European Journal of Engineering and Technology Research
Vol 9 | Issue 4 | July 2024
ISSN 2736-576X

RESEARCH ARTICLE

Effectiveness of Suspended Lead Dampers in Steel Building Structural Model Subjected to Impact Load

Herish Abdullah Hussein*

ABSTRACT

This paper delves into an in-depth experimental investigation focusing on the dynamic behavior of steel frame buildings employing passive damping through suspended lead dampers. The primary objective revolves around scrutinizing a three-story steel frame building model to elucidate the effects of integrating lead dampers into the outer tubular square-section columns. By strategically embedding these dampers, the study aims to showcase the resultant reductions in both acceleration and displacement. To execute this analysis, an impact load is precisely applied to the mid-center of the middle column along the x-axis of the first story of the steel frame. The experimental setup employs six wireless accelerometers strategically positioned across the frame to capture comprehensive data on its response at diverse locations. Various quantities of lead dampers are systematically incorporated into each testing scenario to gauge the extent of passive damping's influence on the structural response of steel buildings to impact loads. Throughout the experiments, acceleration-time relations are meticulously recorded at each story, facilitating a comparative assessment of outcomes with and without the presence of lead dampers. The findings of the study underscore a marked decrease in vibration levels at higher floors of the steel model subsequent to the installation of lead dampers within the structure. Furthermore, a noteworthy trend emerges indicating that an augmented number of lead dampers within the building yields a commensurate decrease in vibration amplitude. This detailed investigation offers valuable insights into the efficacy of passive damping mechanisms, thereby contributing to the advancement of seismic-resistant structural design practices.

Keywords: Impact load, Lead dampers, Tubular columns, Vibration.

Submitted: May 02, 2024
Published: July 06, 2024

10.24018/ejeng.2024.9.4.3176

Department of Public Works, Municipality of Virginia Beach, USA.

****Corresponding Author:***
e-mail: hhussein@vbgov.com

1. Introduction

Tubular square-section steel columns are universally acknowledged as the primary structural members in tall buildings due to their exceptional torsional resistance and favorable geometric properties. In such towering structures, mitigating vibration and lateral displacement assumes paramount importance, thereby propelling researchers to explore and elucidate various methodologies aimed at curbing undesirable motions. Among the plethora of damping systems deployed in the domain, Tuned Mass Dampers (TMDs) have unmistakably emerged as one of the most prevalent solutions. TMDs have garnered extensive utilization in both tall buildings [1] and bridge structures [2], constituting an efficacious means of attenuating vibration amplitudes. This versatile damping system manifests in diverse forms, encompassing mass and coil spring configurations, mass and flexure arrangements, and pendulum types, contingent upon the specific application. By adroitly capitalizing on resonance effects, TMDs adeptly absorb energy and diligently dampen vibrations, evincing markedly higher decay of motion vis-à-vis acceleration reduction. They particularly excel in assuaging wind excitations and impact loads inherent in tall buildings. It's imperative to underscore that the efficacy of TMDs hinges on the meticulous tuning of damping factors, mass, and spring stiffness contingent upon the structure's dominant mode [3]. A notable exemplar of the pendulum TMD system is discernible in the Tapyh Tower, a towering 101-story edifice in Taiwan [4]. This particular pendulum damper garners distinction for being the largest and heaviest ever installed in a building. Comprising a prodigious steel ball measuring a staggering 18 feet in diameter and weighing a colossal 1605 pounds, it's strategically emplaced at the tower's zenith, towering an imposing 1640 feet. This pendulum system effectually mitigates vibration in the structure by a commendable 30% to 40% [4]. However, in the present study, a departure from the conventional one-ball pendulum system is discernible, with a series of lead dampers judiciously deployed at multiple vantage points within a scaled-down model of a steel building frame. The overarching objective is to meticulously scrutinize the potential reduction in vibration during impact loading. This pioneering research endeavor ardently endeavors to unravel the effectiveness of lead-sphere pendulum systems in mitigating vibrations across various scenarios, spanning both high-frequency and low-frequency applications characteristic of short, intermediate, and towering buildings. The pendulum system unequivocally emerges as an archetype of passive damping mechanism ideally suited for towering structures, courtesy of its seamless integration within hollow-sectioned columns sans any ostensible alteration to the building's aesthetic appeal. Furthermore, its operational autonomy, unencumbered by the exigency for any external energy input, serves to underscore its allure. Moreover, its self-sustaining nature, devoid of any feedback loop, bequeaths it with unparalleled reliability [5]. It's noteworthy to underscore that the pendulum system imparts negligible additional weight to the overall building mass [6], ensuring that the augmentation remains well below 5% in the present model. By meticulously scrutinizing the dynamic response of the steel building frame outfitted with lead-sphere pendulum dampers, this seminal study aspires to furnish invaluable insights into the efficacy of this passive damping system in mitigating vibrations induced by impact loads. The prodigious corpus of experimental data amassed via wireless accelerometers meticulously stationed at sundry locations on the frame imperatively facilitates a judicious comparison between the building's response with and sans the implementation of lead dampers. The anticipated revelations portend a palpable diminution in vibration levels, with the magnitude of reduction intricately tethered to the number of lead dampers seamlessly integrated into the building fabric.

2. Problem Statement

The investigation into the behavior of steel buildings under impact loads stands as a pivotal domain of inquiry, particularly within the realm of high-rise structures where dynamic forces can exert significant influence. This research embarks on a comprehensive exploration, aiming to delve into the efficacy of pendulum passive damper systems as a means of mitigating vibration in tall buildings subjected to pendulum impact testing. The overarching objective is to underscore the pivotal role of pendulum-damping mechanisms in ameliorating the detrimental effects of impact loads on building structures, thereby enhancing their resilience and longevity.

Central to this study is the utilization of a fixed-end three-story steel frame, meticulously designed to serve as a representative model for tall buildings. The frame's construction entails the use of tubular sections characterized by specific dimensions, including a wall thickness of 1/16 inch and yielding strength and Young's Modulus of Elasticity values of 66.1 ksi and 28000 ksi, respectively. Both columns and beams within the frame exhibit identical cross-sections, featuring square holes measuring 1/3 inch. The spatial configuration of the steel frame model encompasses a three-bay by two-bays layout, with each bay measuring 8 inches in width and 16 inches in height, mirroring typical proportions found in high-rise construction.

To simulate the impact load, a dynamic pendulum load is generated and meticulously applied to the frame. This dynamic force is induced by releasing a precisely calibrated 38-pound horizontal load from a distance of 7 inches away from the frame's periphery. As illustrated in Fig. 1, the resultant impact impinges upon the exterior middle column of the frame, triggering dynamic responses that are pivotal to the study's objectives.

At the heart of this endeavor lies the primary aim of evaluating the effectiveness of pendulum passive damping systems in attenuating vibration levels in response to impact loads. Through a meticulous examination of the dynamic response exhibited by the steel frame model equipped with these dampers, the research endeavors to quantitatively assess the degree of vibration reduction achieved. This inquiry spans a spectrum of schemes and configurations of pendulum dampers, delving into their performance across both high-frequency and low-frequency scenarios pertinent to the dynamics of tall buildings.

A comprehensive analysis and comparison of the frame's response, both with and without the integration of pendulum dampers, form the crux of this research. By meticulously scrutinizing experimental data collected via strategically positioned wireless accelerometers distributed across the frame, the study aims to unravel the nuanced effects of pendulum-damping systems on vibration mitigation.

The insights gleaned from this study are poised to contribute significantly to the advancement of effective damping strategies tailored to mitigate vibrations induced by impact loads in the context of high-rise structures. Ultimately, these findings hold the potential to enhance the safety, resilience, and overall performance of steel buildings, fortifying them against dynamic forces inherent in their operational environments.

3. Data Collection

This experimental exploration delves deeply into the intricate integration of lead dampers within the exterior columns of a steel-framed edifice, embarking on a meticulous journey to unravel their multifaceted impact on the reduction of vibration levels. Delving into the realms of structural dynamics, this study endeavors to meticulously scrutinize the behavior of these passive damping mechanisms under the duress of impact loading scenarios,

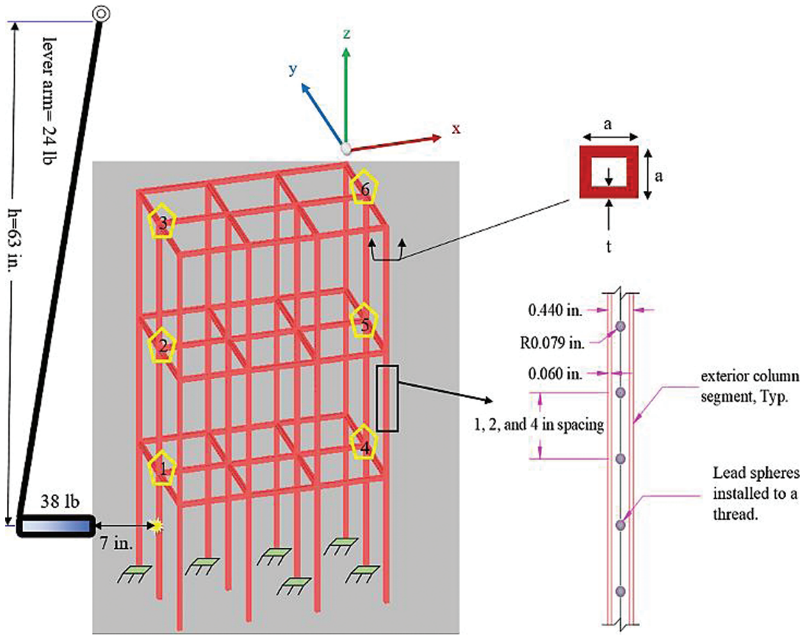

Fig. 1. A steel frame model subjected to impact load.

shedding light on their efficacy in fortifying tall buildings against dynamic forces.

The lead dampers, distinguished by their slender diameter of 0.154 inches, are strategically placed within the exterior columns with a keen eye toward achieving optimal damping efficiency. The exploration encompasses a meticulous consideration of various quantities and spacing configurations, with the spacing between these lead dampers meticulously adjusted across three distinct schemes: 4 inches (housing 12 lead dampers), 2 inches (housing 24 lead dampers), and 1 inch (housing a staggering 48 lead dampers). This deliberate variation in placement seeks to capture the nuanced effects of spacing on the overall damping performance, thereby offering valuable insights into the intricacies of passive damping mechanisms within structural systems.

Facilitating their role as dynamic energy absorbers, the lead dampers are ingeniously anchored with a top-clamping mechanism at the apex of the columns, allowing for unrestricted freedom of movement at their base. This deliberate design configuration enables the lead dampers to operate akin to pendulum dampers, deftly absorbing and dissipating energy during impact events, thus mitigating the adverse effects of transient loading on the structural integrity of the building.

To meticulously gauge the efficacy of these lead dampers in vibration reduction, a meticulously controlled pendulum impact load is orchestrated, precisely targeted toward the exterior middle column of the steel frame. The ensuing dynamic response, captured in terms of acceleration data meticulously recorded at the pinnacle of each story utilizing state-of-the-art wireless accelerometers, furnishes a treasure trove of empirical evidence for in-depth analysis.

The resultant dataset, rich in its granularity and scope, forms the cornerstone of the investigative endeavor, facilitating an exhaustive examination of the impact of lead dampers on vibration attenuation across diverse locations within the building frame. Notably, the experimental findings unveil a nuanced landscape of vibrational dynamics, with the efficacy of lead dampers exhibiting pronounced spatial variability, particularly conspicuous at the uppermost story (Node 3) and its symmetrical counterpart on the opposite side of the frame (Node 6).

Intriguingly, the study's focus extends beyond mere quantitative analysis, delving into the qualitative nuances of structural response under varying damping configurations. This holistic approach enables a comprehensive understanding of the interplay between lead damper placement, spacing, and resultant vibrational response, offering invaluable insights into the underlying mechanisms governing passive damping efficacy.

Furthermore, the meticulous calculation of the pendulum impact load, meticulously accounting for the mass of the pendulum itself and the geometric characteristics of the steel lever arm orchestrating its delivery, underscores the rigor and precision underpinning the experimental methodology. The resultant acceleration-time responses, meticulously documented and visually depicted in Fig. 2, serve as a vivid testament to the dynamic interplay between applied loading and structural response.

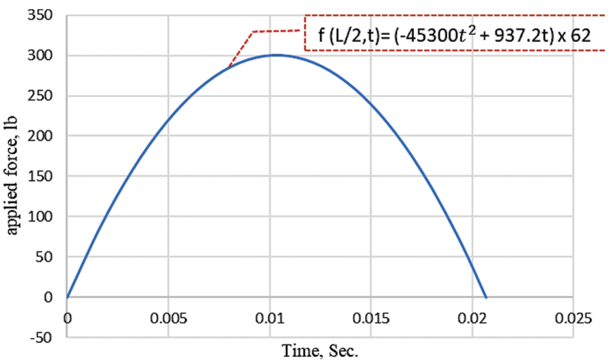

Fig. 2. Applied forcing function.

As the investigative journey unfolds, a thorough examination of the acceleration-time responses at various nodes within the steel frame forms the cornerstone of this empirical inquiry, with a singular aim to unravel the intricate tapestry of lead damper performance under dynamic loading conditions. Through a judicious juxtaposition of experimental observations and theoretical insights, this study endeavors to chart a comprehensive roadmap toward enhancing the safety, resilience, and performance of tall buildings amidst the relentless onslaught of dynamic forces. In doing so, it not only enriches the corpus of knowledge surrounding passive damping systems but also lays the foundation for future advancements in structural engineering practice, fostering a safer and more resilient built environment for generations to come.

4. Numerical Results

The intricate examination of the experimental findings gleaned from the meticulous analysis conducted on the top story's floor (Node 6) presents a rich tapestry of insights, elucidating the multifaceted dynamics of vibration attenuation within the steel-framed edifice. Through a granular exploration of the data, meticulously documented and visually encapsulated within the expansive canvas of Fig. 3, a nuanced understanding emerges, shedding light on the profound impact of lead dampers on the reduction of vibration levels.

In the absence of lead dampers within the structural framework, the steel frame manifests a pronounced acceleration of 3.09 g, encapsulating a temporal window spanning from 2.9 s to 3.2 s. However, the introduction of lead dampers strategically positioned within the exterior columns engenders a discernible reduction in acceleration, marking a transformative shift in the vibrational dynamics. The simultaneous installation of 12, 24, or 48 lead dampers within the structural framework yields acceleration readings of 2.20 g, 1.95 g, and 1.72 g, respectively, unveiling a tangible vibration reduction of 29%, 37%, and 44%, meticulously calculated through the meticulous assessment of the percentage decrease in acceleration relative to the baseline recorded value.

Yet, the narrative of vibrational mitigation unravels further as the temporal evolution of the impact load's effects is scrutinized with a keen eye toward granularity. The intricate interplay between lead damper deployment and vibrational dynamics is artfully depicted within the comprehensive landscape of Fig. 4, offering a panoramic vista into the temporal dynamics of vibration attenuation. Within the initial temporal window stretching from 0 s to 0.4 s, the presence of lead dampers within the structural matrix exerts a nominal influence on the reduction of vibration, as discerned through meticulous analysis. This intriguing revelation underscores the subtle intricacies of the lead damper's response during the embryonic stages of dynamic loading, suggesting a transient delay in the onset of vibrational mitigation.

However, a notable transition in the vibrational landscape is unveiled beyond the temporal threshold of seconds, where the lead dampers seamlessly transition into action, embarking on a journey of diligent motion damping and steadfast vibration attenuation. As time unfolds, the lead dampers progressively augment their damping efficacy, ushering in a realm of sustained vibrational mitigation that permeates the structural fabric. Particularly striking is the scenario where the structural framework is endowed with 48 lead dampers within the exterior columns, where a palpable reduction in vibration

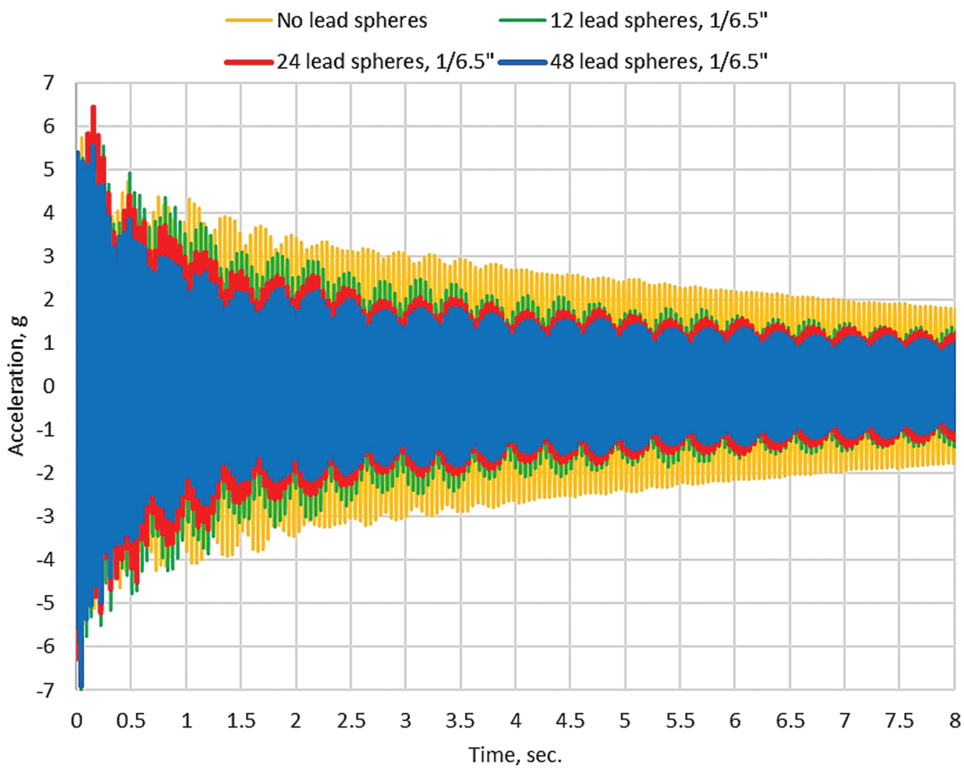

Fig. 3. Acceleration vs. time at node 6.

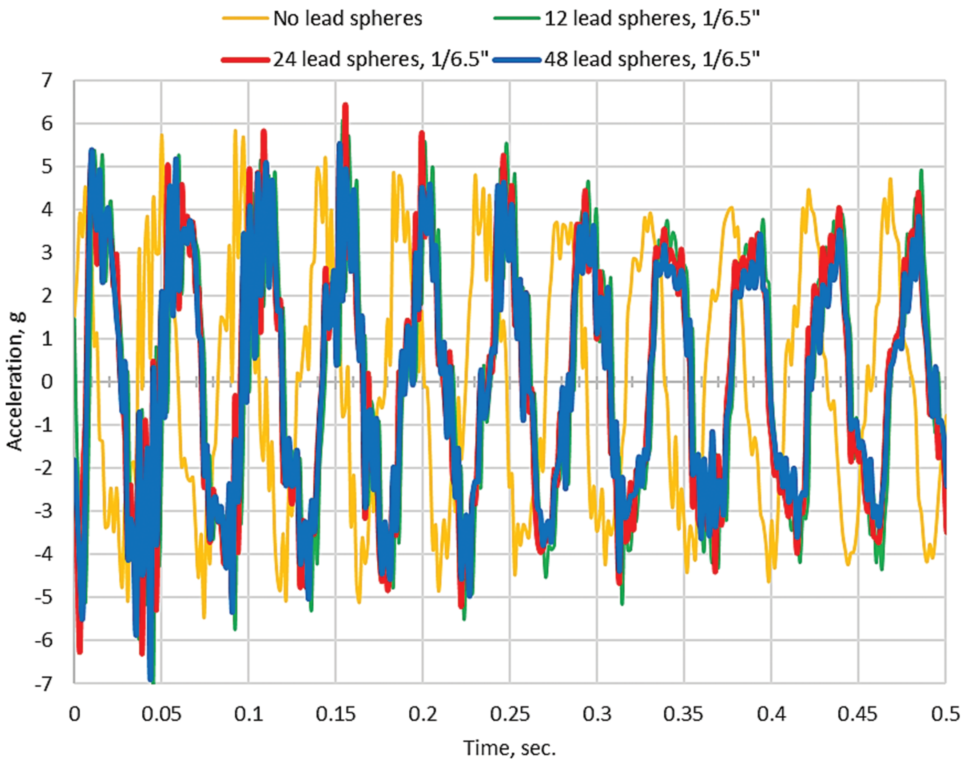

Fig. 4. Acceleration vs. time at node 6 at the instant response.

is observed immediately after the 0.4-second mark, underscoring the lead dampers' agility in swiftly mitigating the deleterious effects of transient dynamic loading conditions.

Transitioning to the examination of the second floor's vibrational response, specifically at Node 5, a discernible impact of the lead dampers on vibration reduction comes to the fore after the 0.4-second mark shown in Fig. 5. As depicted within the expansive canvas of Fig. 6, within the temporal expanse stretching from 3.00 s to 3.50 s, the acceleration undergoes a notable decrease, heralding a transformative shift in the vibrational landscape. The data reveals a pronounced acceleration reduction from 2.50 g (in the absence of lead dampers) to 1.90 g (with 12 lead dampers), 1.63 g (with 24 lead dampers), and 1.43 g (with 48 lead dampers), respectively. These observations offer compelling evidence of the lead dampers' efficacy in attenuating vibrations induced by impact loads, underscoring their pivotal role in fortifying the structural integrity of the edifice amidst transient dynamic loading conditions.

However, the vibrational dynamics observed on the first floor, particularly at Node 4, unveil a comparatively muted response to the lead damper damping system. As portrayed within the expansive landscape of Fig. 7, the data reveals a minimal impact on vibration reduction, with only the presence of 24 and 48 lead dampers yielding a discernible effect. This nuanced observation underscores the varied effectiveness of the lead damper damping system across different floors of the building structure, offering invaluable insights into the complex interplay between structural dynamics and passive damping mechanisms.

In summation, the painstaking analysis of the experimental findings meticulously elucidates the significant role played by the installation of lead dampers within the exterior columns of the steel building frame in effectively

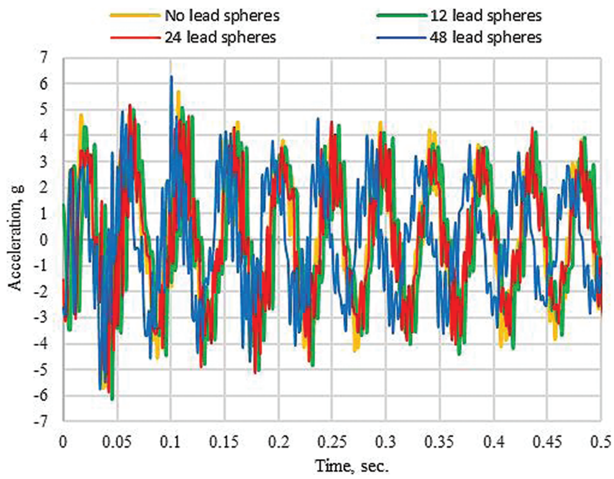

Fig. 5. Acceleration vs. time at node 5 at the instant response.

reducing vibration levels. Particularly noteworthy is the pronounced impact observed at the top story (Node 6), where vibration reduction percentages range from 29% to 44%, contingent upon the number of lead dampers deployed. Similarly, the second floor (Node 5) showcases a commendable level of vibration reduction, spanning from 24% to 43%. However, the first floor (Node 4) exhibits minimal vibration reduction, with only 24 and 48 lead dampers demonstrating a discernible effect. These empirical findings underscore the varied effectiveness of the lead damper damping system across different floors of the building structure, providing invaluable insights into the potential of passive damping mechanisms in mitigating vibrations induced by impact loads and paving the way for further advancements in structural engineering practice.

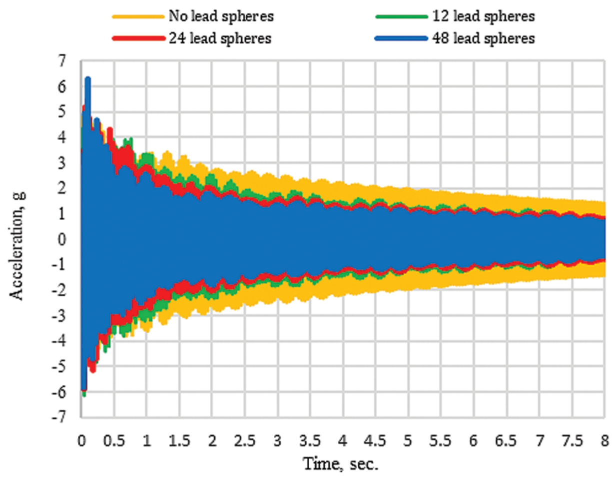

Fig. 6. Acceleration vs. time at node 5.

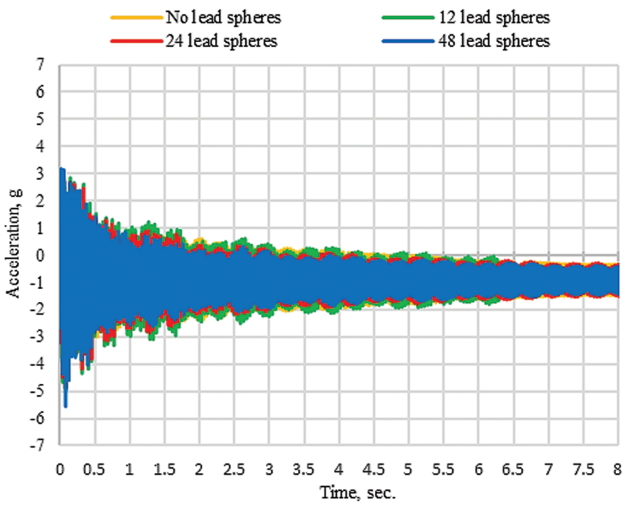

Fig. 7. Acceleration vs. time at node 4.

5. Conclusions

The experimental investigation conducted on the behavior of a steel building frame under impact load, with the installation of lead damper pendulum dampers in the exterior columns, has provided valuable insights into the effectiveness of this passive damping system in reducing vibrations:

1. The results obtained from the top story's floor (Node 6) revealed that the presence of lead dampers significantly decreased the acceleration of the frame by up to 44%.
2. The response of the second floor at Node 5 showed a lesser effect of the lead dampers on decreasing vibration compared to the top story. Acceleration was reduced by up to 43%.
3. On the first floor, specifically at Node 4, the lead damper damping system did not exhibit a considerable impact on decreasing vibration, lead dampers showed a negligible percentage decrease in vibration. This indicates that the lead damper damping system is less effective on the first floor compared to the upper floors of the building.
4. During the initial time period from 0 s to 0.4 s, after the impact load struck the building, the lead dampers did not exhibit a significant impact on reducing vibrations. It was observed that the lead dampers only started actively decaying motion in the building after the 0.4-second mark.

In conclusion, this experimental study highlights the effectiveness of lead damper pendulum dampers in reducing vibrations in a steel building frame subjected to impact loads. The findings demonstrate that the installation of lead dampers in the exterior columns significantly decreases vibration levels, with the greatest impact observed at the top story. The study also emphasizes the time-dependent behavior of the lead damper dampers, with the damping system initiating its effects after 0.4 s. These results contribute to the understanding of passive damping systems and their potential application in enhancing the vibration resistance of steel buildings under dynamic loading conditions.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

References

[1] Johnson JG, Pantelides CP, Reaveley LD. Nonlinear rooftop tuned mass damper frame for the seismic retrofit of buildings. *Earthquake Eng Struct Dyn*. 2015;44(2):299–316.
[2] Latifi R, Razani R. Vibration mitigation of shazand railway bridge induced by train using tuned mass damper (TMD). *Period Polytech. Eng Mech Eng*. 2015;59(4):189.
[3] Datta TK. *Seismic Analysis of Structures*. John Wiley & Sons; 2010.
[4] Ryan KL, Chopra AK. Estimation of seismic demands on isolators based on nonlinear analysis. *J Struc Eng*. 2004;130(3):392–402.
[5] Chopra AK. *Dynamics of Structures: Theory and Applications to Earthquake Engineering*. 5th ed. 2017.
[6] Hussein HA. Effectiveness of suspended lead dampers in steel buildings under localized lateral impact and vertical pulsating load. PhD Dissertation, Civil & Environmental Engineering, Old Dominion University; 2022. doi: 10.25777/mpy5-wt97.