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# Anti-seismic Technology in Suspension Bridge Designs: A Review

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## ABSTRACT

Suspension bridges are vital transportation infrastructures that support high traffic levels. It is of great importance for suspension bridges to remain operational following hazardous earthquake motions. Seismic devices preserve crucial bridge elements and aid in the control of ground motion response through energy dissipation and damping. This literature review introduces and evaluates the performance of widely-applied anti-seismic technologies such as tuned mass dampers, fluid viscous dampers, and seismic isolators in suspension bridge designs. The paper condenses and compares the results of analytical literature surrounding the effectiveness of seismic devices. Conclusions from current research indicate that the implementation of fluid viscous dampers is optimal for deck displacement damping in suspension bridges. Less effectiveness is found for seismic isolators and almost negligible success is found for tuned mass dampers under high seismic motions. The generalization of the results and the potential performance discrepancies due to spatial variability are noted.

## Introduction

Suspension bridges have gained popularity in the field of civil engineering due to their elegant aesthetics, effective structure, and their ability to span impressive distances. As modern bridge design is untethered by strict economic restraints, record spans and innovative forms continue to emerge (Tao & Treyger, 2014). For example, the George Washington Bridge of 1931 with a main span of 1067 m (3501 ft) nearly doubled the previous record held by the Ambassador Bridge (Buonopane & Billington, 1993). Now, the world record for the longest suspension bridge is held by the Akashi Kaikyo Bridge with a whopping span of 1991 m (6532 ft) (Kitagawa, 2004).

In suspension bridges, the deck is supported by vertical suspenders on overhead main cables. The cables, in tension, transfer loads to the two towers which would endure vertical compression (Ren et al., 2004). The girders support live loads such as passing vehicles and pedestrians. Most towers, girders, and cables of long-span suspension bridges are constructed out of steel, which is strong in both tension and compression and contributes to the bridge's flexibility. The material gives bridges a long fundamental vibration period of around 2 - 8 seconds, resulting in a low force response level and a large displacement response (Tao & Treyger, 2014). The stiffening girder can also longitudinally and transversely displace like a pendulum, alleviating external forces that the bridge might encounter (Tao & Treyger, 2014). Over the years as engineers ambitiously opted for imaginative and sleeker designs, many structures such as the Brooklyn Bridge and the Golden Gate Bridge became symbolic landmarks of civil engineering while some led to catastrophe.

Suspension bridges, being vital superstructures that link areas with large transportation demands, must not only reliably withstand daily traffic and harsh climates but also stay functional during natural disasters to enable evacuation and emergency response. As the need for bridges in active seismic zones increases, it has become more crucial to ensure the seismic integrity of a structure. Some suspension bridges are located in fault lines and areas of challenging geotechnical conditions (Nader et al., 2000). To combat such dynamic loads along with various difficulties, anti-seismic technology has been implemented on many modern suspension bridges. Seismic devices are cost-effective energy dampers that reduce potential damage to superstructures in the event of an earthquake.

This paper aims to present a comprehensive literature review regarding the development and application of seismic devices in suspension bridges of diverse contexts. Firstly, in the section 'Early suspension bridges and their performance', suspension bridges without earthquake-resistant features will be analyzed, noting vulnerable components of the structure. Secondly, in 'Seismic devices', commonly used anti-seismic systems in relatively contemporary bridges, including tuned mass dampers, fluid viscous dampers, and seismic isolators will be introduced. Thirdly, in the 'Analysis and discussion' section, by gathering pieces of relevant literature that assess the effectiveness of each method, energy dissipation performance will be discussed and compared.

## Early suspension bridges and their performance

To fulfill the fundamental function of a bridge, engineers design suspension bridges capable of withstanding forces that exceed the maximum live load (vehicles, trains, pedestrians, etc.) and dead load (weight of the bridge itself). This ensures that the bridge will not collapse under vertical overloading. Despite the intrinsic rigidity of suspension bridges against vertical loads, lateral loads such as wind loads and seismic loads were given comparatively minor attention during the design of early bridges. For instance, the Menai Bridge, widely considered as one of the earliest suspension bridges, faced challenges with wind-induced vibrations nearing its opening to the public. Billington and Deodatis (1995) report that during storms in 1825 and 1826, the deck of the Menai Bridge went through vigorous undulating motions, implying longitudinal and torsional movement. The truss deck was stiffened and elements of the bridge were modified following the incident (Billington & Deodatis, 1995). Overlooking lateral motions continued to pose problems even decades later. At the beginning of the 1900s, a new theory for long-span suspension bridges known as Deflection Theory replaced the previously-used Elastic Theory. While Elastic Theory mainly relied on the stiffening truss deck for supporting loads, Deflection Theory, by including the cable stiffness as a factor, allowed the decks to be thinner (Buonopane & Billington, 1993). Suspension bridges built with Elastic Theory, such as the Williamsburg Bridge, had span length-to-truss depth ratios of approximately 40:1 and appeared bulkily oversized. Deflection Theory, on the other hand, paved the way for more slender, elegant forms as seen in the Manhattan Bridge (span-to-depth ratio of 60:1) and the Golden Gate Bridge (168:1) (Buonopane & Billington, 1993). However, the Tacoma Narrows Bridge of 1940 with a span-to-depth ratio of 350:1 proved to be excessively unstable (Petroski, 2009). On November 7th, 1940, the Tacoma Narrows Bridge experienced violent torsional and vertical oscillations due to the wind blowing at 80 km/h, eventually leading to a dramatic collapse (Arioli & Gazzola, 2013). This event publicized the importance of considering aerodynamic loads and other lateral loads in bridge construction.

While most cable-supported bridges today are fitted with little or no anti-seismic features, with no reported cases of collapses caused directly by earthquakes, the performance of suspension bridges is rather satisfactory (Tao & Treyger, 2014). Analysis of the Chacao Channel Bridge in Chile, for example, found that the installation of seismic devices on the deck was not necessary to minimize earthquake impact (Laursen & Fuglsang, 2004). On the other hand, in the mid-1900s, two relatively short suspension bridges in Japan (the Arakawa Bridge and the Gosho Bridge) sustained extensive damage such as cracked towers and buckled girders (Castellini). Furthermore, many engineers believe that current structures are yet to be tested by earthquakes of great magnitudes (Tao & Treyger, 2014). Nonetheless, while suspension bridges have had success due to their innate design, it is essential to investigate potential seismic vulnerabilities to retrofit existing suspension bridges and assist in the new design of robust forms.

Stiffening girders are one of the most vulnerable parts of suspension bridges according to seismic analysis (Tao & Treyger, 2014). Stiffening girder members, taking the form of steel trusses in old models and steel box girders in newer models, support live loads and wind loads. Under seismic conditions that exceed the intended wind tolerance level, the lateral braces are particularly susceptible to damage. The top half of lateral braces in the Golden

Gate Bridge were replaced with new ductile members after the Loma Prieta earthquake of 1989 (Ingham et al., 1995).

Furthermore, expansion joints and wind connections in almost all suspension bridges in the United States are likely to be damaged even in an operational level earthquake event (Tao & Treyger, 2014). In the case of the Higashi-Kobe Bridge (cable-stayed), the wind shoes were severely damaged during the Hyogo-ken Nanbu earthquake in 1995 (Naganuma et al., 2000).

The bridge towers mainly carry gravity loads, live loads, and wind loads. As seismic load is considered to be only 7.5% - 10% of gravity load, the design of towers of long-span suspension bridges is usually governed by wind load (Tao & Treyger, 2014). In a maximum considered earthquake event, structures such as the Golden Gate Bridge are susceptible to tower shaft buckling due to excessive compressive forces at the base (Ingham et al., 1995). Suspension systems such as the main cable, suspenders, cable bands, and saddles are least likely to fail as they are commonly built with a safety factor of 2.2 (Tao & Treyger, 2014). While there is limited research, slacking of suspenders and slipping of cable saddles do not seem to pose a detrimental effect to the seismic integrity of suspension bridges (Tao & Treyger, 2014).

To minimize the inflicted damage on most of the mentioned vulnerable components and ensure the safety of bridges, earthquake-induced deck and tower motion must be dampened through the installation of seismic devices.

## Seismic devices

Seismic devices are innovative structural components that protect bridges from earthquake-induced motion by assimilating or dissipating energy. These elements alter the dynamic characteristics of suspension bridges such as the natural period or damping to secure the bridge during a hazardous event (Agrawal & Amjadian, 2016). Commonly used devices, namely seismic dampers and isolators, are designed to localize input external forces in these devices, diverting potential damage away from key structural members. Unlike steel bracings and additional support members, seismic devices can efficiently diminish impact from lateral forces without compromising aesthetic form. This section will introduce and provide example applications of tuned mass dampers, fluid viscous dampers, and seismic isolators. The basic information presented will establish the foundations of discussion in the ‘Analysis and discussion’ section.

### Tuned mass damper

A tuned mass damper (TMD) is a device that is attached to a structure to minimize vibrations. In this device, a relatively small mass is mounted on damped springs which are tuned to oscillate out of phase to the structure’s natural frequency, reducing the primary structure’s maximum amplitude and dissipating the vibration energy (Murudi & Mane, 2004). A well-known application of TMD in a skyscraper is the world’s largest spherical TMD of Taipei 101 which helps resist wind-induced sway of the 508m-tall superstructure (Poon et al., 2004). TMDs have been found to be effective against harmonic and wind excitations and are successfully applied in buildings, towers, and chimneys worldwide for wind response regulation (Murudi & Mane, 2004). The same study by Murudi and Mane (2004) concluded that TMDs are most ideal for structures with light damping and are particularly effective in long-duration earthquake ground motion. However, the performance of TMDs is highly dependent on their parameters (mass, frequency, damping ratio, etc.) and can be suboptimal when mistuned (Chey et al., 2010).

TMDs are implemented in various modern suspension bridges to offer stability. When London’s Millennium Bridge, a shallow suspension footbridge over the River Thames, faced excessive pedestrian-induced vibrations, a biaxial TMD was placed in the center of the deck along with two viscous dampers (Pavic et al., 2002). The addition is estimated to increase the damping ratio from below 1% to 4% (Pavic et al., 2002).

In the case of the record-setting Akashi Kaikyo Bridge (as seen by Figure 1), multiple TMDs are installed in each tower, accommodating the high-rise, flexible steel structure that is unavoidably vulnerable to wind vortex (Kitagawa, 2004). While the devices have a sufficient level of robustness for gust response, the same suppression effectiveness was not observed for seismic response (Casciati & Giuliano, 2009).


**Figure 1.** TMD installation design for the Akashi Kaikyo Suspension Bridge (Kitagawa, 2004).

## Fluid viscous damper

A fluid viscous damper (FVD) is a device that dissipates energy through the flow of fluid (Figure 2). As the steel piston moves, the fluid transfers from one chamber to another through the orifices, resulting in energy dissipation due to head loss (Agrawal & Amjadian, 2016). Originated with aerospace and military uses, the FVD later started to prevent destructive shocks and vibrations for structural purposes (Lee & Taylor, 2001). Research from Huang et al. (2019) found that the addition of viscous dampers at key areas of suspension bridges has been found to effectively reduce the relative displacement of the main position of the bridge under earthquakes. The same paper noted that FVD parameters such as the damping coefficient and the velocity index have a critical role in the effectiveness of the device (Huang et al., 2019).

The Vincent Thomas Bridge that crosses the Los Angeles Harbor is located near the Palos Verdes fault of southern California. Impacted by numerous earthquakes in the past and being prone to future seismic events, the 457 m (1500 ft) suspension bridge was retrofitted with viscous dampers between the tower and the deck (Nazmy et al.). Analysis of the seismic retrofit scheme concluded that the FVDs were very efficient in mitigating seismic demand on the truss members (Nazmy et al.).

Following the cataclysmic Loma Prieta earthquake and the damage of the East Span of the San Francisco-Oakland Bay Bridge, the old East Span double-decker truss was replaced with a state-of-the-art self-anchored suspension bridge and the West Span suspension bridge was retrofitted for seismic safety (Middlebrook, 2014). The west cross improvement included new bracings, steel plates, and 96 FVDs strategically placed at vital points (Middlebrook, 2014). The addition minimized deck displacement and eliminated potential impact between the span and the towers (Ingham et al., 1997).

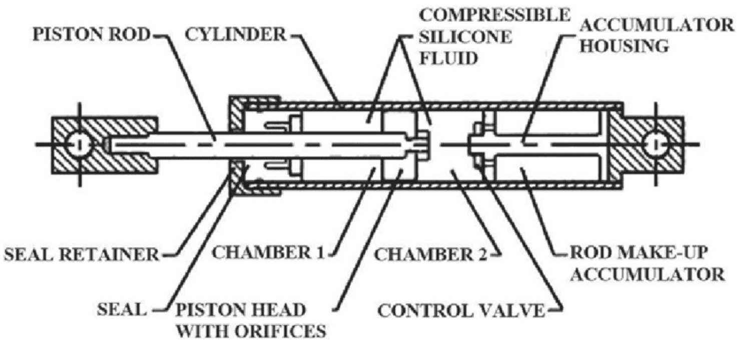


**Figure 2.** Blueprint of key components of a FVD manufactured by Taylor Devices (Agrawal & Amjadian, 2016).

## Seismic isolator

Seismic isolation systems (Figure 3) decouple the movement of the superstructure from the substructure, elongating the natural period of the body past the period of the ground motion (Agrawal & Amjadian, 2016). Base isolators are often installed between the deck and the abutments of suspension bridges. There are two main types of seismic isolators: elastomeric and sliding isolators. Elastomeric-based isolators (which include lead-rubber bearings, friction pendulum bearings, etc.) are multi-layered rubber sheets fused with steel plates designed to withstand vertical loads while allowing horizontal deformations (Agrawal & Amjadian, 2016). Sliding-based isolators allow slippage between the support and the sliding surface, hence providing damping through friction (Agrawal & Amjadian, 2016).

The North and South Approach Viaducts of the Golden Gate Bridge are currently equipped with elastomeric lead-core rubber bearings after a thorough seismic retrofit procedure ("Seismic Retrofit," n.d.). The isolator is predicted to decrease damage on the bridge in the event of a maximum considered earthquake ("Seismic Retrofit," n.d.). The Osmangazi Suspension Bridge in Turkey has a main span of 1550 m (5085 ft) and crosses the North Anatolian fault, an area of high seismicity. Both types of seismic isolators are used in the bridge; sliding spherical bearings carry vertical loads and elastomeric bearings provide lateral restraint (Erdik, 2017). Furthermore, multiple lead-rubber bearing units were employed for the North and South Approach Viaducts (Erdik, 2017).

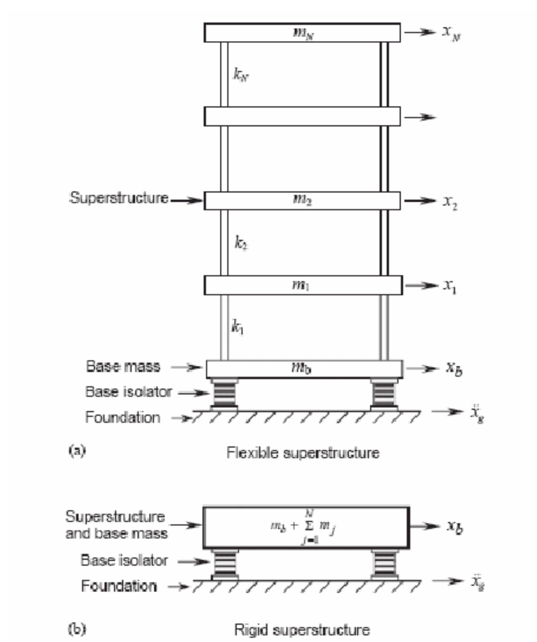


**Figure 3.** Seismic isolator installed under the superstructure (Turer).

## Analysis and discussion

This paper has introduced the leading seismic devices in structural engineering and some of their applications. This section aims to assess and compare mentioned earthquake protection methods, referencing results from relevant research. Table 1 compiles current literature surrounding the performance of TMDs, FVDs, and various seismic isolation systems in cable-supported bridge models. The gathered research papers assess the effectiveness of each structural technique through nonlinear time-history analyses, numerical analyses, or experimental modeling. Indicated parameters noted in the literature (input ground motion type, damping coefficient, damping force, tuning ratio, etc.) are listed in the 'Methods and Parameters' column. Significant results, quantitative or qualitative, summarize the papers' conclusions on the efficacy of respective devices subjected to dynamic loads.

**Table 1**. *An overview of significant results from existing literature on seismic devices. Seismic analyses, computer-assisted, numerical, and experimental, evaluate the degree of success of TMDs, FVDs, and seismic isolators in cable-supported bridge models subjected to external motions.*

| Author(s) | Literature Title | Structure | Device(s) Analyzed | Methods and Parameters | Significant Results |
|---|---|---|---|---|---|
| Casciati<br>Guiliano | Performance of Multi-TMD in the Towers of Suspension Bridges | Suspension bridge<br><br>Akashi Kaikyo Bridge | TMD | Time-history analysis<br><br>TMD tuning central ratio: 0.994 | TMD showed negligible effectiveness of suppression, especially for high impulse ground motions (2-3% reduction in base moment) |
| Mokrani<br>Tian<br>Alaluf<br>Meng | Passive damping of suspension bridges using multi-degree of freedom tuned mass dampers | Suspension bridge<br><br>Simplified mock-up | TMD | Numerical and experimental lab analysis<br><br>TMD mass: 0.7% of total structure | Bending and torsional modes were damped with TMDs |
| Meng<br>Wan<br>Xia<br>Ma<br>Tu | A Multi-Degree of Freedom Tuned Mass Damper Design for Vibration Mitigation of a Suspension Bridge | Suspension bridge<br><br>Simplified mock-up | TMD | Numerical and experimental lab analysis<br><br>TMD frequency ratios: 0.942 & 0.959<br>TMD damping ratios: 13.5% & 17.6% | Complex vibration modes were very effectively suppressed with reductions in amplitude |
| Vader<br>McDaniel | Influence of Dampers on Seismic Response of Cable-Supported Bridge Towers | Self-anchored suspension bridge<br><br>San Francisco-Oakland Bay Bridge | FVD (with friction dampers and shear links) | Nonlinear analysis<br><br>Subjected to safety evaluation earthquake (SEE) event of San Andreas and Hayward Faults<br><br>FVD maximum | Tower base shear force demands:<br>Transverse: 31 MN<br>Longitudinal: 28-29 MN<br><br>FVDs had lowest base shear demands and yielded best results for |

| | | | | | |
|---|---|---|---|---|---|
| | | | | damping force: 9000 kN<br>FVD damping coefficient: 100 MNs/m | transverse motion model |
| Ingham<br>Rodriguez<br>Nader | Nonlinear analysis of the Vincent Thomas Bridge for Seismic Retrofit | Suspension bridge<br><br>Vincent Thomas Bridge | FVD | Nonlinear analysis<br><br>Subjected to maximum considered earthquake (MCE) event of Palos Verde fault<br><br>Damping ratio using Rayleigh damping: 1.5-2 % | Linear (exponent of one) dampers were optimal<br><br>Damper absorbed energy during the period of largest ground motion and limited displacement |
| Lu<br>Wang<br>Qiu | Fragility-Based Improvement of System Seismic Performance for Long-Span Suspension Bridges | Suspension bridge<br><br>Taoyuan Bridge | FVD<br><br>Seismic isolator (elastomeric) | Nonlinear analysis<br><br>Subjected to 100 recorded ground motions<br><br>FVD damping coefficients: 2500-5000 kN (m/s)<br>FVD velocity exponents: 0.3-0.5 | FVD yielded best results for displacement and force attributes<br><br>Seismic isolators reduced demands on columns and can reasonably achieve seismic resistance |
| Raheem<br>Hayashikawa<br>Dorka | Earthquake ground motion spatial variation effects on seismic response control of Cable-Stayed Bridges | Cable-stayed bridges<br><br>Benchmark bridge model | FVD (with friction dampers)<br><br>Seismic isolator (elastomeric) | Nonlinear analysis<br><br>Subjected to 3 historic ground motions<br><br>Bearing initial elastic shear stiffness/post-yield shear stiffness: 0.10 | FVDs, compared to base isolators, were more effective in reducing maximum displacement and force responses.<br><br>Seismic forces are significantly reduced with a reasonable increase in deck displacement. |
| Javanmardi<br>Ghaedi | Seismic response characteristics of a base-isolated cable-stayed bridge under moderate and strong ground motions | Cable-stayed bridges<br><br>Shipshaw Bridge | Seismic isolator (elastomeric) | Nonlinear analysis<br><br>Subjected to 4 historic ground motions | Change of deck displacement in isolated system:<br>Transverse: 178%<br>Longitudinal: 114%<br><br>Deck acceleration reduction in isolated system:<br>Transverse: 35%<br>Longitudinal: 62% |

TMDs do have sufficient ability in dissipating complex vibrational modes (wind loads in towers, human-induced vibrations, etc.) and damping torsional movements in decks (Casciati & Giuliano, 2009; Mokrani et al., 2017; Meng et al., 2020). Despite this, they are not particularly practical for resisting large earthquake motions. The multi-TMD model analysis revealed that the devices provided insignificant amounts (2 - 3% of reduction of base moment) of damping against high impulse ground motions (Casciati & Giuliano, 2009). While there is little research done regarding the application of TMDs in suspension bridges mainly for seismic response control, the current data suggests that TMDs are inadequate for seismic motion suppression.

FVDs, on the other hand, are widely used in numerous suspension bridges for retrofitting and for new designs. Their effectiveness is supported by the literature presented in Table 1. Out of three different anti-seismic methods (FVDs, friction dampers, shear link method), the FVD had the lowest base shear demands and had the most beneficial effects on the bridge model in the transverse direction (Vader & McDaniel, 2007). Analyses from both the Vincent Thomas Bridge and the Taoyuan Bridge commonly uphold the result that FVDs can limit earthquake-induced displacements and damp forces at a satisfactory level (Ingham et al., 1997; Lu et al., 2020).

Seismic isolators, according to analyses, can also reduce the stress put on bridges during earthquakes. The elastomeric isolator system of the Taoyuan Bridge was found to be able to lessen the demand on the bridge column (Lu et al., 2020). Similarly, the Shipshaw Cable-stayed Bridge (although not a suspension bridge,) had substantial decreases in deck acceleration, base moment, and shear force with seismic isolators compared to a model without (Javanmardi et al., 2017). Despite the increase in deck displacement with isolators, the displacement does not exceed the design range (Javanmardi et al., 2017).

Reviewing current literature, FVDs are a favorable option in comparison with TMD and seismic isolation systems. Analysis from Raheem et al. (2011) found that FVDs and similar friction damping systems are significantly more effective at dissipating seismic forces relative to passive control lead-rubber bearing isolators (Raheem et al., 2011). FVDs considerably decrease deck displacement (unlike seismic bearings which slightly increase displacement), diminishing the potential for tower damage and cable overstress (Ingham et al.,1997; Raheem et al., 2011). FVDs' seismic control efficacy, coupled with their ability to be incorporated in new designs as well as retrofit measures, make FVDs a popular, reliable option in bridge engineering.

Most research, including papers from Casciati and Guiliano (2009), Vader and McDaniel (2007), Ingham et al. (1997), Lu et al. (2020), Raheem et al. (2011), and Javanmardi and Ghaedi (2017), examined performance through nonlinear modeling analyses of simplified bridge forms or mock structures derived from existing bridges. Other research from Mokrani et al. (2017) and Meng et al. (2020) performed experimental labs to confirm findings from numerical analyses. Each research has limitations and perceptible differences from other studies from the same field. All types of modeling methodologies inevitably deviate from precise real-life bridges as myriad factors (structure dimensions, structure material, soil type, etc.) contribute to the response of such complex superstructures. However, simplified models still can predict the general effectiveness of control systems applied in a cable-supported bridge form to a certain extent. Secondly, the criteria for success of a seismic device may vary between authors and contextual standards. Evaluations, especially qualitative statements, might have discrepancies depending on external circumstances such as expectations, regional or national structural codes, etc. Models are subjected to distinct ground motions and the number of sampled results is drastically different. Ingham et al. (1997) and Vader and McDaniel (2007) simulated recorded earthquake events from the respective tectonic faults in which the subject bridges were located. Javanmardi and Ghaedi (2017) tested their models against 4 recorded historic ground motions while Lu et al. (2020) ran up to 100 earthquake samples. Additionally, the scope of each literature limits the content analyzed. The investigations of TMDs from Mokrani et al. (2017) and Meng et al. (2020) do not explore the dampers' performance against seismic motions, but rather against wind and human-induced vibrations. Casciati and Guiliano (2009) only briefly discuss TMDs' seismic energy reduction levels.

Although this literature review has generalized the effectiveness of TMDs, FVDs, and seismic isolators to compare each device, separate studies should be constructed upon designing of a specific bridge. The performance of seismic devices is extremely dependent on the context of their application; therefore, spatial variability is a critical factor that must be taken into consideration when designing bridge models with anti-seismic technology. The advantages of FVDs found in this study may be refuted in other analysis models.

Potential areas of future research include the thorough examination of TMD systems in suspension bridges under seismic settings. While the efficacy of TMDs against complex vibrational modes is proven through intensive research, very few amply investigate their performance in suspension bridges against earthquake ground motions. Though one piece of existing evidence from Casciati and Giuliano (2009) dismisses TMDs as a practical anti-seismic option, it is beneficial to verify and corroborate the result with supporting studies. An additional area of further exploration is the optimization of earthquake control devices. Diverse types of fluids in FVDs and their performance can be tested. Extensive study can be done on magnetorheological dampers which contain fluid activated by electromagnets. Recent research trajectories in structural and earthquake engineering also probe into active and semi-active seismic devices. Emerging models of active and semi-active TMDs can be simulated in suspension bridge application.

## Conclusion

In this study, common seismic devices used in structural engineering have been reviewed in the context of suspension bridges. The dynamic characteristics of suspension bridges are described. The function of anti-seismic technology and their real-world applications have been presented. The collected literature examined the performance of tuned mass dampers, fluid viscous dampers, and seismic isolators using various model analysis methods.

Current research suggests that tuned mass dampers, while viable for wind response control, are only marginally effective for seismic motion suppression. According to literature, the installation of seismic isolators and, more preferably, fluid viscous dampers are practical due to their considerable capability of reducing structural motions or stress that may lead to damage. Multiple analyses support the notion that fluid viscous dampers can significantly reduce deck displacement in longitudinal and transverse directions during earthquake ground motions.

It is essential to note that spatial variability can drastically influence the seismic performance of suspension bridges. Seismic devices must be adjusted according to their environmental context and installed after meticulous planning.

Future research can be done on the implementation of TMD systems in suspension bridges for earthquake load suppression and exploration of material optimization of seismic devices.

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