 2026

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