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Seismic Qualification Of An Exhaust Gas Silencer In A Nuclear Power Plant Using Finite Element Analysis

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Abstract
This study presents the seismic qualification of an Exhaust Gas Silencer (EGS) installed in the Emergency Diesel Generator (EDG) system of a nuclear power plant. Using Finite Element Analysis (FEA) with ANSYS 12.1, the structural performance of the EGS was assessed under normal, upset (½ Safe Shutdown Earthquake), and faulted (Safe Shutdown Earthquake) conditions, in accordance with KEPIC MN Class 3 and ASME Section III standards. Modal analysis confirmed a fundamental natural frequency of 69.13 Hz, exceeding the 33 Hz threshold, thereby validating the use of equivalent static seismic analysis. Locations of analysis which were critical, including saddle supports, head-to-shell junctions and reinforced areas, proved that the maximum combined membrane and bending stresses did not exceed those defined by code. The maximum stress of 240.62 MPa was observed at the reinforced angle, which remained below the permissible stress of 243.12 MPa during faulted seismic loading. These findings justify the structural integrity and seismic resilience of the EGS.
By maintaining emission control during seismic events, the qualified EGS ensures safe dispersal of exhaust gases, preventing uncontrolled environmental release and supporting sustainability in nuclear operations.
The study also establishes a replicable and code-compliant methodology for qualifying auxiliary components in nuclear systems subjected to seismic loading.

Keywords:
1. ***ANSYS***
2. ***Emergency Diesel Generator***
3. ***Exhaust Gas Silencer***
4. ***Finite Element Analysis***
5. ***Nuclear power plant***
6. ***Seismic qualification***
7. ***Structural integrity***

1. INTRODUCTION

Silencers used overhead and specifically Exhaust Gas Silencers (EGS) are important ancillary components in nuclear power plants and in Emergency Diesel Generator (EDG) under emergency conditions and are assured of safe and efficient discharge of the acoustic gases [3]. With the rising rate of Roentgen magnitude seismic and its related hazard in nuclear systems, structural qualification of such elements has become a necessity [4,5]. Nevertheless, due to complex geometries, variable force loads, and lower classification compared to main systems, many silencers have been designed with conservative assumptions—often resulting in over-engineered products, inefficient material use, and high costs [6,7]. It is due to these limitations that development of reliable, code-verified, and efficient methodologies of seismic qualification of auxiliary components in the nuclear sector is necessary [5].

Although such developments exist, auxiliary systems like silencers are not featured much in literature. Traditionally, pressure vessels, piping systems, and containment boundaries have been in focus. The proposed study addresses this gap by providing a code-based, simulation-based qualification of an EGS using Finite Element Analysis (FEA). Structural and dynamic behavior (modal frequencies, stress distributions, and loading conditions) are evaluated assuming normal (Service Level A), upset (1/2 SSE, Level B), and faulted (SSE, Level D) conditions using KEPIC MN Class 3 and ASME Section III criteria [1,2].

The research aims to maximize seismic performance and follow industry codes while reducing over-conservatism and improving design reliability. Although earlier literature has proposed nonlinear dynamic simulations or fragility-based techniques for seismic design, few have focused on auxiliary structures such as silencers. In addition, earlier literature often lacked a fully integrated qualification strategy based on regulatory documents and simulation validation.

2. SEISMIC QUALIFICATION THEORY

This section presents the theoretical framework, standards and seismic analysis processes that are used to certify the Exhaust Gas Silencer (EGS) in structural worthiness concerning seismic occasions. The assessment is strongly by binding code whether of the nuclear industry in code KEPIC MN[1] and ASME Section III, Division 1[2].

2.1 Regulatory Framework and Design Criteria

Seismic qualification: Seismic qualification is achieved when the safety related items in the nuclear facilities can both withstand the structural integrity and functionality during and after the seismic disturbance. The design and analysis of the study are in line with the following: **KEPIC MN [1], Class 3**: Requirements for pressure boundary components.

- **KEPIC MN [2]:** Requirements for structural supports and attachments.
- **ASME Section III [1], Division 1**: Supplementary criteria for nuclear class components.

Allowable stresses are defined based on service levels and material properties as per KEPIC MND-3416 and MNF-3250.[11] The stress categories include:

 Membrane stress P_m : Mid-surface stress across thickness.
 Bending stress P_b: Stress gradient across thickness.
 Combined stress $P_m + P_b$**:** Sum of membrane and bending effects.

Service Level	Membrane Stress σallow	Membrane + Bending σallow
A (Normal)	s	1.5 S
B (Upset)	1.1S	1.65S
D (Faulted)	2.0S	2.4S

Table 1: Service Level Stress Limits Based on KEPIC and ASME Criteria

Where S is the basic allowable stress in MPa, determined based on material yield strength S_y or ultimate strength S_u, or ultimate strength, as defined in KEPIC MND-3416 and MNF-3250 **[11].'** The allowable stress can be expressed as: σallow =1.65·S. Stress evaluations were conducted at critical locations, including saddle supports, shell intersections, nozzle zones, and reinforced areas.

2.2Modal Analysis for Dynamic Behaviour

Modal analysis was performed to determine the natural frequencies of the EGS, a prerequisite for seismic evaluation. The fundamental natural frequency, $f_n$is calculated as:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Where:

f_n: Natural frequency (Hz),k: Stiffness of the structure ,m: Modal mass.

According to KEPIC MN §7.2. g**,** if the lowest natural frequency f_{min}>33 Hz, then the component can be for **equivalent static seismic analysis**, avoiding the need for complex time-history methods.

The first natural frequency obtained for the silencer was:

$f_{n,1}$=69.13Hz

satisfying the code requirement and enabling the use of equivalent static methods for seismic load application.

2.3 Seismic Load Combinations

Seismic evaluation considered multiple load combinations as required by **KEPIC Appendix 4I**, addressing various operational and seismic scenarios. These combinations are summarized in Table 2.

Service Level	Combination	Description
A (Normal)	L1=W+P+T+ O	Dead weight, pressure, thermal, operational loads
B (Upset)	L2=W+P+T+O+ $Seismic_{(½\ SSE)}$	Includes Operating Basis Earthquake (OBE)
D (Faulted)	L3=W+P+T+O+ $Sesismic_{(SSE)}$	Includes Safe Shutdown Earthquake (SSE)

Table 2: Load Combinations for Seismic Qualification According to KEPIC Appendix 4I
Where: W: Dead weight,P: Internal pressure,T: Thermal expansion,O: Operational loads (e.g., nozzle piping),S_{OBE}, S_{SSE} : Seismic loads from OBE/SSE response spectra.

Each combination is evaluated independently, and resultant stresses are verified against allowable limits for corresponding service levels. The **Square Root of the Sum of Squares (SRSS)** method was used to conservatively combine independent load effects.

$$\sigma_{total} = \sqrt{\sigma_{static}^2 + \sigma_{piping}^2 + \sigma_{seismic}^2}$$

2.4 Equivalent Static Seismic Loads
With modal analysis validating a frequency above 33 Hz, constant acceleration loads from site-specific seismic response spectra are used. The equivalent seismic force is calculated per Newton's Second Law. $F_s = m.a$. Where: F_s: Seismic force,m: Mass of component,a: Spectral acceleration. The acceleration values used are:

Direction	OBE (g)	SSE (g)
E-W	0.425	0.85
N-S	0.425	0.85
Vertical	0.425	0.85

Table 3: Peak Ground Acceleration Values Used for Seismic Load Cases (g)

Seismic accelerations were applied at the centre of gravity of the EGS in the finite element model developed in ANSYS 12.1. Stress evaluations under these seismic loads considered both: Mid-wall stress → Membrane stress Pm and Outer and inner surface stresses → Membrane + bending stress Pm+ Pb. These are defined in KEPIC MNF-3251.1, MND-3416 **[1]**, and ASME Section III **[2]**.

3 Methodology for Structural and Seismic Qualification
To support the dynamic qualification workflow, a bar chart (Figure 1) was developed, illustrating the estimated effort distribution across each major analysis step. Estimated Effort per Step in the Dynamic Qualification Analysis Workflow. Interpretation**:** The bar graph (Figure 1) indicates that the highest effort is typically allocated to **Finite Element Modelling** and **Stress Analysis in ANSYS**, reflecting the complexity and precision required for nuclear component qualification.

Workflow Step	Effort Estimate (%)
Component Definition	10%
Finite Element Modelling	25%
Modal Analysis	15%
Load Definition	10%
Stress Analysis in ANSYS	25%
Code Compliance Check	10%
Conclusion	5%

Table 4: Estimated Effort Distribution for Each Qualification Phase

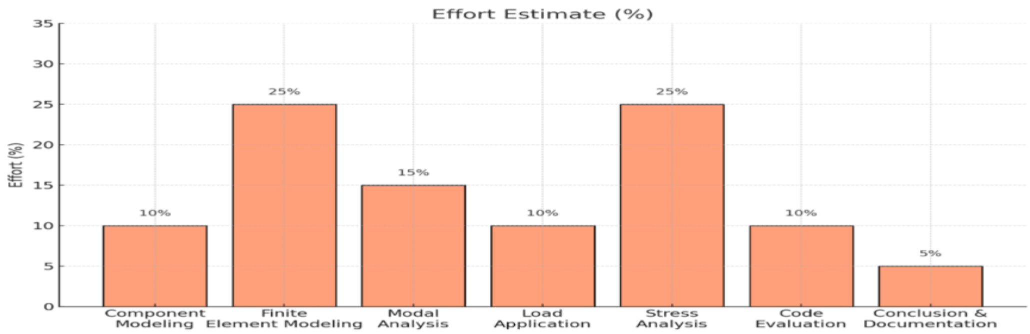

Figure 1: Estimated effort distribution (%) across key phases of seismic qualification analysis.

3.1 Finite Element Modelling (FEM)

The structural integrity evaluation of the Exhaust Gas Silencer (EGS) was performed using ANSYS 12.1, utilizing **SHELL63** elements, appropriate for thin-walled pressure components.

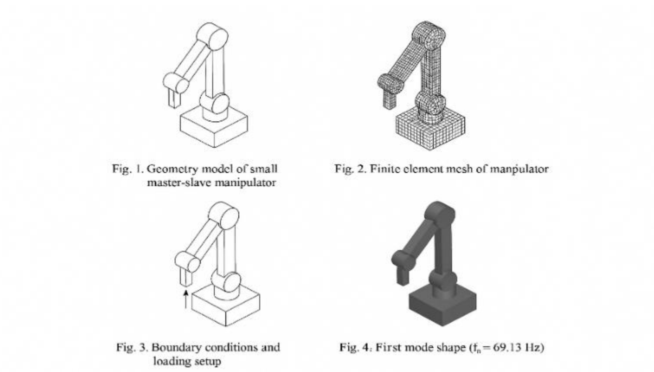

Figure 2: Finite element modeling of a small manipulator: (a) geometry, (b) mesh, (c) boundary conditions and loading, (d) first mode shape (fn = 69.13 Hz).

The boundary conditions included fixed supports at the saddle anchors, providing both vertical and lateral restraints, along with applied nozzle loads to represent operational forces. Mesh refinement was applied in critical regions such as the nozzle-shell intersections, saddle supports, and reinforced zones to improve accuracy. The stress output was categorized into membrane stress (Pm), representing mid-wall shell stress; combined membrane and bending stress (Pm + Pb), representing stress at the top and bottom shell surfaces; and peak and total stresses for further post-processing and evaluation.

3.2 Modal Analysis

Modal analysis was performed to determine EGS's natural frequencies, as per KEPIC MN §7.2.g[1] criteria. The first six modes are listed in Table 4 (presented earlier). The fundamental natural frequency was found to be **69.13 Hz**, well above the 33 Hz threshold, thereby validating the use of equivalent static seismic analysis.

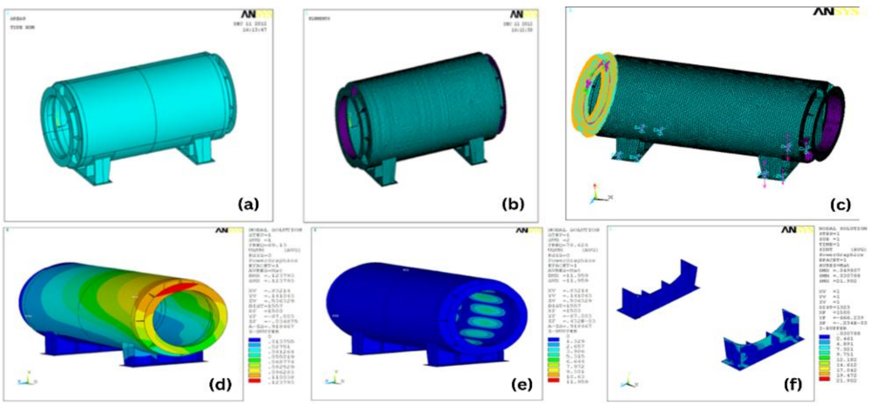

Figure 4: (a) Geometry of the EGS showing pressure-retaining components; (b) Finite element mesh using SHELL63 with refinement at critical regions; (c) Boundary conditions and loading setup including nozzle loads and seismic input; (d) First mode shape (69.13 Hz) from modal analysis; (e) Second mode shape (78.61 Hz); (f) Stress distribution at saddle support under SSE loading.

Figure 1(d) shows that silencer exhibits a global lateral deformation mode at a natural frequency of 69.13 Hz. As this value exceeds the 33 Hz threshold specified in KEPIC MN §7.2.g, the component qualifies for equivalent static seismic analysis. The uniform color bands indicate a stable modal response, dominated by structural rigidity and effective support configuration. Furthermore, the Figure 1(e) represents that second mode also lies well above the seismic qualification threshold (78.624 Hz), and the consistent deformation pattern suggests no unexpected local vibrations. This output was used for comparison with KEPIC MN **[1]** and ASME Code [2] allowable stress limits under various service levels.

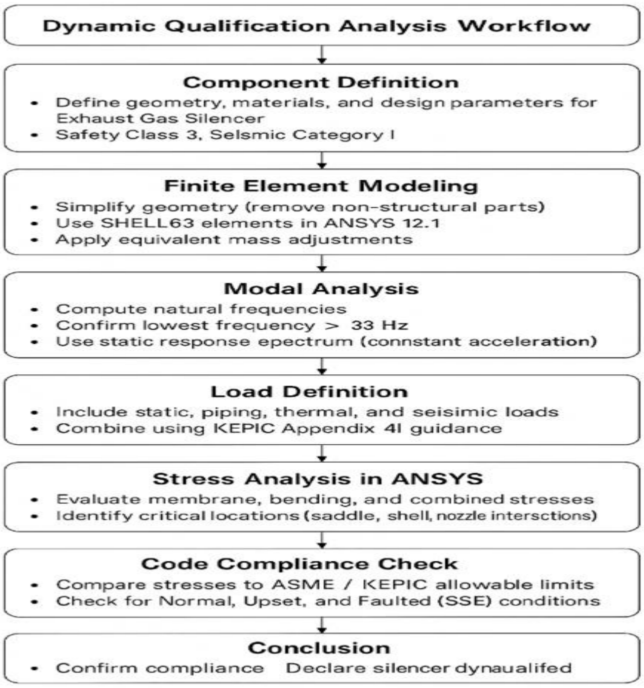

Figure 3: Workflow diagram for dynamic seismic qualification of the Exhaust Gas Silencer, outlining key steps from component definition to final compliance verification.

4. RESULTS

4.1 Modal Analysis

The first six natural frequencies obtained are summarized in Table 4.

Mode	Natural Frequency (HZ)
1	69.13 Hz
2	78.61 Hz
3	78.78 Hz
4	80.40 Hz
5	80.45 Hz
6	82.00 Hz

Table 5: Natural Frequencies from Modal Analysis

The first mode shape (Figure 4) indicated global deformation at 69.13 Hz, significantly above the 33 Hz threshold, justifying the use of equivalent static analysis. Higher mode shapes (Figures 5) similarly confirmed global dynamic stability.

4.2 Seismic Loading Application

Based on the modal analysis results, constant acceleration seismic loads were applied in accordance with site-specific response spectra. Peak Ground Accelerations (PGA) were:

Direction	½ SSE(g)	SSE(g)
E-W	0.425	0.85
N-S	0.425	0.85
V-S	0.425	0.85

Table 6: Peak Ground Accelerations Used for Seismic Load Cases.

As the lowest mode frequency exceeds 33 Hz, constant acceleration was applied per the standard response spectrum method according to KEPIC MN Appendix 4I9].The Figure 1(f) discusses the stress distribution at saddle support under SSE conditions; the saddle support experiences combined membrane and bending stress. It illustrates the stress concentration patterns, particularly at the curved base plate. **The maximum stress of 15.63 MPa was significantly lower than** the Service Level D allowable limit of 372.6

MPa, confirming the robustness of the support system during a seismic event. Seismic loads were included in load combinations defined per KEPIC Appendix 4I, covering:

- **Normal Operation (Level A)**
- **Upset Condition (½ SSE, Level B)**
- **Faulted Condition (SSE, Level D)**

Load combinations followed KEPIC Appendix 4I, considering operating, upset (1/2 SSE, 2% damping), and faulted (SSE, 3% damping) conditions. The total loading conditions analysed include:

- Weight (dead and operational)
- Piping loads (inlet/outlet nozzle forces and moments)
- Thermal expansion
- Seismic accelerations

Seismic loads were superimposed onto dead weight, internal pressure, thermal, and operational piping loads, following KEPIC Appendix 4I. The load combinations were:

Condition	Combination	Code Limit Type
Normal	W + P + T + O	Service Level A
Upset	W + P + T + O + S (1/2 SSE)	Service Level B
Faulted	W + P + T + O + S (SSE)	Service Level D

Table 7: Combined Load Cases Considered for Normal, Upset, and Faulted Conditions

All components used in this experiment are W = Weight, P = Pressure, T = Thermal, O = Operational loads (e.g. nozzle/ piping, and S_{OBE},S_{SSE}: Seismic loads from Operating Basis Earthquake and Safe Shutdown Earthquake spectra respectively. Seismic accelerations were applied at the EGS's centre of gravity, and the Square Root of the Sum of Squares (SRSS) method was used for conservative load combination.

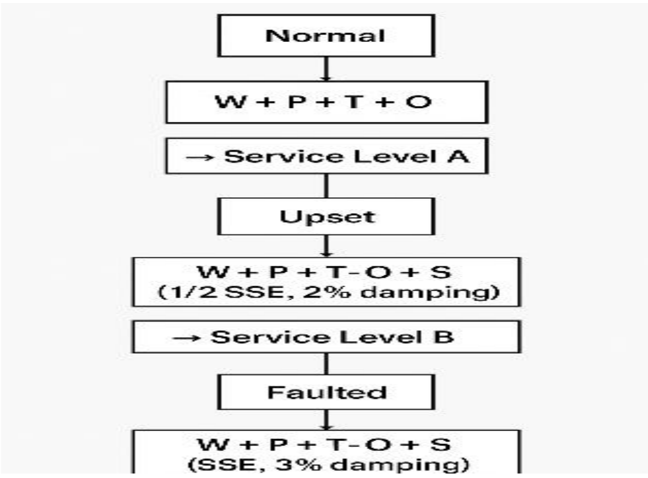

Figure 5: Stress Distribution at Saddle support under dead weight loading.

The Figure 7 illustrates that the combined bending stress intensity and membrane on the saddle support under static load conditions. It offers a reference for stress behaviour in the absence of dynamic or operational piping forces. The result—9.36 MPa—demonstrates low stress levels, validating the strength of the saddle design under baseline loading. This provides important contrast against dynamic load cases like seismic and piping events shown in later Figures.

4.5 Modelling Assumptions and Methodological Justification

ANSYS 12.1 was used due to its robustness for analyzing shell-type components. SHELL63 elements were selected for modeling the thin-walled Exhaust Gas Silencer (EGS), as they accurately capture membrane and bending stresses and are suitable for both linear static and modal analysis. Equivalent static analysis was justified by the fundamental frequency of 69.13 Hz, exceeding the 33 Hz threshold defined in KEPIC MN §7.2.g, allowing the use of site-specific peak accelerations as static loads. Although nonlinear time-history analysis offers more realistic responses under severe seismic excitation, the high stiffness of the EGS makes equivalent static analysis a conservative and practical approach. A linear elastic material model was used, excluding nonlinearities such as plasticity, geometric nonlinearity, or contact effects. These assumptions, while common in preliminary qualification studies, may underestimate localized responses during intense seismic events. Nonlinear finite element analysis is recommended for future studies, especially under SSE conditions. The mass of non-structural elements (e.g., insulation and cladding) was included using an equivalent shell density, ensuring conservative inertia representation. Standard damping ratios of 2% for OBE and 3% for SSE were adopted, though actual values may vary due to fabrication quality, joint rigidity, and aging. Sensitivity analysis or experimental calibration is suggested to improve confidence in damping assumptions.

4.6 Stress Evaluation and Figures

Stress evaluation was conducted at critical points, such as the saddle supports, shell intersections, and reinforced areas. The stress categories considered included:

- **Membrane stress (Pm)**: Mid-wall shell stress
- **Combined membrane and bending stress (Pm + Pb)**: Total linear stress across thickness
- **Local membrane plus secondary bending (PL + Q)**: Stress at intersections and discontinuities

Stress intensity was extracted using ANSYS POST1 and compared against allowable values according to **KEPIC MN [1]** and ASME Section III **[2]** standards.

Stress Categories:

- Pm: General membrane stress
- Pm + Pb: Membrane + Bending stress (total linear stress)
- PL + Q: Local membrane + secondary bending (used in intersections)

Stress Limits: Defined by KEPIC MND 3416 and MNF for various service levels:

- Service Level A: Normal Operation
- Service Level B: Upset (1/2 SSE)
- Service Level D: Faulted (SSE)

4.7 Stress Evaluation Summary Table

Stress evaluation results for critical regions of the Exhaust Gas Silencer (EGS) are summarized in Table 7. The evaluated locations include the saddle supports, shell regions near supports, shell-to-head intersections, and reinforced structural areas. **Table 7** presents the maximum combined membrane and bending stresses (Pm + Pb) observed under different loading conditions, compared against the allowable limits specified by KEPIC MN [1] and ASME Section III [2] codes.

Interpretation:

All maximum stress values remained within the allowable limits across all service conditions. The highest stress concentrations were observed near the reinforced angles; however, they did not exceed the safety margins. These results confirm the structural adequacy of the EGS under normal, upset, and faulted seismic conditions.

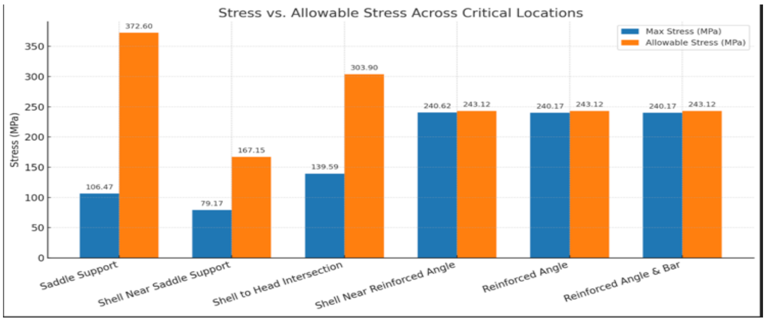

Table 7: Summary of Stress Evaluation Results at Key Locations (Units: MPa)

Location	Load Case	Stress Type	Max Stress (MPa)	Allowable (MPa)	Status
Saddle Support	Faulted	Pm + Pb	106.47	372.6	OK
Shell Near Saddle Support	Upset	Pm + Pb	79.17	167.15	OK
Shell to Head Intersection	Normal	PL + Q	139.59	303.9	OK
Shell Near Reinforced Angle	Faulted	Pm + Pb	240.62	243.12	OK
Reinforced Angle & Bar	Faulted	Pm + Pb	240.17	243.12	OK

Figure 6: Comparison of maximum stress vs. allowable stress across critical locations of the Exhaust Gas Silencer, confirming all values remain within code-defined limits.

Stress vs. allowable Stress across critical location

This chart compares the maximum stress and allowable stress at five key structural regions of the pressure vessel. All maximum stress values are within safe limits, indicating the design is structurally sound. The regions near the reinforced angle show the highest stress but remain below allowable values, confirming no risk of failure under the given load conditions. All values conform to KEPIC MN [1] and ASME [2] Service Level D limits. These results confirm that under all service conditions—including seismic loading—all evaluated stress values remain within the allowable design limits. Figures in the following section visualize the stress distributions across critical locations.

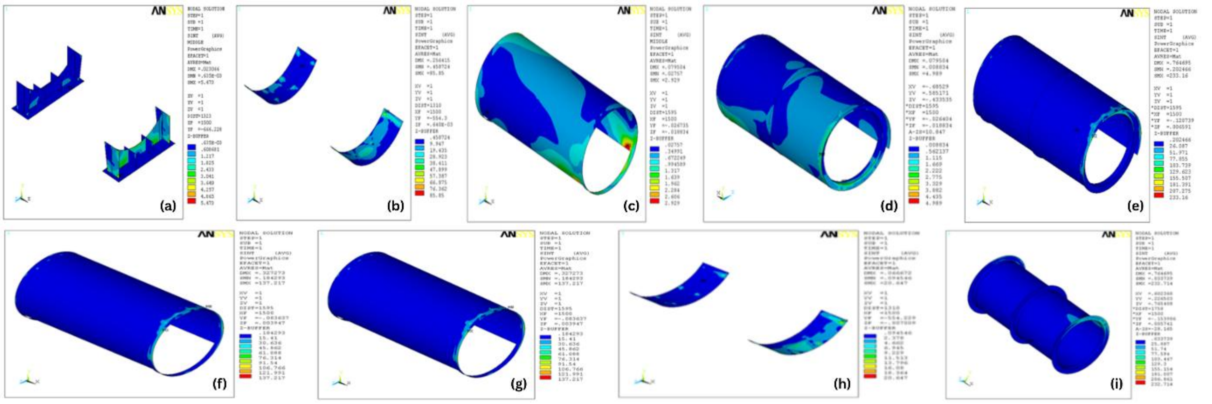

Figure 7: Stress distribution in critical regions of the EGS: (a) Saddle support under dead weight load; (b) Shell near saddle under SSE piping load; (c) Shell-to-head junction under SSE; (d) Reinforced angle under SSE load; (e) Reinforced angle under faulted piping load; (f) Shell-to-head under normal/upset load; (g) Shell near saddle under SSE; (h) Reinforced angle under faulted piping; (i) Reinforced angle, bar, and splitter plate under faulted load.

4.8 Modelling Assumptions and Limitations

This study adopts a linear elastic model for the Exhaust Gas Silencer (EGS), which is appropriate given its high stiffness and a fundamental frequency of 69.13 Hz—well above the 33 Hz threshold defined in KEPIC MN, justifying the use of equivalent static seismic analysis. The analysis assumes idealized material behavior, excluding nonlinear effects such as plastic deformation, geometric nonlinearity, and contact interaction. While conservative and suitable for preliminary design, these assumptions limit the accuracy in capturing local stress redistribution or post-yielding phenomena during extreme seismic events. Saddle supports were modeled as fully fixed in both vertical and lateral directions, simplifying the actual boundary flexibility. This may underestimate localized stresses that occur due to partial movement or soil-structure interaction. Standard damping ratios of 2% for OBE and 3% for SSE were applied based on welded steel nuclear components, although real damping could vary with fabrication, connection details, or aging effects. These assumptions are conservative but introduce uncertainty, suggesting the need for future sensitivity analysis and experimental validation.

4.9 Combined Stress Analysis Summary

The stress distributions across critical regions of the Exhaust Gas Silencer (EGS) were evaluated under normal, upset, and seismic (SSE/faulted) conditions. Under normal static loading (Fig. 8a), membrane stress on the saddle support was minimal (5.47 MPa), well below the Service Level A limit. Combined membrane and bending stresses (Pm + Pb) at the shell near saddle and reinforced angle (Figs. 8b, 8h) reached up to 240.62 MPa under SSE and faulted piping loads, nearing but not exceeding the 243.12 MPa Service Level D threshold—indicating effective use of reinforcement. Stress at the shell-to-head junction (Figs. 8c, 8g) remained low (4.62 MPa and 143.08 MPa) under seismic and operational loads, confirming good geometric design at transitions. Stress near reinforced angles and splitter plates (Fig. 8i) also approached the limit (240.17 MPa) but stayed within safe margins. Across all cases, stress levels remained below KEPIC MN and ASME design limits, verifying the structural adequacy of the EGS under all service conditions.

4.10 Mathematical Notes:

Stress intensity was calculated from ANSYS POST1 linearized output, and the peak values are defined as: Total stress Intensity $\sigma_{Total} = P_m + P_b$ and the Local Stress $\sigma_{local} = P_L + Q$. Where:

- P_m: Membrane stress (mid-surface)
- P_b: Bending stress (outer surfaces)
- P_L: Local membrane stress at nozzle or discontinuity
- Q: Secondary bending stress due to constraints

All results meet the allowable stress criteria defined in KEPIC MND-3416 and MNF-3251.

5. DISCUSSION

5.1 Stress regions at the Borderline

Certain areas, especially near reinforced angles and saddle supports, exhibited stress levels close to allowable limits under SSE loading. Though within code limits, these tight margins suggest a need for design refinement. To enhance structural performance, the following measures are recommended: applying local mesh refinement in high-stress zones to improve accuracy; introducing geometric reinforcement such as thicker walls or additional stiffeners; and conducting future nonlinear analysis to evaluate plasticity, buckling, or potential failure mechanisms under extreme loading conditions.

5.2 Recommendations of future work

To enhance the seismic qualification of the Exhaust Gas Silencer (EGS), the following directions are proposed:

- Nonlinear Time-History Analysis: Explore transient dynamic simulations to capture nonlinear behaviors like plasticity, contact separation, and local failure—effects not seen in static analysis. Studies such as Suresh/Rao [18] highlight the potential of nonlinear FEA for nuclear-grade components.
- Experimental Validation (Shake Table Testing): Conduct vibration or shake table tests to measure natural frequencies and damping ratios. Use experimental data to validate FEA results. Ghanem et al. [19] emphasized FSI modeling to assess pressure dynamics, which could improve EGS safety analysis under combined seismic and pressure loading.
- Fatigue and Life Assessment: Evaluate the effects of operational and seismic vibrations on fatigue life. A fragility-based probabilistic framework (e.g., Song et al. [20]) can estimate failure probabilities across different seismic levels.
- Parametric Optimization of Stress Zones: Optimize wall thickness, reinforcement, and supports in high-stress regions to reduce peak stress and improve margins, without significantly increasing material usage.

Implementing these improvements can strengthen the structural and functional reliability of the EGS under both normal and extreme conditions.

6. CONCLUSION

This study confirmed the structural adequacy and seismic resilience of the Exhaust Gas Silencer (EGS) used in Emergency Diesel Generator systems in nuclear power plants. Finite Element Analysis (FEA) using ANSYS 12.1 was conducted under normal, upset (½ SSE), and faulted (SSE) seismic conditions. Modal analysis demonstrated a fundamental natural frequency of 69.13 Hz, exceeding the 33 Hz threshold and justifying the use of equivalent static seismic analysis. Stress evaluations revealed that all critical regions, including the reinforced angles and saddle supports, maintained stress levels within allowable limits as defined by KEPIC MN and ASME Section III standards. While some areas exhibited stresses approaching code-defined thresholds under faulted conditions, no exceedances were observed, confirming compliance and structural safety.

This qualification ensures that the EGS maintains its exhaust-handling function during seismic disturbances, thereby minimizing the risk of environmental contamination from unfiltered or uncontrolled emissions.

The study provides a replicable methodology for seismic qualification of auxiliary components in nuclear facilities, particularly for high-frequency, rigid structures like silencers.

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