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A COMPUTATIONAL FRAMEWORK FOR HFRP-BASED REHABILITATION OF REINFORCED CONCRETE CHEMICAL CONTAINMENT POOLS

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Abstract:

Reinforced concrete chemical containment pools are exposed to hydrostatic pressure, chemical attack, and moisture penetration, which can compromise their structural integrity and liquid-retaining performance. This study presents a preliminary computational framework for evaluating the effect of hybrid fiber-reinforced polymer (HFRP) rehabilitation on such structures, demonstrated through finite element modal analysis. Two three-dimensional SAP2000 models with identical geometry, material properties, and support conditions were compared: an existing reinforced concrete pool and the same pool retrofitted with a 5 mm thick HFRP layer applied to the inner and outer wall faces and the bottom slab. The modal analysis showed that HFRP rehabilitation increased all of the first five natural frequencies by approximately 25%. Because the composite layer adds little mass, this increase is attributed mainly to the additional stiffness it provides. The results indicate that modal frequencies can serve as a practical indicator of the stiffness change produced by rehabilitation. However, the present analysis is limited to the free vibration of an undamaged, empty pool. Hydrostatic and fluid–structure loading, stress and displacement response, local stress concentrations, concrete–composite interface behavior, and chemical durability were not evaluated, and the numerical results have not been experimentally validated. The framework is therefore intended as a basis for the preliminary comparison of HFRP rehabilitation alternatives and for subsequent static, dynamic, and durability studies.

Keywords: Hybrid fiber-reinforced polymer (HFRP); reinforced concrete; chemical containment pools; modal analysis; finite element method.

I. INTRODUCTION

Reinforced concrete chemical containment pools are critical components of industrial facilities in which hazardous liquids, process chemicals, and potentially corrosive substances must be stored or controlled safely. The structural integrity of these systems is essential not only for maintaining operational continuity but also for preventing environmental contamination and minimizing risks to human health. Unlike conventional reinforced concrete structures, chemical containment pools may be exposed simultaneously to sustained hydrostatic pressure, aggressive chemical agents, moisture penetration, temperature variations, and localized mechanical damage. The combined influence of these conditions can accelerate material degradation and compromise both the load-bearing capacity and liquid-retaining performance of the structure. Consequently, the rehabilitation of existing containment pools requires an approach that addresses structural safety and long-term durability within a unified engineering framework.

Concrete provides favorable compressive strength and construction versatility; however, its performance may deteriorate when it is exposed to chemically aggressive environments. Depending on the chemical composition, concentration, exposure duration, and environmental conditions, aggressive substances can alter the cementitious matrix, increase permeability, and promote the deterioration of embedded steel reinforcement. The development of cracks, surface deterioration, reinforcement corrosion, and the loss of effective concrete cover may further reduce structural reliability. In containment facilities, these deterioration mechanisms are particularly significant because structural damage can lead to leakage even when the remaining load-bearing capacity appears adequate. Therefore, rehabilitation strategies should consider multiple performance requirements, including strength, stiffness, crack control, chemical resistance, and containment integrity.

Conventional rehabilitation techniques, such as concrete replacement, section enlargement, and the application of protective coatings [1]-[4], can provide practical solutions for particular deterioration mechanisms. Nevertheless,

these methods may involve substantial construction activities, extended shutdown periods, additional structural weight, or difficulties in achieving durable protection under severe exposure conditions. Furthermore, repairing visible damage does not necessarily restore the original mechanical behavior of the structure or prevent the recurrence of deterioration. These limitations have encouraged the development of advanced composite-based rehabilitation systems that can supplement the existing structural material while providing additional resistance against environmental degradation [5]-[7].

Fiber-reinforced polymer (FRP) composites represent a promising option for strengthening and protecting deteriorated reinforced concrete elements [8]-[11]. Their potential advantages include a high strength-to-weight ratio, corrosion resistance, and the ability to be installed as externally bonded reinforcement with relatively limited changes to the existing structural geometry. Hybrid fiber-reinforced polymer (HFRP) systems extend this concept by combining different fiber types within a composite configuration [12], [13]. Depending on the selected fibers, matrix properties, reinforcement arrangement, and bonding characteristics, hybridization may provide opportunities to balance stiffness, tensile capacity, deformation behavior, durability, and material cost. However, the effectiveness of an HFRP rehabilitation system cannot be assumed to be identical for all structures or exposure conditions. Its performance depends on the interaction between the composite layer, the existing concrete substrate, the reinforcement detailing, and the demands imposed on the containment structure.

The application of HFRP to chemical containment pools presents a specific engineering challenge because structural strengthening and environmental protection must be considered together. The addition of a composite layer may modify the stiffness distribution, stress transfer mechanisms, crack development, and deformation response of the rehabilitated structure. At the same time, the durability of the intervention depends on the integrity of the composite matrix, the quality of the concrete composite interface, surface preparation, and the compatibility of the rehabilitation materials with the anticipated chemical exposure. Particular attention must also be given to local stress concentrations around corners, wall base junctions, discontinuities, and existing cracks. These regions may govern the performance of the rehabilitation system even when the overall structural response appears satisfactory.

Computational modelling offers an effective means of investigating these interacting mechanisms and evaluating alternative rehabilitation configurations before implementation [12], [14]-[19]. Numerical analysis can be used to establish the response of an existing containment pool, identify critical stress and deformation regions, and estimate the changes associated with the introduction of an HFRP strengthening system. Finite element modelling, in particular, enables the representation of the pool geometry, material properties, support conditions, loading scenarios, and reinforcement configurations within a consistent analytical environment. When supported by appropriate constitutive assumptions and reliable material parameters, such models can facilitate comparisons between unrehabilitated and rehabilitated configurations and help identify the parameters that most strongly influence structural performance. Nevertheless, numerical predictions remain dependent on modelling assumptions, boundary conditions, interface representation, and the availability of suitable validation data.

Despite the growing engineering interest in composite-based strengthening, the rehabilitation of reinforced concrete chemical containment pools requires a performance-oriented methodology that reflects the combined structural and environmental demands specific to these facilities. A framework developed for conventional beams, columns, tunnels, or culverts [10], [11] cannot automatically be transferred to containment pools without accounting for their distinct geometry, liquid-retaining function, exposure conditions, and local stress distributions. In particular, a systematic computational procedure is needed to connect the assessment of the existing structure with the selection of HFRP properties, the definition of rehabilitation configurations, and the evaluation of post-rehabilitation performance. Such a procedure should also distinguish improvements in structural response from assumptions concerning long-term chemical durability, which require appropriate material characterization and, where necessary, experimental verification [20], [21].

In this context, the present study proposes a preliminary computational framework for the HFRP-based rehabilitation of reinforced concrete chemical containment pools and demonstrates its use through finite element modal analysis. Two models of the same pool, one existing and one retrofitted with HFRP, are created under identical conditions, and their natural frequencies and mode shapes are compared to quantify the change in dynamic behavior and stiffness produced by the rehabilitation system. The study is limited to free-vibration behavior of an undamaged, empty pool. Stress and displacement response, hydrostatic and fluid–structure loading, local stress concentrations, interface behavior, and chemical durability are outside its scope and are identified as subjects for further investigation.

The contribution of this work is a comparative numerical basis for evaluating how HFRP rehabilitation modifies the stiffness and modal properties of a reinforced concrete containment pool. The modal frequencies obtained for the existing and retrofitted configurations provide a simple and practical indicator for the preliminary comparison of rehabilitation alternatives. The framework is intended as a starting point for subsequent studies that include fluid–structure loading, parametric variation of HFRP thickness, fiber hybridization, and coverage area, interface modelling, and experimental validation together with durability tests under representative chemical exposure.

II. MATERIAL AND METHOD

A preliminary computational framework was developed to investigate the effect of hybrid fiber-reinforced polymer (HFRP) rehabilitation on the dynamic characteristics of reinforced concrete chemical containment pools. Two three-dimensional finite element models with identical geometry were considered: an existing reinforced concrete pool and

the same pool retrofitted with HFRP. To ensure that the differences in the results are attributable to the rehabilitation alone, the pool geometry, wall and slab dimensions, support conditions, and concrete properties were kept the same in both models, so that the presence of the HFRP layer was the only variable. Both models were analyzed in SAP2000 by modal analysis under free-vibration conditions, and the first five natural frequencies and mode shapes were compared as indicators of the change in structural stiffness. The pools were modelled in an undamaged and empty state; hydrostatic loading, fluid–structure interaction, and material deterioration were not considered. The modelling follows conventional finite element principles commonly employed in the assessment of reinforced concrete structures retrofitted with FRP [10], [11], [16].

A. Description of RC Chemical Containment Pools

The reinforced concrete chemical containment pool model is a single-story reinforced concrete structure with five spans in the x-direction and three spans in the y-direction (4 m) and a story height of 2 m. Slab and wall thickness is 15 cm. The finite element model of the RC chemical containment pool was created using the SAP2000 program. The finite element model of the pool is given in Figure 1. Mechanical properties of concrete are given in Table 1.

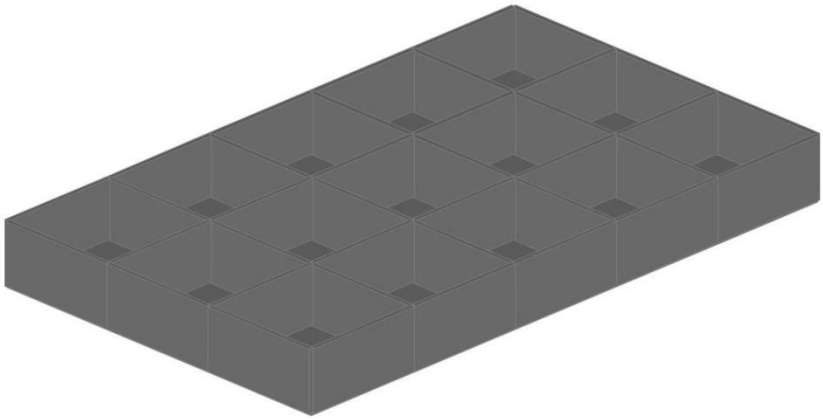


Fig 1. 3D View of existing reinforced concrete chemical containment pool

Table 1. Mechanical properties of concrete

Material	Modulus of Elasticity (kN/m^2)	Poisson's Ratio	Weight Per Unit Volume (kN/m^3)
Concrete	$33x10^6$	0.20	25

B. Description of Chemical Retrofitted RC Containment Pools

The existing reinforced concrete chemical containment pool is retrofitted with a 5 mm thick HFRP layer applied to the inner and outer faces of the walls and to the bottom slab. Thus, a retrofitted model was created. The finite element model of the retrofitted pool is given in Figure 2. Mechanical properties of HFRP are given Table 2.

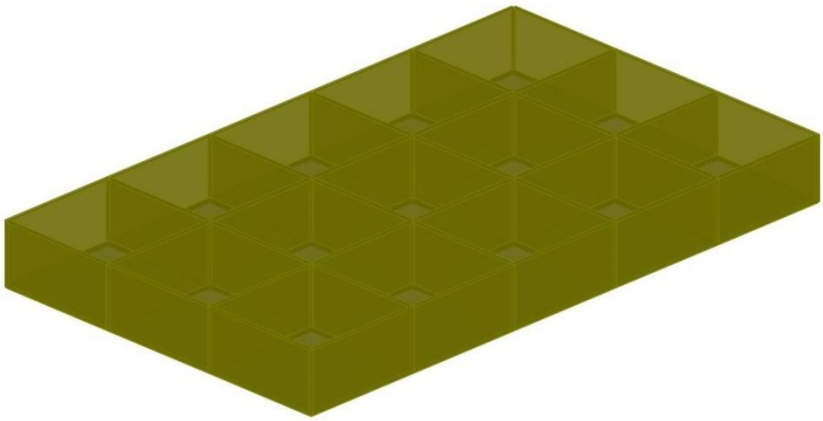


Fig 2. 3D View of retrofitted reinforced concrete chemical containment pool

Table 2. Mechanical properties of HFRP

Material	Modulus of Elasticity (kN/m^2)	Poisson's Ratio	Weight Per Unit Volume (kN/m^3)
HFRP	$85x10^6$	0.34	15.50

III. RESULTS

A. Modal Analysis Results of RC Chemical Containment Pools

The modal analysis of the reinforced concrete chemical containment pool was conducted to investigate its dynamic properties under free-vibration conditions and to assess the potential influence of HFRP-based rehabilitation on its vibration behavior [8], [22]. The first five vibration modes and shapes were considered to characterize the predominant dynamic response of the structure and to identify the principal deformation patterns that may influence its overall structural performance. The natural frequencies and their corresponding mode shapes obtained from the finite element analysis provide valuable information regarding the stiffness characteristics, mass distribution, and dynamic behavior of the containment pool. A comparative evaluation of the existing and HFRP-rehabilitated configurations enables the effects of the rehabilitation system on the modal properties of the structure to be examined. The results of the modal analysis are presented in Figures 3-7, illustrating the first five natural frequencies and their associated mode shapes, followed by an assessment of their significance in evaluating the dynamic performance of the reinforced concrete chemical containment pool.

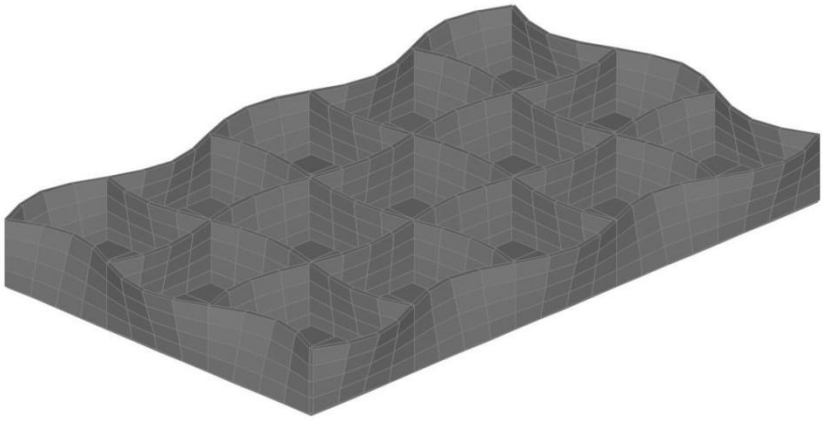


Fig. 3 1st Mode shape (Frequency value = 31.68 Hz)

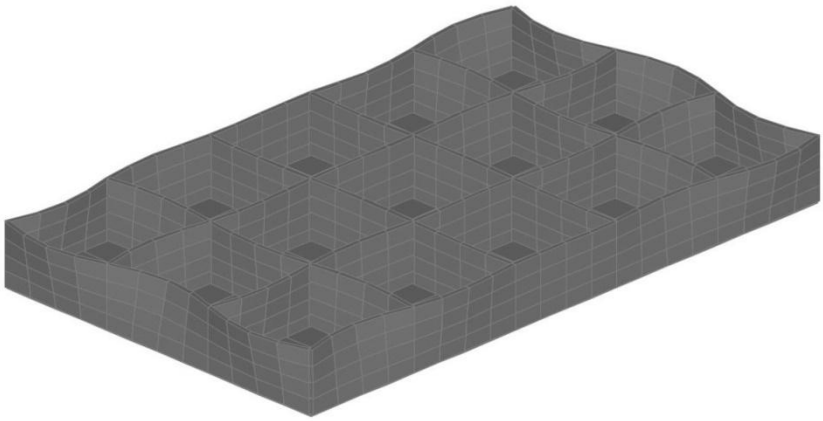


Fig. 4 2nd Mode shape (Frequency value = 31.96 Hz)

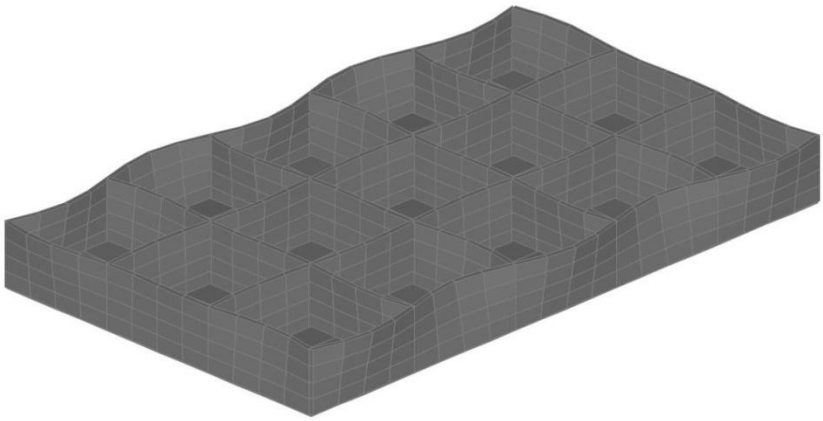


Fig. 5 3rd Mode shape (Frequency value = 32.27 Hz)

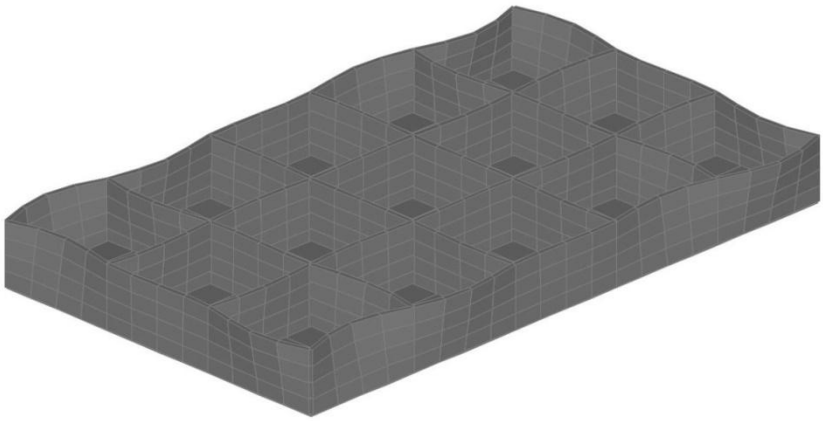


Fig. 6 4th Mode shape (Frequency value = 32.89 Hz)

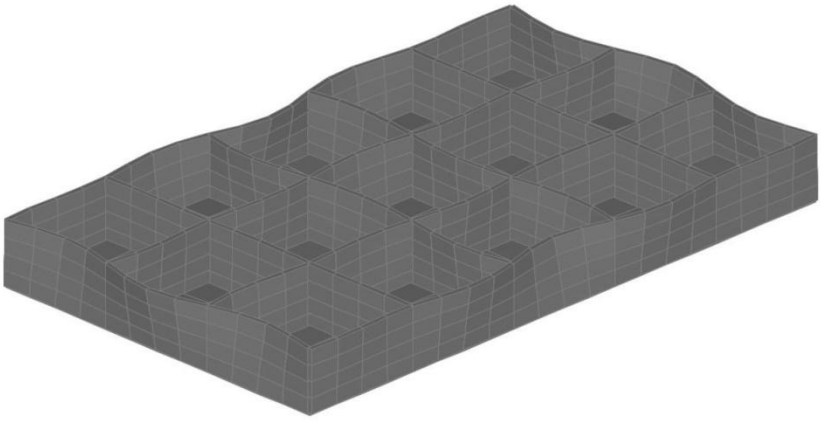


Fig. 7 5th Mode shape (Frequency value = 33.05 Hz)

B. Modal Analysis Results of Retrofitted RC Chemical Containment Pools

The modal analysis of the HFRP-rehabilitated reinforced concrete chemical containment pool was performed to examine how the rehabilitation system influences the dynamic properties of the structure. The first five vibration modes and shapes were analyzed to identify the predominant global deformation patterns and characterize the structural response under free-vibration conditions. The application of HFRP materials may modify the effective stiffness distribution of the reinforced concrete components, potentially leading to changes in the natural frequencies and corresponding mode shapes [5], [6], [17]. These modal parameters provide a basis for comparing the dynamic behavior of the rehabilitated pool with that of the existing configuration and evaluating the contribution of HFRP rehabilitation to its overall structural performance. The first five natural frequencies and their associated mode shapes obtained from the finite element analysis are presented in Figures 8-12, illustrating the modal characteristics of the HFRP-rehabilitated reinforced concrete chemical containment pool.

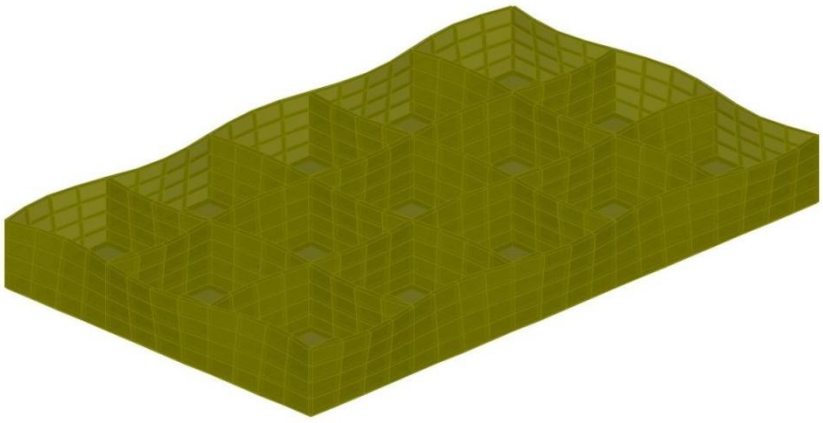


Fig. 8 1st Mode shape (Frequency value = 39.39 Hz)

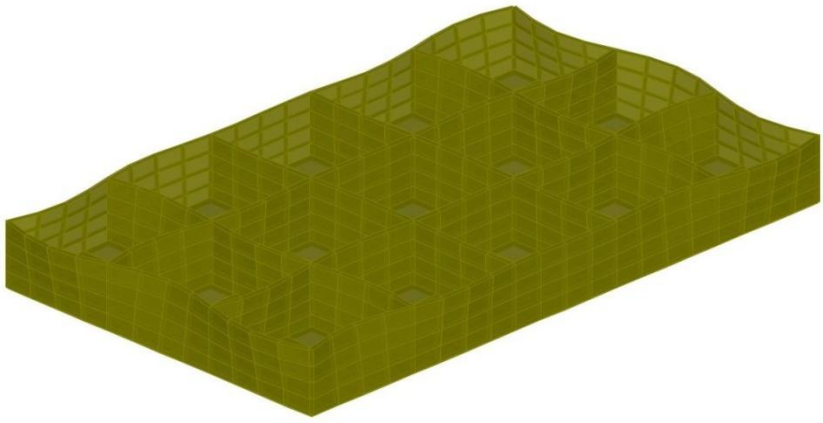


Fig. 9 2nd Mode shape (Frequency value = 39.80 Hz)

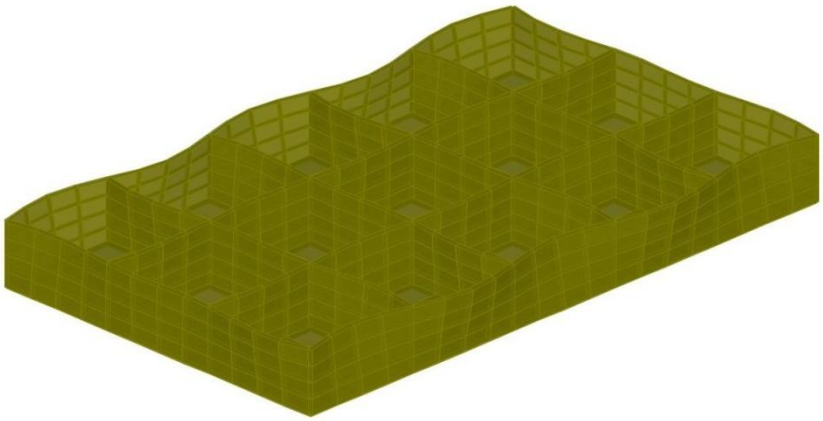


Fig. 10 3rd Mode shape (Frequency value = 40.33 Hz)

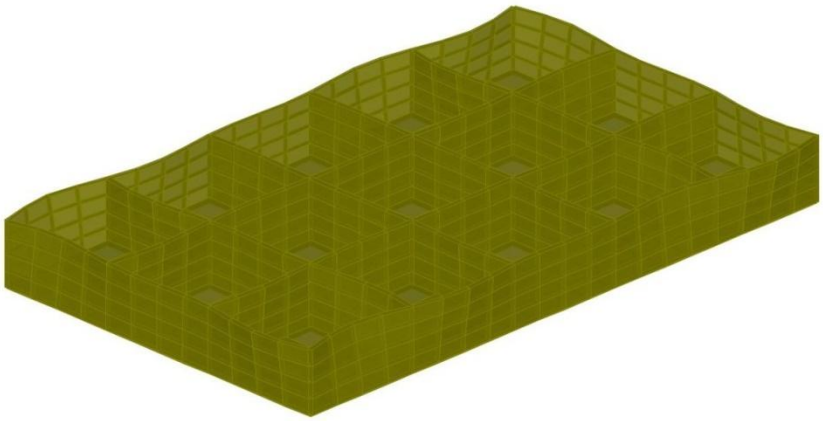


Fig. 11 4th Mode shape (Frequency value = 41.18 Hz)

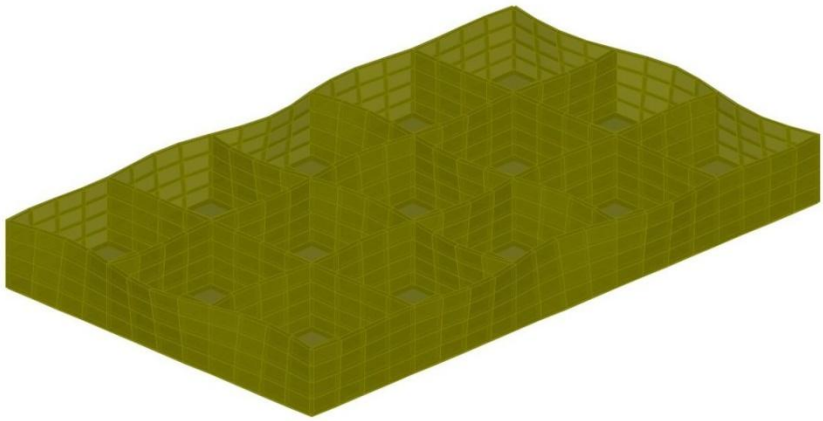


Fig. 12 5th Mode shape (Frequency value = 41.53 Hz)

IV. DISCUSSION

Table 3 summarizes the comparative natural frequency results obtained for the reinforced concrete chemical containment pool models before and after HFRP-based rehabilitation. This comparison provides a quantitative basis for evaluating the influence of the rehabilitation strategy on the dynamic characteristics of the structure. By examining the modal frequencies of the original and rehabilitated configurations, the effects of HFRP strengthening on structural stiffness and vibration behavior can be systematically assessed. Variations in the natural frequencies indicate changes in the dynamic properties of the containment pool and provide insight into the effectiveness of the proposed computational framework in evaluating the structural performance of HFRP-rehabilitated reinforced concrete systems. The increases of 24.33-25.65% obtained here are of the same order as the average frequency differences of approximately 33.9% and 34.4% reported for GFRP- and CFRP-retrofitted model steel structures [5], [6], and the influence of FRP strengthening on dynamic characteristics has also been examined for other structural members [23].

Table 3. Comparison of frequency values

Mode	1	2	3	4	5
Existing	31.68	31.96	32.27	32.89	33.05
Retrofitted	39.39	39.80	40.33	41.18	41.53
Difference (Hz)	7.71	7.84	8.06	8.29	8.48
Difference (%)	24.33	24.53	24.97	25.20	25.65

V. CONCLUSION

In this study, a computational framework was developed for the rehabilitation of reinforced concrete chemical containment pools using hybrid fiber-reinforced polymer (HFRP) composites, and its applicability was demonstrated through finite element modal analysis. Two three-dimensional SAP2000 models were created under identical geometric, material, support, and modelling conditions: the existing pool, with five spans in the x-direction, three spans in the y-direction, a story height of 2 m, and 15 cm thick slab and walls, and the same pool retrofitted with a 5 mm thick HFRP

layer applied to the inner and outer wall faces and the bottom slab. Because the rehabilitation was the only variable between the two models, the differences in dynamic response can be attributed directly to the HFRP system.

The modal analysis results showed that HFRP rehabilitation increased all of the first five natural frequencies. The frequencies rose from 31.68, 31.96, 32.27, 32.89, and 33.05 Hz for the existing pool to 39.39, 39.80, 40.33, 41.18, and 41.53 Hz for the retrofitted pool, corresponding to increases of 7.71-8.48 Hz, or 24.33%-25.65%. The relative gain grew steadily with mode number (24.33%, 24.53%, 24.97%, 25.20%, and 25.65%), indicating that the HFRP layer modifies the global stiffness of the structure rather than affecting a single vibration mode. Because the 5 mm HFRP layer has a low unit weight (15.50 kN/m³) and therefore adds little mass, this increase can be attributed mainly to the additional stiffness provided by a material whose modulus of elasticity (85 GPa) is considerably higher than that of the concrete (33 GPa).

These findings are consistent with the frequency increases reported in earlier studies of FRP-retrofitted structures [5]-[7], [17], and they show that modal frequencies can serve as a practical indicator of the stiffness change produced by rehabilitation. The upward shift of the dominant frequency band, from 31.68-33.05 Hz to 39.39-41.53 Hz, also changes the relationship between the pool and potential excitation sources; whether this reduces the risk of resonance must be checked against the actual excitation frequencies of the facility.

The present results are limited to free-vibration behavior. Hydrostatic and operational loading, stress and displacement response, local stress concentrations at corners and wall–base junctions, concrete–composite interface behavior, and long-term chemical durability were not evaluated, and the numerical results have not yet been validated experimentally. Future work should therefore extend the framework to static and dynamic fluid–structure loading cases, parametric studies of HFRP thickness, fiber hybridization, and coverage area, and interface modelling, and should verify the predictions through operational modal analysis of scaled or full-scale pools [20], [21], [24], [25], together with material tests under representative chemical exposure. Within these limits, the proposed framework provides a consistent and transparent basis for the preliminary evaluation of HFRP rehabilitation alternatives for reinforced concrete chemical containment pools.

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