FEA-Based Seismic Qualification of a Class 150LB WYE-Type Water Box for Nuclear Auxiliary Cooling Systems

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Full Text

Preamble

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Abstract

This study presents a finite element-based seismic qualification of a Class 150LB WYE-type water box used in nuclear auxiliary cooling systems. Although not part of the primary containment, its integrity is essential for post-seismic operability and condenser performance. A high-fidelity finite element model was developed in ANSYS Workbench using SHELL63 elements to represent the cylindrical shell, large-diameter nozzles, and bolted covers. Internal pressure (0.345 MPa), gravity, and static-equivalent seismic loads corresponding to 9.27 g acceleration were applied in accordance with KEPIC MGE and ASME Section III criteria.

Modal analysis determined the first natural frequency as 41.6 Hz, exceeding the 33 Hz threshold required for static-equivalent seismic loading. Stress evaluation confirmed that both membrane and combined membrane-plus-bending stresses remain below ASME Section III allowable limits (207 MPa and 414 MPa, respectively). The maximum combined stresses were 322.4 MPa in the shell, 315.1 MPa in the cover, and 295.8 MPa in the nozzle, with all regions demonstrating full code compliance. Stress concentrations at nozzle-shell and cover transitions were resolved through mesh refinement, and no overstress was detected.

The results confirm that the WYE-type water box maintains structural adequacy under conservative seismic and operational conditions. The validated methodology provides a scalable framework for the seismic qualification of Class 3 auxiliary components in nuclear power plants.

Keywords: Seismic qualification · Finite element analysis · Nuclear auxiliary cooling system · WYE-type water box · ASME Section III · KEPIC MGE

Nomenclature

Symbol	Description
Pm	Primary membrane stress
Pb	Primary bending stress
Pl	Local membrane stress
Pl+Pb	Local membrane plus bending stress
Sm	Allowable design stress at temperature (per ASME Section III)
1.5Sm	Limit for membrane stress
3.0Sm	Limit for membrane plus bending stress
σm	Membrane component of equivalent stress
σb	Bending component of equivalent stress

Symbol	Description
f_1	First natural frequency of the structure
g	Gravitational acceleration (9.81 m/s^2); used in seismic base acceleration
	Poisson' s ratio
E	Young' s modulus
MPa	Megapascal (unit of pressure/stress)
Hz	Hertz (unit of frequency)
SHELL63	ANSYS shell element used for thin-walled modeling

Introduction

In nuclear power plants, auxiliary components such as water boxes play an essential role in supporting the operation of heat exchangers and condenser systems by regulating fluid flow under high pressure and temperature [?]. Although they lie outside the primary containment boundary, their structural integrity is critical to sustaining condenser vacuum, plant efficiency, and post-seismic operability [?]. The Class 150 LB WYE-type water box examined here must therefore withstand internal pressure, temperature cycling, and seismic excitation without compromising safety margins [?].

Design guides such as KEPIC MGE [?], ASME Section III [?], and IEEE Std 344 [?] mandate that local membrane and combined membrane + bending stresses in discontinuity regions (e.g., shell-nozzle junctions) remain below 1.5 Sm and 3 Sm, respectively, and they permit static-equivalent seismic loading when the first natural frequency exceeds roughly 33 Hz [?]. However, the complex geometry of water-box flanges, covers, and nozzles introduces stress distributions that simplified methods cannot capture, warranting high-fidelity finite-element analysis (FEA).

Previous studies highlight complex multi-physics challenges inherent in water-box systems. Amrute and Yadav [?] carried out a thermal–hydraulic analysis showing that partial filling and flow maldistribution elevate back-pressure and cut heat-transfer effectiveness. An IOSR-JMCE FEA study confirmed that membrane and membrane + bending stresses in water-box regions of a shell-and-tube exchanger comply with ASME Section VIII limits, validating detailed simulation for design verification [?]. Wang et al. [?] used a 3-D electrochemical model to reveal uneven potential fields that undermine cathodic protection and proposed optimised sacrificial-anode layouts. Mukhopadhyay et al. [?] documented abrasive wear in 17-4 PH stainless-steel water-box nozzles and showed that solution-aging heat treatment nearly doubled service life. Together, these studies highlight the need to couple thermal, structural, electrochemical, and materials analyses when designing or refurbishing water-box assemblies.

More recent investigations (2022–2025) underscore emerging reliability concerns.

Swardhamana et al. [?] linked internal fouling to diminished condenser performance and demonstrated performance recovery via targeted maintenance. Albdour et al. [?] introduced a machine-learning model for predicting condensation heat-transfer coefficients in the presence of non-condensable gases, offering new predictive capabilities for system-level thermal analysis. Surface-engineering studies by Hu [?] and Stendardo [?] showed that micro-structured coatings can enhance condensation efficiency—benefits that translate downstream to water-box flow conditions. A 2025 case study detailed a complete water-box relining, supplying practical guidance for repairing severely corroded units [?]. These findings collectively support the adoption of comprehensive, multi-physics modelling—such as the ANSYS-based pressure, modal, and stress analysis performed here—to ensure code compliance and long-term durability.

Accordingly, this study performs a simulation-based seismic qualification of a Class 150 LB WYE-type water box using ANSYS Workbench 11.0. Modal analysis confirms that the fundamental frequency exceeds 33 Hz, validating the static-equivalent seismic approach. Stress distributions extracted at key discontinuities are benchmarked against KEPIC MGE [?] and ASME Section III [?] limits, demonstrating seismic adequacy and providing a validated workflow for qualifying similar auxiliary components in nuclear condenser systems.

2.1 System Configuration

The subject of this study is a Class 150LB WYE-type water box (strainer) used in the auxiliary cooling system of a nuclear power plant. The water box is a pressure-retaining component installed at the terminal end of a condenser or heat exchanger to regulate the flow of circulating water. It features a horizontal cylindrical shell with two large-diameter inlet and outlet nozzles, flanged end covers, and internal flow partitions. The component is designed to operate under moderate internal pressure and is connected to adjoining piping systems via bolted flanges.

Key geometric features of the water box include: - Shell outer diameter: 3978 mm - Shell thickness: 14 mm - Nozzle diameter: 2266 mm - Nozzle thickness: 10 mm - Cover thickness: 14 mm - Flange thickness: 51 mm - Material: SA 516 Gr. 70 (Carbon Steel)

The component operates at a service temperature of 60°C and under an internal pressure of 50 psi (0.345 MPa). The partition wall within the water box, if present, was excluded from the current analysis for simplification.

Table 1: Geometric and Material Specifications of the Water Box

Parameter	Value	Notes
Shell outer diameter	3978 mm	Cylindrical shell
Shell thickness	14 mm	Uniform thickness

Parameter	Value	Notes
Inlet/outlet nozzle diameter	2266 mm	Identical inlet and outlet sizes
Nozzle thickness	10 mm	Welded to shell
Cover thickness	14 mm	Flat, bolted end cover
Flange thickness	51 mm	Supports bolted connection
Material	SA 516 Gr. 70	Per ASME Table 1A
Design pressure	0.345 MPa	Equivalent to 50 psi
Operating temperature	60°C	Typical for cooling systems
Allowable membrane stress	207 MPa	1.5 × Sm
Allowable membrane + bending	414 MPa	3.0 × Sm

As illustrated in Figure 1 [Figure 1: see original paper], the finite element model accurately incorporates the complex wall thickness distributions used in the Class 150LB WYE-type water box. Figure 1(a) presents View 1 of the geometry, detailing local shell, nozzle, and flange wall thicknesses—ranging from 10 mm to combined plate stacks of 24 mm. Figure 1(b) shows View 2, highlighting the reinforcement strategies at nozzle interfaces, where plate stacks reach up to 44 mm to improve strength in critical load paths. These configurations are essential to represent realistic fabrication and weld buildup in the FE model.

Figure 1: Thickness configuration of the WYE-type water box used in the FE model. (a) View 1: Wall and reinforcement plate thicknesses near nozzle and flange interfaces. (b) View 2: Reinforcement layout across nozzle-shell transitions and bottom plate for structural realism.

2.2 Functional Requirements

The water box must maintain structural integrity under the combined effects of internal static pressure, dead weight, and external seismic excitation. It must also remain leak-tight at bolted flanges and resist fatigue at high-stress regions such as nozzle-shell junctions and discontinuities during seismic events. Structural failure could lead to cooling system malfunction, which is critical for reactor shutdown and decay heat removal processes.

2.3 Design Codes and Criteria

The structural qualification of the water box follows the requirements of: - KEPIC MGE: Korean Electric Power Industry Code for the seismic qualification of mechanical equipment - ASME Section III, Division 1: For classification of stress types and allowable limits in nuclear components - ASME BPVC Table 1A (SA 516 Gr.70): For material properties and mechanical strength criteria

Stress categorization is performed as per ASME: - Membrane stress (Pm) - Membrane + bending stress (Pm + Pb) - Local membrane stress (Pl) - Local membrane + bending stress (Pl + Pb)

Allowable stress limits are defined based on the Sm value of the material (SA 516 Gr.70 = 138 MPa): - Allowable for membrane = 1.5Sm = 207 MPa - Allowable for membrane + bending = 3.0Sm = 414 MPa

The design criteria can be expressed as: - Pm $\leq$ 1.5Sm = 207 MPa - Pm + Pb $\leq$ 3.0Sm = 414 MPa

Where Pm is primary membrane stress and Pb is primary bending stress. Special attention is paid to discontinuity regions such as nozzle-shell intersections, cover-shell junctions, and flange interfaces. These regions are evaluated using local stress limits due to geometric discontinuities, following guidance in ASME NB-3200 [**?**] and KEPIC MGE 3420 [**?**].

As illustrated in Figure 2 [Figure 2: see original paper], the finite element model of the Class 150LB WYE-type water box incorporates a refined quadrilateral mesh using SHELL63 elements to ensure accurate stress resolution, particularly around geometric transitions such as the nozzle-to-shell interface. The applied boundary conditions, visible as purple constraints along the base, simulate fixed support conditions at bolted anchor points. This setup reflects realistic in-situ restraints, enabling proper simulation of load transfer and structural deformation under operating and seismic conditions.

Figure 2: Finite element mesh and boundary conditions applied to the WYE-type water box.

2.4 Seismic Loading Criteria

The water box is seismically classified according to nuclear safety class requirements. As per KEPIC MGE guidelines, a modal analysis is performed to confirm the fundamental frequency exceeds 33 Hz. Once confirmed, static equivalent seismic loads are applied as per design-basis acceleration levels. The resultant seismic acceleration used in the analysis reaches up to 9.27 g, applied in three orthogonal directions in a conservative combination, simulating worst-case loading during a design-basis earthquake.

Table 2: Modal analysis result confirming that the fundamental frequency exceeds the 33 Hz threshold required by KEPIC MGE for applying static equivalent seismic loading.

Natural Frequency (Hz)	Threshold (KEPIC MGE)	Pass/Fail
41.6	33 Hz	Pass

Figure 3 Figure 3: see original paper illustrates the primary loading conditions applied in the simulation, including internal pressure and seismic acceleration

in the Fx and Fz directions. Figure 3(b) identifies geometrically sensitive areas, such as the nozzle-shell junction and cover interface, where stress concentrations are expected due to discontinuities.

Figure 3: Load directions and critical stress regions in the WYE-type water box. (a) Applied load directions. (b) Regions of expected stress concentration.

3. Finite Element Model Development

The research methodology flowchart for seismic qualification of the WYE-type water box is presented in Figure 4 [Figure 4: see original paper].

Figure 4: Research methodology flowchart used for seismic qualification of the WYE-type water box.

3.1 Geometry Modeling

The finite element model of the Class 150LB WYE-type water box was developed using ANSYS Workbench 11.0. The geometry includes the cylindrical shell, two large-diameter inlet/outlet nozzles, bolted end covers, and reinforcement flanges. The internal partition wall was omitted in this analysis to simplify the model without compromising the accuracy of stress evaluation at critical structural zones.

The CAD geometry was imported into ANSYS SpaceClaim and prepared for meshing by removing minor features such as bolt holes and gasket grooves. These details were excluded to focus on global structural behavior under seismic and pressure loads, in line with typical industry practice for Class 3 component qualification [**?**].

3.2 Element Types and Mesh Strategy

The water box was meshed using SHELL63 elements, which are suitable for thin-walled pressure components. Each element has six degrees of freedom per node (three translational and three rotational), allowing the capture of membrane and bending behavior. This choice was guided by the geometry’ s shell-dominant configuration and by prior validation in similar nuclear auxiliary component studies.

Mesh refinement was applied near nozzle-shell junctions, cover–shell interfaces, and flange and pad regions to ensure accurate stress recovery in regions with high stress gradients due to geometry discontinuities. A convergence study was performed by successively refining the mesh until changes in maximum equivalent stress were within 3%.

Table 3: Mesh statistics used for the finite element model of the water box in ANSYS Workbench 11.0.

Parameter	Value	Notes
Total elements	~22,000	SHELL63 element type
Average element size	30 mm (global)	Near nozzles, cover, and flange zones
Refined element size	10 mm	Ensured mesh quality
Element aspect ratio	< 5	Between refinement levels
Mesh convergence	$< 3\%$ stress variation	Maintained < 5 for quality assurance

3.3 Boundary Conditions and Load Cases

Boundary conditions were applied to represent realistic support and connection conditions during seismic excitation. Fixed supports were assigned to the nozzle flanges to simulate rigid piping attachments. Internal pressure of 0.345 MPa (equivalent to 50 psi) was uniformly applied to internal surfaces. Dead weight (gravity load) was applied in the global -Z direction. Static equivalent seismic loads were applied in three orthogonal directions (X, Y, and Z) based on a resultant ground acceleration of 9.27 g, as defined in the site-specific seismic envelope.

Load combinations followed KEPIC MGE [?] prescriptions, including pressure-only case (P), pressure + seismic (P + SSE), and combined local stress extraction cases (for membrane and bending). Equivalent Stress (von Mises) is calculated as:

$$\sigma_{eq} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

where σ_1, σ_2, and σ_3 are principal stresses.

4.1 Modal Characteristics and Seismic Applicability

A modal analysis was conducted to determine the dynamic behavior of the water box and to validate the use of static-equivalent seismic loading in accordance with KEPIC MGE [?] and ASME Section III [?] guidelines. The lowest natural frequency of the structure was found to be 41.6 Hz, which is well above the required threshold of 33 Hz specified by KEPIC MGE [?]. This confirms that the structure is sufficiently rigid and that its fundamental period is short enough to avoid resonance with typical seismic frequencies. Consequently, the use of static-equivalent seismic loading is justified and ensures conservative seismic design while avoiding unnecessary complexity associated with time-history or response spectrum analysis.

4.2 Stress Distribution in the Water Box

A finite element analysis was conducted on the Class 150LB WYE-type water box using ANSYS (v11), considering internal pressure loading of 0.345 MPa (50 psi) at 60°C operating temperature. The structure comprises a cylindrical shell, large-diameter inlet/outlet nozzles, and flat end covers. Element type SHELL63 was used for all surfaces, excluding the internal partition wall.

As shown in Figure 5 [Figure 5: see original paper], the comparison of actual membrane + bending stress against the allowable stress limit (3.0Sm = 414 MPa) across critical regions of the water box—shell, cover, and nozzle—demonstrates full compliance with ASME Section III [**?**] criteria. The peak stress was observed in the shell (322.40 MPa), with the cover (315.06 MPa) and nozzle (295.79 MPa) following closely. All values remain well below the allowable limit, confirming the component' s structural integrity under combined internal pressure and seismic loading.

Figure 5: Stress Distribution vs. Allowable Limits in Critical Regions. Bar chart showing membrane + bending stresses for shell, cover, and nozzle regions compared with the ASME allowable stress limit (3.0Sm = 414 MPa).

Shell region: - Maximum membrane stress: 173.52 MPa - Maximum membrane + bending stress: 322.40 MPa - Both values remain within ASME-defined limits of 207 MPa (1.5Sm) and 414 MPa (3.0Sm), respectively.

As shown in Figure 6 [Figure 6: see original paper], detailed stress evaluations were conducted on the saddle-to-shell interface under seismic loading conditions. Figure 6(a) shows that peak Von Mises stress values are concentrated near the saddle welds, a known fatigue-sensitive region. Figure 6(b) highlights directional stress gradients, with high intensities observed along the curved shell segment.

Figure 6: Stress distribution at the saddle-to-shell interface under seismic loading. (a) Von Mises stress. (b) Directional (XZ) stress.

Cover region: - Maximum combined stress: 315.06 MPa - Below the allowable 414 MPa

Figure 7 [Figure 7: see original paper] presents a refined stress evaluation of the shell structure near the saddle interface, focusing on seismic loading conditions. In Figure 7(a), the stress distribution across a partial shell segment and reinforcing gusset plate shows moderate stress levels, particularly along the weld toe and flange transitions. In Figure 7(b), the full shell section under seismic excitation reveals more extensive stress propagation along the bottom curvature, with high stress concentrations forming near the bolt hole regions and geometric cutouts. In Figure 7(c), the analysis isolates the left shell region, confirming the presence of high stress gradients near the bolt connections and around discontinuities. These findings are essential for evaluating fatigue-critical locations and validating weld design.

Figure 7: Seismic stress distribution across shell regions adjacent to the saddle support. (a) Partial shell and gusset segment showing weld and edge stress. (b) Full shell section with pronounced stress propagation near bolt regions. (c) Left shell side highlighting localized peak stresses at structural discontinuities.

Nozzle region: - Maximum membrane stress: 200.32 MPa (just below 1.5Sm) - Maximum combined stress: 295.79 MPa - Both values meet design code limits

Figure 8 [Figure 8: see original paper] illustrates the stress analysis of the WYE-branch shell junction under seismic loading. In Figure 8(a), the internal curvature of the nozzle-shell interface shows elevated Von Mises stresses, particularly near the weld toe. Figure 8(b) reveals asymmetric stress development in the XZ direction, indicating a complex load path redirection.

Figure 8: Stress evaluation of the WYE-junction under seismic loading. (a) Von Mises stress. (b) Directional (XZ) stress.

4.3 Design Code Compliance

According to ASME Section III [?] and KEPIC MGE [?] requirements, all evaluated locations are within code-allowed stress margins. Local membrane stresses at discontinuity regions do not exceed 1.5Sm = 207 MPa, and combined membrane and bending stresses remain under 3.0Sm = 414 MPa.

Table 4: Summary of design code compliance based on ASME Section III [?] and KEPIC MGE [?] standards.

Design Code / Criteria	Applied Limits	Result	Compliance
ASME Section III - Membrane	1.5Sm = 207 MPa	Max = 200.32 MPa (Nozzle)	Yes
ASME Section III - Membrane+Bending	3.0Sm = 414 MPa	Max = 322.40 MPa (Shell)	Yes
KEPIC MGE -Modal Requirement	$f_1 > 33$ Hz	$f_1 = 41.6$ Hz	Yes
Local Stress Regions	Evaluated via Pl, Pl+Pb	All < 414 MPa	Yes

Table 5: Stress summary and code compliance check for critical regions under seismic loading.

Region	Membrane Stress (MPa)	Membrane + Bending (MPa)	Allowable (1.5Sm / 3.0Sm)	Compliance
Shell	173.52	322.40	207 / 414	Yes
Cover	–	315.06	–/ 414	Yes
Nozzle	200.32	295.79	207 / 414	Yes

4.4 Local Stress Distribution Insights

The FEA plots revealed that the highest stress concentrations occur at the nozzle-shell junction and the inner edge of the cover plate, where geometric discontinuities and load transfer interactions are dominant. These regions experience combined membrane and bending stresses due to internal pressure and lateral seismic effects. Stress gradients near these transition zones are expected and were mitigated through mesh refinement and use of SHELL63 elements. Despite localized peaks, no regions exceeded the ASME-allowed 3.0Sm limit (414 MPa). The smooth variation of stress away from the discontinuity zones further supports the adequacy of the model and structural detailing.

4.5 Engineering Insights

The highest stress regions are located at geometric discontinuities–specifically nozzle-to-shell and cover transitions. Despite these stress amplifications, no component exceeded its allowable limit, validating the structural adequacy of the water box under design conditions. The use of SHELL63 [**?**] elements proved sufficient in capturing the combined stress states in thin-walled pressure zones. Overall, the design is confirmed to be code-compliant and seismically robust.

Table 6: Comparison of FEA-calculated maximum stress with allowable stress for seismic qualification.

Location	FEA Max Stress (MPa)	Allowable Stress (MPa)	Margin (%)
Shell-Nozzle Junction	295.8	414	17.8%
Cover Plate Edge	–	414	22.0%
Lower Saddle Support	263.9	414	26.7%

Note: Margin percentages represent safety margins against allowable stress limits.

4.6 Future Work

Although the current analysis demonstrates structural integrity under combined internal pressure and static-equivalent seismic loading, several areas warrant further investigation. Future studies should incorporate thermal stresses during startup and shutdown transients to assess combined thermo-mechanical performance. Fatigue analysis under repeated seismic and operational loading would further demonstrate long-term reliability. Additionally, future models could include internal partitions and tube supports to capture more accurate local stress interactions. Probabilistic seismic or sensitivity analyses could quantify the impact of uncertainties in material properties and boundary conditions on design margins. It should be noted that internal partitions and gasket details were not explicitly modeled, which may affect local stress distribution in real-world conditions.

4.7 Benchmarking Against Literature

The results of this study are consistent with existing literature on the structural and thermal behavior of water boxes and related components in nuclear systems. Prior work by Amrute and Yadav [?] emphasized the need for detailed flow modeling in condensers, noting that flow maldistribution can negatively affect performance, which reinforces the importance of structural integrity in water boxes to ensure reliable flow regulation. Similarly, the finite element analysis (FEA) approach adopted in the present study aligns with the methodology validated by IOSR-JMCE [?], where stress assessments of exchanger components confirmed compliance with ASME stress limits, supporting the use of high-fidelity FEA for code verification. Mukhopadhyay et al. [?] demonstrated that appropriate material treatments can significantly improve the fatigue life of nozzle components, highlighting the relevance of controlling local stresses at discontinuities—an objective met in this work through mesh refinement and stress evaluation at critical junctions.

Recent developments in performance optimization, such as those by Swardhamana et al. [?] and Albdour et al. [?], underscore how internal fouling and non-condensable gases can degrade heat transfer in auxiliary systems. These findings indirectly support the need for mechanically robust water boxes capable of maintaining performance under fluctuating thermal and hydraulic conditions. Additionally, studies by Hu [?] and Stendardo [?] on micro-structured surfaces for condensation enhancement suggest that upstream component design, such as that of water boxes, must maintain structural resilience to support evolving efficiency measures. The present analysis confirms that even under worst-case seismic loads, the Class 150LB WYE-type water box remains within ASME and KEPIC stress limits, thereby validating both the modeling approach and the design. Collectively, these comparisons reinforce the reliability of the proposed qualification methodology and its applicability to similar nuclear auxiliary components.

5. Conclusion

This study presents a comprehensive seismic qualification of a Class 150LB WYE-type water box used in a nuclear auxiliary cooling system. The key findings and engineering insights are summarized as follows:

The ANSYS-based FEA model effectively simulated combined loading conditions—including internal pressure (0.345 MPa), gravity, and seismic acceleration (up to 9.27 g). The lowest natural frequency was 41.6 Hz, exceeding the KEPIC MGE threshold of 33 Hz, thereby justifying the use of static-equivalent seismic loads.

The use of SHELL63 elements with mesh refinement at nozzle-to-shell and cover transitions allowed accurate stress capture. Convergence was confirmed with less than 3% variation in maximum stress values. Maximum combined membrane and bending stresses were recorded as 322.40 MPa (shell), 315.06 MPa (cover), and 295.79 MPa (nozzle), all below the allowable ASME Section III [?] limit of 3Sm (414 MPa). Membrane-only stresses at critical zones remained below 1.5Sm (207 MPa), ensuring compliance with KEPIC MGE and ASME primary stress limits. Although stress concentrations occurred at geometric transitions, no overstress was detected, verifying the component's structural adequacy under conservative seismic loading conditions.

Rigid nozzle supports and envelope seismic loads were used to replicate worst-case nuclear service conditions, ensuring robustness of the qualification. The validated methodology offers a scalable and code-compliant framework for the seismic evaluation of auxiliary Class 3 pressure-retaining components in nuclear power plants.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data supporting the findings of this study are available within the article. Additional datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Note: Figure translations are in progress. See original paper for figures.