APPLICATION OF RESPONSE SPECTRUM ANALYSIS (RSA) IN THE DESIGN OF HIGH-RISE BUILDING WITH VISCOELASTIC DAMPER (VED)

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Abstract
Earthquake-resistant structures using dampers have begun to be implemented in Indonesia. Structures equipped with dampers can reduce plastic deformation in primary structural elements, inter-story drift, and floor acceleration. According to SNI 1726:2019 Article 13, the seismic design analysis of structures with damping systems may employ nonlinear time history analysis (NLTHA) or alternative procedures such as response spectrum analysis (RSA) and equivalent lateral force (ELF). However, NLTHA is computationally inefficient and requires considerably longer processing time compared to alternative procedures. The RSA procedure also stipulates that dampers may be used solely to satisfy inter-story drift requirements per SNI 1726:2019, so that bare frame structures can be analysed conventionally to meet the strength requirements of SNI 2847:2019. The novelty of this research lies in applying the RSA method as a computationally efficient alternative to NLTHA for the analysis and design of structures with viscoelastic dampers (VED), which is not yet widely practiced by engineers in Indonesia. In this study, the structure was modelled with VED and analysed using RSA through iterative stages: viscous damping iteration (βvm), iteration at the DBE earthquake level to satisfy the minimum base shear V and $\beta md \leq 35\%$, and iteration at the MCER earthquake level to satisfy story drift and story displacement limits. Using the RSA method, 12 dampers per direction (24 per floor) were installed, satisfying the RSA minimum requirement of 2 dampers per direction and 4 dampers per floor. Based on the analysis, the minimum base shear (Vmin) was 0.9085V. It is concluded that the alternative RSA procedure can be applied and satisfies the requirements of SNI 1726:2019 for damping systems.

Keywords: *response spectrum analysis (RSA), viscoelastic damper (VED), nonlinear time history analysis (NLTHA), seismic design with damping system, damper optimization*

INTRODUCTION

Dampers in earthquake-resistant structures have been widely adopted, particularly in developed countries. Dampers serve as seismic energy dissipation devices to direct damage away from primary structural elements. Compared to structures without dampers, structures with dampers demonstrate reduced plastic deformation in primary structural elements, lower inter-story drift, and decreased floor acceleration [1]. In Indonesia, the design of earthquake-resistant structures with dampers is governed by SNI 1726:2019 Article 13, which specifies two permissible analysis procedures: nonlinear time history analysis (NLTHA) and alternative procedures.

NLTHA is the most commonly used procedure for designing structures with dampers, as it allows direct observation of the energy dissipated by the dampers and follows a relatively straightforward analytical process. However, NLTHA is computationally inefficient due to the significantly longer processing times compared to alternative procedures, and computation time is highly dependent on computer specifications. According to Lumantara [2], a simpler yet accurate and conservative nonlinear static analysis is needed to replace NLTHA for assessing structural performance. The alternative procedures consist of response spectrum analysis (RSA) and equivalent lateral force (ELF), both of which are considerably faster than NLTHA [3].

RSA is rarely used for structures with dampers because the analysis method is less straightforward compared to NLTHA. RSA also stipulates that dampers may be used only to satisfy inter-story drift requirements per SNI 1726:2019, meaning that the bare frame structure can be analysed conventionally to meet the strength requirements of SNI 2847:2019. Furthermore, the RSA method for structures with dampers requires a minimum number of dampers per floor, specifically at least 2 dampers per principal direction, such that no floor is left without dampers. However, according to Najam [4], a modified RSA can still be used for the analysis of structures with dampers and provides a reasonable level of accuracy, even with different ground motion inputs.

NLTHA is widely recognized as the primary method for seismic analysis of structures equipped with damping systems, its high computational demand and complex analytical procedures limit its practical application in routine structural design. Conversely, the implementation of RSA for high-rise buildings with VED remains insufficiently explored, particularly regarding compliance with SNI 1726:2019 requirements, iterative viscous damping evaluation, minimum base shear verification, and inter-story drift control under DBE and MCER earthquake levels. Previous RSA-based approaches also rely on equivalent linear assumptions that may inadequately represent nonlinear damper behavior. Therefore, this study aims to investigate the applicability and effectiveness of RSA as a computationally efficient alternative method for the seismic design and performance evaluation of high-rise buildings equipped with VED systems.

This paper therefore employs the RSA method with viscoelastic dampers

(VED), given that RSA is already familiar to engineers in Indonesia and is computationally more efficient. The objective of this study is to apply the RSA analysis method to structures with dampers in accordance with SNI 1726:2019 and to observe the application challenges, particularly in the context of response spectrum analysis (RSA).

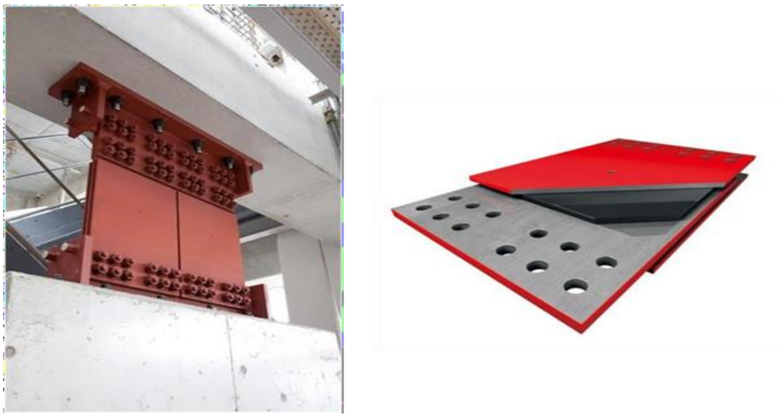

Figure 1. Viscoelastic Damper (VED) Panels

THEORETICAL BACKGROUND

Seismic Force-Resisting System (Bare frame) and Damping System

The analysis procedure for structures with dampers follows SNI 1726:2019 Article 13, which specifies two structural systems: the seismic force-resisting system (SFRS or bare frame) and the damping system. The SFRS is designed for a strength no less than 75% of the full strength of the SFRS without dampers. Analysis of structures with dampers must be conducted at two earthquake levels: the design basis earthquake (DBE) and the maximum considered earthquake (MCER).

At the MCER level, the device displacement limit of the damper is evaluated because the damper must remain elastic under MCER conditions. The structure with the damping system must also comply with a maximum inter-story drift ratio of 3%. At the MCER level, force-controlled elements in the damping system (DS) must be designed for forces at least 20% greater than the mean MCER response. The DS includes pedestals connecting the DS to the SFRS.

Design Procedure for Structures with Dampers

According to SNI 1726:2019 regarding structures with damping systems, the standard primary analysis procedure is nonlinear time history analysis (NLTHA), which applies earthquake load histories to evaluate structural capacity. As noted by Lumantara [2], NLTHA requires very long computation times, necessitating a simpler yet accurate and conservative nonlinear static analysis to replace NLTHA for performance assessment.

According to Najam [4], response spectrum analysis (RSA) can serve as an alternative to NLTHA. When modified, RSA can provide a reasonable level of accuracy with different ground motion inputs. RSA requires a minimum of 2 dampers per principal direction on every floor, yielding a minimum of 4 dampers per floor.

Response Spectrum Analysis (RSA)

Response spectrum analysis for structures with dampers, following the requirements of SNI 1726:2019, is a simplified method that tends to yield more conservative inter-story drift values compared to NLTHA. According to Kitayama and Constantinou [5], the design and analysis procedure is simplified in parallel with the ASCE 7-2010 approach in Chapter 18. Inter-story drift is the primary RSA requirement because, per SNI 1726:2019, dampers may be used solely to satisfy drift requirements. The analysis procedure for structures with damping systems must satisfy the following requirements per SNI 1726:2019:

1. In each principal direction, the damping system must have at least two damper devices on every floor, configured to resist torsion.
2. The total effective damping ratio in the fundamental mode, βmd (m = 1), in the direction considered shall not exceed 35% of critical damping.
3. The spectral acceleration parameter S1 at the site shall be less than 0.6g.

The simplified RSA method, as permitted by ASCE 7-16 Chapter 18, relies on the following key assumptions:

1. The nonlinear behaviour of the bare frame can be represented by an equivalent linear stiffness and viscous damping.
2. The structure is designed with a single degree-of-freedom failure mechanism.
3. The inelastic response of the structure can be represented by an elastic-perfectly-plastic model.
4. In each principal direction, the structure is analysed with one degree of freedom per floor.

RESEARCH METHODS

The analysis procedure employs response spectrum analysis (RSA) in accordance with SNI 1726:2019 Article 13 on damping systems. This method requires a minimum of 2 dampers per principal direction on every floor, yielding a minimum of 4 dampers per floor. RSA is applied at both the DBE and MCER earthquake levels. At the MCER level, the device displacement limit is evaluated to ensure the dampers remain elastic, and the maximum inter-story drift is checked against the 3% limit. The research methodology for designing structures with VED using RSA is divided into four stages: (1) analysis of the bare frame structure and pushover analysis, (2) viscous damping iteration (βvm), (3) iteration at the DBE earthquake level, and (4) iteration at the MCER earthquake level. The overall research flowchart is presented in Figure 2.

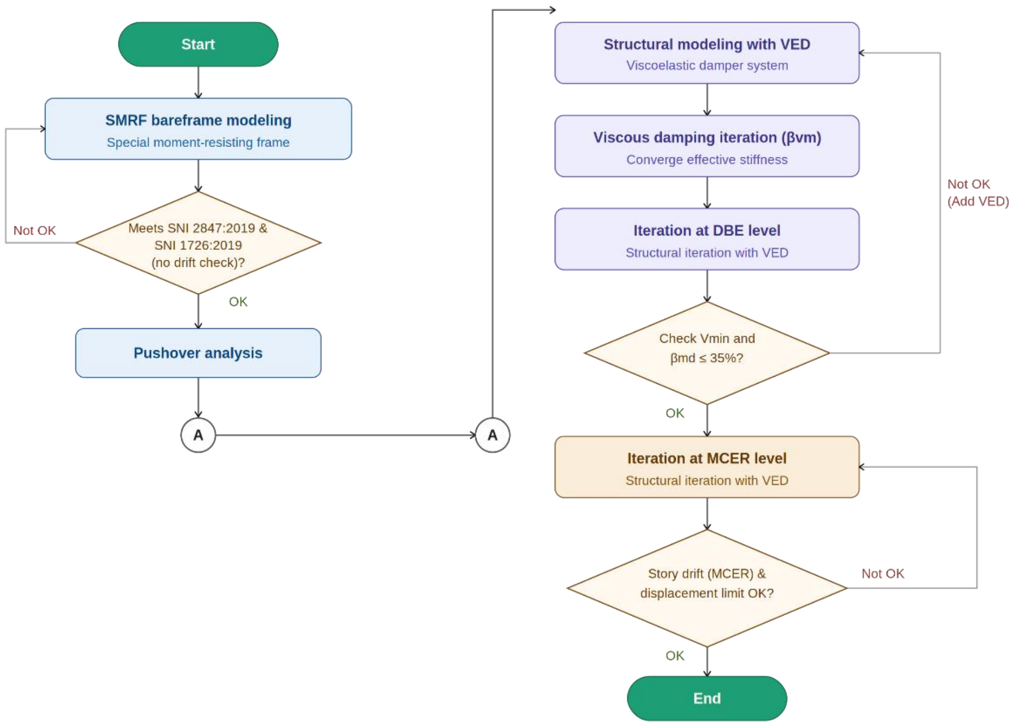

Figure 2. Research Flowchart

Bare frame Structural Analysis and Pushover Analysis

The seismic force-resisting system used in this study is the Special Moment Resisting Frame (SMRF), designed without the need to satisfy the inter-story drift requirements of SNI 1726:2019. Pushover analysis is subsequently performed to obtain the parameters needed for the viscous damping iteration (βvm).

The building investigated in this study is located in Jakarta, Indonesia, a region characterized by considerable seismic activity. According to seismic design provisions, the structure is classified under Risk Category II, indicating a standard occupancy building with a moderate level of risk to human safety. The subsurface condition at the site is categorized as Site Class SE, representing soft soil with a significant potential to amplify ground motion during seismic events.

Viscous Damping Iteration (βvm)

Viscoelastic Dampers (VED) are displacement-dependent dampers. Per SNI 1726:2019, viscous damping must be designed such that the modal displacement equals the effective yield displacement of the structure. This requires the effective yield displacement (Dy) and the effective yield force from the pushover curve. The nonlinear displacement behaviour of the VED can be represented by an effective stiffness, enabling its incorporation into RSA. As an initial assumption, the VED displacement is taken as 70% of the inter-story drift and is then iterated by incorporating the effective stiffness into the structural model until the structural and VED displacements converge, yielding the viscous damping in the m-th mode (βvm) at the fundamental mode (m = 1).

Iteration at the DBE Earthquake Level

At the DBE level, the effective stiffness is also used to represent the VED displacement, with the initial VED displacement assumed at 70% of the inter-story drift. Iteration begins from the βvm value obtained in Stage 3.2. For higher modes (m > 1), the βvm and DBE iterations may be conducted simultaneously, as the viscous damping does not need to be at the level of the effective yield displacement but rather at the smaller of the effective yield displacement and the design roof displacement (DmD). The DBE level is used to verify that the seismic base shear exceeds the minimum value of 0.75V or V/BV+I, and that the total effective damping in the first mode (β1D) does not exceed 35%.

Iteration at the MCER Earthquake Level

At the MCER level, the iteration also employs the effective stiffness with an initial VED displacement assumption of 70% of the inter-story drift until convergence. The MCER level is used to verify that the inter-story drift ratio does not exceed 3% or the minimum limit from Table 20 of SNI 1726:2019 multiplied by 1.5R/Cd and 1.9. The VED displacement must not exceed 300% of the VED thickness. The roof design displacement in the first mode (D1M) is set equal to twice the effective yield displacement (Dy), and iterations continue until the effective stiffness (Keff) converges.

Structural Modelling with Dampers

The structure is modelled with a viscoelastic damper (VED) system. Based on RSA requirements per SNI 1726:2019, a minimum of 2 dampers per direction (x and y) must be installed on each floor. The VED dimensions used are 400 mm × 400 mm with a thickness of 20 mm. In this study, 6 VED units are installed in each direction (x and y), and the damper installation scheme on the structure is shown in Figure 3.

RESULTS AND DISCUSSION

The structure is modelled with VED 400 mm × 400 mm and a thickness of 20 mm. VED parameters were obtained from Sumitomo Rubber Industries based on the natural period and frequency of the modelled bare frame. The hysteretic curve of the VED used is shown in Figure 4. In the RSA simulation, the VED is modelled as a spring with an equivalent stiffness equal to the secant stiffness corresponding to the assumed VED displacement, while the damping value is determined through an iterative process applied directly outside the analysis as a reduction in seismic forces. No viscous element is explicitly modelled in ETABS.

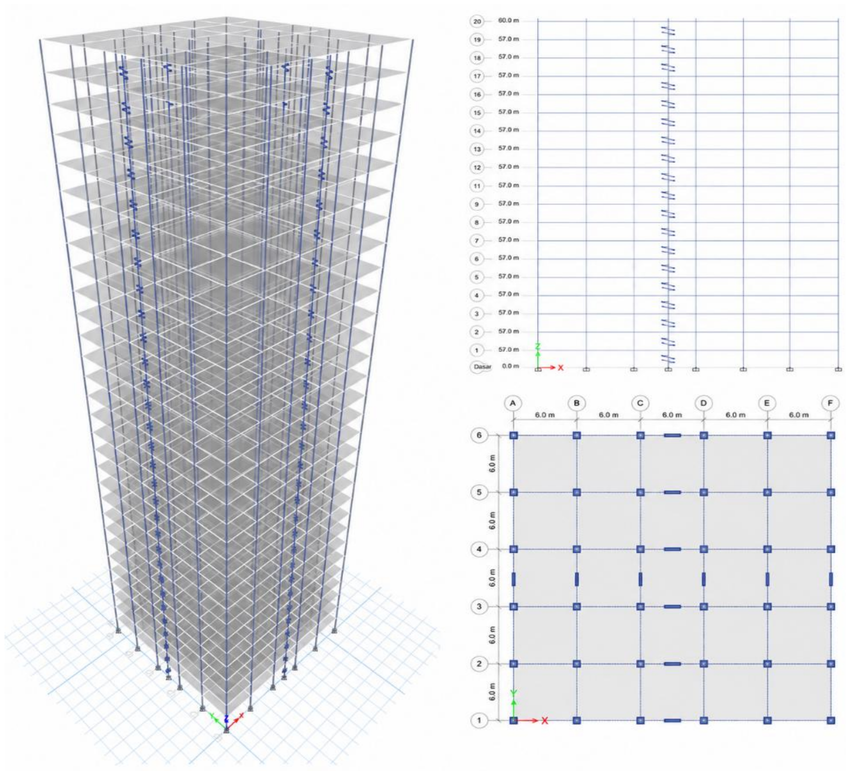

Figure 3. VED Modelling on Bare frame Structure

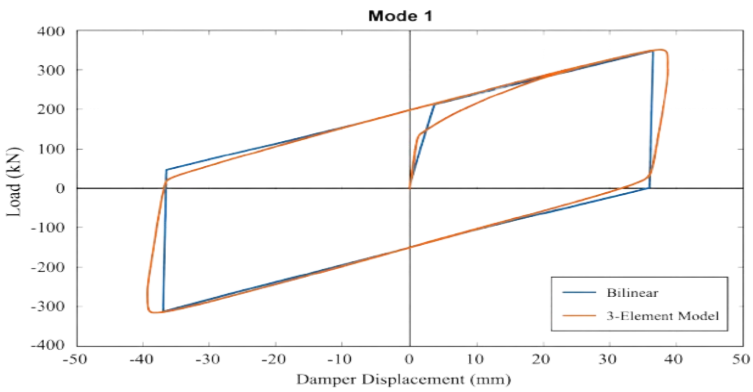

Figure 4. VED Hysteretic Curve for Bare frame 1V

The structural design results for reinforced concrete with dampers use 6 VED units in each direction (x and y). The VED parameters at a frequency of 0.1435 Hz are presented in Table 1. Symbol definitions: X1 & X2 = Damper Displacement; Y1 & Y2 = Load; Q2 = Load at effective yield condition (Dy); d2y = Damper displacement at effective yield condition (Dy). The structural design process requires the effective yield value (Dy) obtained from pushover analysis. Based on the pushover analysis of bare frame 1V, the effective yield displacement (Dy) is 1461.97 mm.

Table 1. VED Parameters

t	x_1 (m)	x_2 (m)	y_1 (N)	y_2 (N)	K_2 (N/m)
20	-0.03719	0.03764	17568.40	336077.45	4256646.25

Q_1 (N)	Q_2 (N)	d1y (m)	d2y (m)
0	191901.018	0	0.00376433

Viscous Damping in the M-th Mode (βvm)

The viscous damping in the m-th mode (βvm) converges through 7 iterations. The iteration begins with the modal participation mass ratio (MPMR) of 6.968 s, story displacement (δi), and mass (wi) from bare frame 1V. Initial assumptions include: Dy = 1461.97 mm; roof design displacement in the first mode (D1D) = Dy = 1461.97 mm; μD = 1; and initial assumed βvm = 0.04. After 7 iterations, βvm converges to 0.04518 (4.518%). The iteration process is presented in Table 2.

Table 2. Viscous Damping Iteration Process (βvm)

Iteration	βvm	Convergence (%)
Iteration 0 (Initial Assumption)	0.0400	0.00%
Iteration 1	0.0697	74.29%
Iteration 2	0.0523	-24.97%
Iteration 3	0.0479	-8.46%
Iteration 4	0.0463	-3.31%
Iteration 5	0.0456	-1.43%
Iteration 6	0.0453	-0.68%
Iteration 7	0.0452	-0.32%

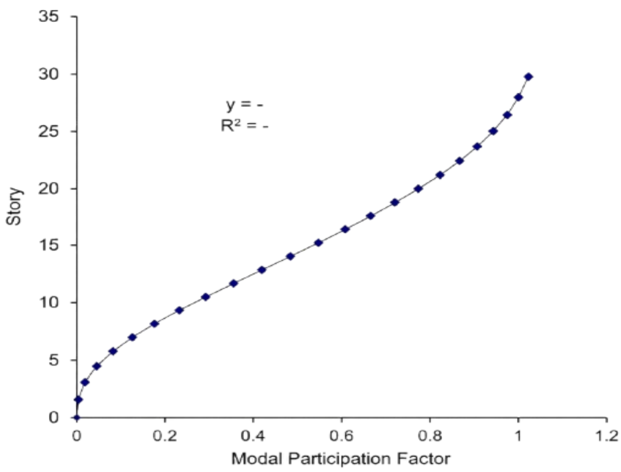

Figure 5. Mode Shape Iteration of Viscous Damping in the M-th Mode (βvm)

Design Earthquake (DBE)

The DBE iteration converges through 9 iterations. Initial conditions are the same as for the βvm iteration, with βvm = 0.04517 (4.517%) from Stage 4.1. The effective damping in the m-th mode (βmD) converges to 0.07517 (7.517%) at iteration 7. Per SNI 1726:2019, βmD must not exceed 35%; therefore, this value satisfies the requirement. The DBE iteration process is presented in Table 3. The minimum base shear for the structure with dampers is evaluated at the DBE iteration, at iteration 9. The minimum base shear V is determined as the maximum of 0.75 and 1/(Bv+1), where βv+I = βvm + β1. For bare frame 1V with 12 VED units per direction, Vmin = 0.9085V, satisfying the SNI 1726:2019 requirement.

Table 3. DBE Earthquake Level Iteration Process

Iteration	βmD	Convergence (%)
Iteration 0 (Initial Assumption)	0.0700	0.00%
Iteration 1	0.0997	42.45%
Iteration 2	0.0823	-17.46%
Iteration 3	0.0779	-5.38%
Iteration 4	0.0763	-2.04%
Iteration 5	0.0756	-0.87%
Iteration 6	0.0753	-0.41%
Iteration 7	0.0752	-0.19%

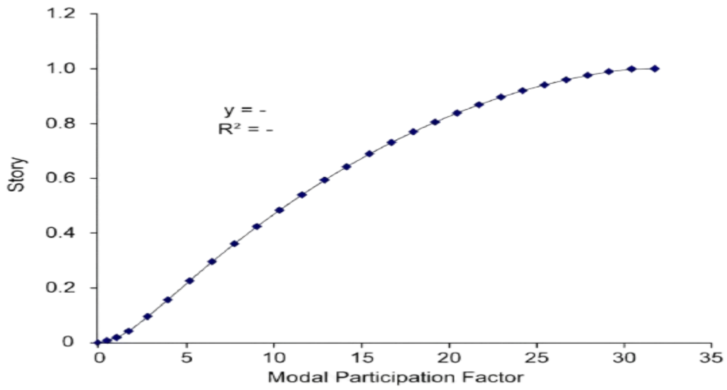

Figure 6. Mode Shape Iteration of DBE Earthquake Level

Maximum Considered Earthquake (MCER)

The MCER iteration converges through 8 iterations, with the same initial conditions as for βvm. The roof design displacement in the first mode (D1M) is set to 2 × Dy = 2923.93 mm, and μM = 2. The βvm value of 0.04517 (4.517%) from Stage 4.1 is used. The maximum inter-story drift of the bare frame 1V was 6.517%. After applying 12 VED units per direction, the maximum story drift is reduced to 2.60%, satisfying the SNI 1726:2019

MCER level limit of 3%. The VED system reduces the bare frame story drift by 3.917%.

The device displacement limit is also checked at the MCER level. The device displacement limit (DmM) equals three times the VED thickness; i.e., VED displacement must not exceed 300% of thickness. The Damper values for all stories are presented in Table 4. All 30 stories satisfy the device displacement limit of 60 mm (= 300% × 20 mm thickness). The mode shape at the MCER level is shown in Figure 8.

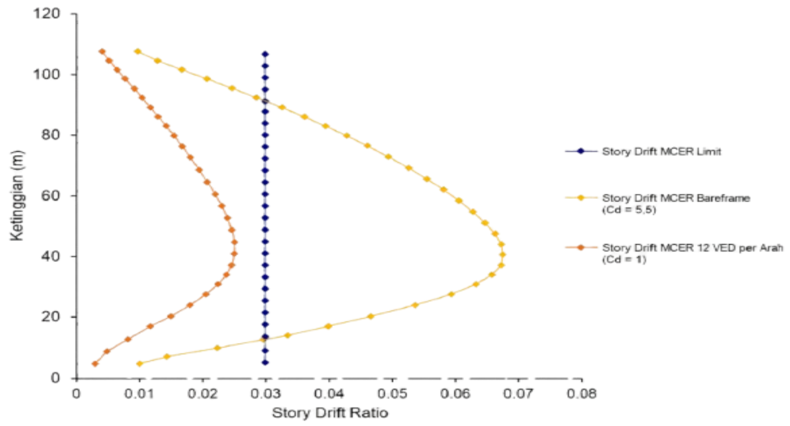

Figure 7. Story Drift with 12 VED per Direction

Table 4. Device Displacement Limit (DmM)

Story	Δdamper (mm)	Limit (mm)	Story	Δdamper (mm)	Limit (mm)
Story30	1.77	60 ✓	Story15	23.86	60 ✓
Story29	0.33	60 ✓	Story14	26.08	60 ✓
Story28	0.48	60 ✓	Story13	28.32	60 ✓
Story27	1.14	60 ✓	Story12	30.42	60 ✓
Story26	1.94	60 ✓	Story11	32.18	60 ✓
Story25	2.18	60 ✓	Story10	32.69	60 ✓
Story24	2.70	60 ✓	Story9	33.23	60 ✓
Story23	3.61	60 ✓	Story8	32.79	60 ✓
Story22	5.73	60 ✓	Story7	31.28	60 ✓
Story21	8.88	60 ✓	Story6	29.43	60 ✓
Story20	10.47	60 ✓	Story5	25.56	60 ✓
Story19	12.89	60 ✓	Story4	20.68	60 ✓
Story18	15.71	60 ✓	Story3	15.25	60 ✓
Story17	18.77	60 ✓	Story2	9.33	60 ✓
Story16	22.06	60 ✓	Story1	3.61	60 ✓

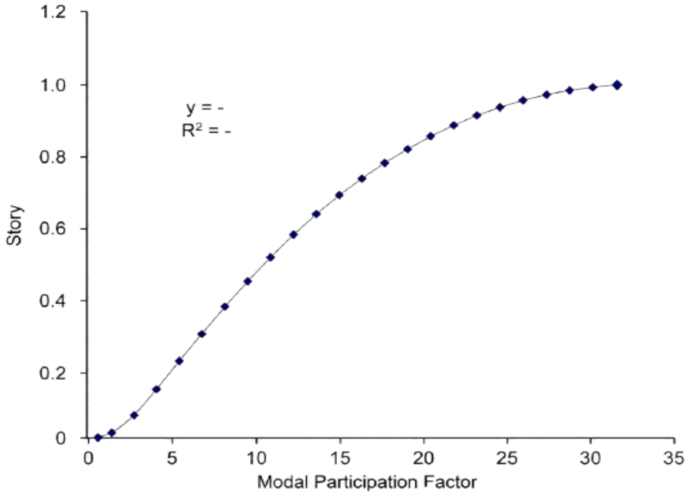

Figure 8. Mode Shape at MCER Earthquake Level

Comparative Disscussion with Previous Studies About RSA and NLTHA

The results obtained in this study demonstrate that the Response Spectrum Analysis (RSA) procedure can be successfully applied to the seismic design of high-rise reinforced concrete buildings equipped with Viscoelastic Dampers (VED) while satisfying all requirements specified in SNI 1726:2019. The implemented damping system, consisting of 12 VED units in each principal direction, effectively reduced the maximum inter-story drift from 6.517% in the bare-frame structure to 2.60% under the Maximum Considered Earthquake (MCER) level, representing a drift reduction of 3.917%. In addition, the structure achieved a minimum base shear value of 0.9085V, exceeding the minimum requirement stipulated by the code, while the effective damping ratio at the Design Basis Earthquake (DBE) level converged to 7.517%, which is significantly lower than the maximum allowable limit of 35%.

These results indicate that the incorporation of VEDs significantly improves the seismic performance of the structure by reducing lateral deformation demands and increasing the energy dissipation capacity of the structural system. The findings of this study are consistent with those reported by Najam and Warnitchai (2017), who demonstrated that a modified RSA procedure could provide a reasonable estimation of nonlinear seismic demands in high-rise structures when compared with Nonlinear Time History Analysis (NLTHA).

Similar to their findings, the present study confirms that RSA is capable of producing reliable seismic performance predictions while requiring substantially less computational effort than NLTHA. Furthermore, the results also support the work of Kitayama and Constantinou (2016), who concluded that equivalent linear analysis procedures may be effectively employed for structures equipped with supplemental energy dissipation devices, provided that the assumptions regarding effective damping and structural behavior are properly satisfied.

The successful convergence of the viscous damping iterations and the compliance of all performance parameters with SNI 1726:2019 requirements in this study further validate the applicability of equivalent linear approaches for the design of damped structures. Despite these similarities, the present research differs from previous studies in several important aspects. While Najam and Warnitchai (2017) focused primarily on high-rise buildings with shear wall systems and investigated modified RSA procedures under different ground motion records, the current study examines a Special Moment Resisting Frame (SMRF) structure equipped with Viscoelastic Dampers and evaluates its performance through an iterative RSA procedure specifically developed in accordance with SNI 1726:2019 provisions.

In addition, this study explicitly incorporates iterative calculations of modal viscous damping ratios, effective damping at the DBE level, minimum base shear verification, and performance evaluation at the MCER level, including checks on inter-story drift and damper displacement limits. These aspects are rarely discussed comprehensively within a single RSA-based design framework, particularly in the context of Indonesian seismic design regulations.

The significant reduction in inter-story drift observed in this study is also in agreement with the findings of Gimenez and Takehiko (2018), who reported that the implementation of supplemental damping systems can substantially reduce the lateral response of high-rise buildings when compared to conventional bare-frame structures. From a physical perspective, this reduction occurs because the VED system introduces additional damping into the structural system, thereby dissipating a portion of the earthquake input energy before it can be transferred to the primary structural elements.

As the effective damping ratio increases, the dynamic amplification of structural response decreases, resulting in lower displacement demands and improved overall seismic performance. Moreover, the effectiveness of the damping system observed in this study is further supported by the work of Terazawa (2019), who emphasized that the arrangement and distribution of dampers significantly influence the effectiveness of seismic response control. The uniform distribution of dampers on every floor adopted in the present study not only satisfied the minimum RSA requirements of SNI 1726:2019 but also contributed to a more stable and efficient structural response under seismic loading.

The primary contribution of this research lies in demonstrating a practical and code-compliant RSA-based design methodology for high-rise buildings equipped with Viscoelastic Dampers under

Indonesian seismic regulations. Unlike NLTHA, which requires extensive computational resources, multiple earthquake records, and significantly longer analysis times, the proposed RSA procedure provides a more efficient alternative while maintaining compliance with seismic performance requirements.

The iterative methodology developed in this study enables engineers to determine effective damping ratios, evaluate minimum base shear requirements, verify damper displacement limits, and control inter-story drift within a unified analytical framework. Therefore, the results not only support previous international studies regarding the applicability of RSA to damped structures but also extend existing knowledge by providing practical implementation procedures for VED-equipped high-rise buildings based on SNI 1726:2019. Consequently, RSA may be considered a reliable, efficient, and practical alternative to NLTHA for the seismic design and performance evaluation of structures incorporating supplemental damping systems, particularly in engineering practice where computational efficiency and design simplicity are important considerations.

CONCLUSION

The structural design process for structures with dampers can be analysed using the alternative NLTHA procedure, namely response spectrum analysis (RSA), although the method is not straightforward. Using the RSA method, 12 dampers per direction (24 per floor) were installed, satisfying the SNI 1726:2019 minimum requirement of 2 dampers per direction and 4 dampers per floor.

In addition to the minimum damper count, the RSA method imposes a requirement on the minimum base shear (Vmin) at the DBE level: Vmin < 1/(Bv+1). Based on the analysis, Vmin = 0.9085V, satisfying SNI 1726:2019. The alternative RSA procedure can therefore be applied in the design of structures with dampers, with shorter computation times compared to NLTHA.

This study demonstrates that Response Spectrum Analysis (RSA) can be effectively applied to high-rise buildings equipped with Viscoelastic Dampers (VED) in accordance with SNI 1726:2019. The implementation of VED successfully reduced the maximum inter-story drift from 6.517% to 2.60%, satisfying the required performance criteria, while achieving a minimum base shear value of 0.9085V in compliance with code provisions. The findings support previous studies regarding the effectiveness of RSA as an alternative to Nonlinear Time History Analysis (NLTHA) and contribute a practical, efficient, and code-compliant design procedure for the seismic design of damped structures in Indonesia.

The study confirms that Response Spectrum Analysis (RSA) can be effectively applied to high-rise buildings equipped with Viscoelastic Dampers (VED) in accordance with

SNI 1726:2019. The proposed system successfully reduced inter-story drift, satisfied minimum base shear requirements, and demonstrated results consistent with previous studies, indicating that RSA is a reliable and computationally efficient alternative to NLTHA.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Institut Teknologi Bandung, PT. Gravena Episintesa Struktur, and the Universitat Politecnica de Valencia (UPV) for their support and collaboration throughout this research.

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