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Review on Investigating the Impact of Steel Plate Shear Walls on Building Performance

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ABSTRACT

Steel Plate Shear Walls (SPSWs) are emerging as a highly effective lateral load-resisting system, addressing the growing need for resilient structural solutions in earthquake-prone regions. SPSWs consist of thin steel plates connected to a boundary frame, providing an efficient means of dissipating seismic energy while maintaining structural integrity. Unlike traditional concrete shear walls or braced frames, SPSWs offer enhanced ductility, reducing damage during cyclic loading and ensuring better post-event operability. The adaptability of SPSWs makes them suitable for both low- and high-rise buildings, offering improved safety, reduced repair costs, and faster recovery after seismic events. Additionally, the use of high-strength steel and composite materials has expanded the application of SPSWs, improving performance while reducing construction costs and material weight. SPSWs are also a promising solution for retrofitting existing buildings, improving seismic resilience without extensive reconstruction. Despite their advantages, challenges related to connection design and fabrication precision remain, requiring innovative solutions to optimize their effectiveness. The development of self-centering SPSWs and advanced materials further enhances their potential, making them a key component of modern structural design.

Keywords : Steel Plate Shear Walls (SPSWs), Lateral Load Resistance, Seismic Energy Dissipation, Ductility and Structural Integrity, Retrofitting and Construction Efficiency

1. Introduction

The need for resilient structural systems to manage lateral loads in buildings has become increasingly critical as the frequency and intensity of natural hazards such as earthquakes continue to pose significant threats to modern infrastructure (Astaneh-Asl, 2001). Earthquake-prone areas, in particular, **demand innovative solutions that not only ensure structural integrity and occupant safety but also reduce economic losses and downtime associated with seismic events.** Traditionally, reinforced concrete shear walls and braced frames have been widely used to resist lateral forces due to their proven effectiveness in enhancing building stability (Driver et al., 1998). However, as building designs have evolved to accommodate greater heights, complex geometries, and tighter construction timelines, **there is a growing demand for more efficient, ductile, and adaptable structural solutions.**

Steel Plate Shear Walls (SPSWs) have emerged as a promising alternative and complement to conventional lateral force-resisting systems (Sabelli &

Berman, 2001). The core of SPSW technology involves thin steel plates that are connected to a boundary frame system, creating an integrated framework capable of resisting significant lateral forces induced by seismic activity, wind, and other dynamic events (Thorburn et al., 1983). This structural innovation enables SPSWs to act as efficient energy dissipation devices due to their ability to undergo controlled buckling, allowing for substantial energy absorption during seismic events. Unlike traditional reinforced concrete shear walls or braced frames, SPSWs offer enhanced ductility, which is critical for maintaining structural integrity under cyclic and extreme loading conditions, ultimately reducing structural damage and providing superior post-event operability (Berman & Bruneau, 2003).

The ductility of SPSWs is of particular interest due to their ability to undergo large deformations without significant loss of strength, effectively dissipating seismic energy and reducing the impact on connected structural elements. This characteristic, combined with their resilience and adaptability, makes them a suitable choice for both low- and high-rise buildings. Furthermore, SPSWs contribute to reduced repair costs and faster recovery following seismic events, enhancing overall building resilience and post-disaster functionality.

Beyond their mechanical advantages, SPSWs provide several economic and construction-related benefits. The use of thin steel plates results in reduced weight compared to traditional concrete-based systems, which not only lowers the overall structural load on the foundation but also decreases transportation and handling costs. Faster construction is another notable advantage; SPSWs can be prefabricated, minimizing on-site labor and accelerating construction schedules. This feature is particularly advantageous in projects with tight timelines or those located in densely populated urban areas where minimizing disruption is a priority (Vian & Bruneau, 2005).

In addition to these advantages, SPSWs offer flexibility in retrofitting applications. Aging or seismically deficient buildings can be upgraded with SPSWs, improving their performance and safety without the need for extensive reconstruction. This makes SPSWs an attractive option for enhancing the resilience of existing infrastructure in earthquake-prone regions or areas prone to windstorms.

The versatility of SPSWs is evident in their wide range of applications, from residential buildings to critical infrastructure projects. Design flexibility, coupled with advancements in material properties, such as high-strength steel and hybrid composite materials, has further expanded the potential applications of SPSWs. However, the design and implementation of SPSWs present their own set of challenges. Connection details and fabrication precision are critical to ensuring optimal performance and preventing issues such as out-of-plane buckling, which can compromise system stability. To address these concerns, researchers have been developing innovative connection designs, advanced analytical models, and the use of stiffeners to enhance stiffness and stability under various loading scenarios (Lee & Kim, 2002; Shishkin et al., 2009).

Recent advancements in material science have significantly influenced the evolution of Steel Plate Shear Walls (SPSWs), enhancing their capabilities and broadening their applications in modern construction. The development of high-strength steel alloys and innovative composite systems has led to substantial improvements in key performance metrics, such as strength-to-weight ratios, corrosion resistance, and overall durability. These advancements have rendered SPSWs not only more robust but also more efficient in resisting lateral loads caused by seismic activity, wind forces, and other dynamic environmental stresses. By reducing material weight without sacrificing strength, SPSWs contribute to more streamlined and cost-effective construction processes, offering considerable benefits in both new construction and retrofitting existing structures. Enhanced corrosion resistance and durability also increase the longevity of SPSW systems, reducing maintenance needs and improving long-term structural resilience.

The performance of SPSWs is primarily dictated by their geometry, material properties, and connection details, each of which can be precisely engineered to meet specific design criteria (Driver et al., 2008). These parameters directly influence the structural behavior of SPSWs, including their energy dissipation capabilities, deformation characteristics, and overall stability. By optimizing these design variables, engineers can tailor SPSW systems to maximize efficiency and safety in a wide range of building types, from low-rise structures to high-rise buildings and critical infrastructure.

Research has demonstrated that SPSWs exhibit superior energy absorption, enhanced deformation capacity, and increased stability under cyclic loading conditions, which are common during seismic events (Purba & Bruneau, 2010). This makes them especially attractive for buildings located in earthquake-prone regions, where the ability to dissipate energy and deform without significant loss of strength is critical for occupant safety and structural integrity. The controlled buckling behavior of SPSWs contributes to their exceptional ductility, allowing them to absorb seismic energy while minimizing damage to the overall structure. This characteristic ensures that buildings equipped with SPSWs can recover quickly after an earthquake, reducing downtime and associated economic losses.

SPSWs are also well-suited for critical infrastructure and facilities that must remain operational during and after extreme environmental events. Their capacity to withstand substantial lateral forces without excessive damage makes them a preferred choice for hospitals, emergency response centers, and other vital structures. Additionally, the adaptability of SPSWs allows for innovative design solutions that accommodate complex architectural geometries, providing flexibility for architects and engineers to create aesthetically pleasing and structurally resilient buildings.

Despite their many benefits, the implementation of SPSWs requires careful attention to design and fabrication details. Connection design, in particular, plays a crucial role in ensuring the stability and effectiveness of SPSWs. Proper detailing of connections is essential to prevent issues such as out-of-plane buckling and to guarantee seamless load transfer within the system. To address these challenges, researchers have developed advanced connection designs, the use of stiffeners, and sophisticated analytical models to predict and optimize the behavior of SPSWs under various loading scenarios (Lee & Kim, 2002; Shishkin et al., 2009). These innovations enhance the reliability and performance of SPSWs, making them a valuable addition to modern structural design practices.

As material science continues to advance, new high-strength alloys, hybrid materials, and composite systems are being developed to further improve the efficiency and versatility of SPSWs. These materials offer increased strength, reduced weight, and enhanced resilience, paving the way for even more efficient and sustainable structural solutions. The integration of these advancements into SPSW technology ensures that they remain at the forefront of resilient structural design, capable of meeting the demands of increasingly complex and challenging construction projects in the years to come.**Despite their numerous advantages, the adoption of SPSWs presents several challenges (Kulak & Driver, 1999).** Design complexities related to connections, the need for precise fabrication, and potential issues such as out-of-plane buckling require careful consideration. Researchers have been investigating various methods to address these challenges, including the development of innovative connection designs, the use of stiffeners (Lee & Kim, 2002), and advanced analytical models to predict the behavior of SPSWs under different loading scenarios (Shishkin et al., 2009). Furthermore, **recent advancements in material science, such as high-strength steel alloys and composite systems, have further expanded the potential applications of SPSWs in modern construction.**

2. Background and Literature Review

Historical Development of SPSWs

Steel plate shear walls were first introduced in the 1970s to address the limitations of conventional bracing systems (Thorburn et al., 1983). Over time, the design has evolved from using simple thin steel plates to advanced systems incorporating varying thicknesses, corrugation, and hybrid materials (Elgaaly, 1998). The progression from early experiments to modern standards highlights their versatility.

Design Requirements and Standards

The design of SPSWs requires strict adherence to specific codes and standards to ensure that they meet safety requirements (Sabelli & Berman, 2001). These standards focus on factors like plate thickness, panel configuration, and the connections between the steel plate and boundary elements (Driver et al., 1998). The American Institute of Steel Construction (AISC) sets guidelines for these systems, and each component must be carefully designed to allow controlled buckling, ensuring energy dissipation rather than structural failure.

Seismic Performance of SPSWs

In earthquake engineering, SPSWs are highly valued for their ability to deform in a controlled manner under seismic loads (Berman & Bruneau, 2003). Research reveals that double corrugation can significantly increase energy absorption (Purba & Bruneau, 2010). Studies also show that SPSWs can reduce the overall weight of the structure without compromising performance, an essential feature in tall buildings (Lubell et al., 2000).

Recent Innovations in SPSW Design

Recent advancements include the development of self-centering SPSWs that employ post-tensioned connections, allowing the structure to return to its original position after deformation (Vian & Bruneau, 2006). This approach's benefits include reduced residual displacement after seismic events, making these systems particularly valuable in high-seismic zones.

3. Analysis of SPSW Components and Design Features

Steel Infill Plates

The steel infill plate is the core component of a Steel Plate Shear Wall (SPSW), primarily responsible for resisting lateral forces and effectively transferring these forces to the surrounding boundary elements (Berman & Bruneau, 2005). This component operates by undergoing controlled buckling and dissipating energy through cyclic deformation, thus enhancing the seismic performance of the system. Recent research has demonstrated that corrugated infill plates offer superior performance due to enhanced out-of-plane stiffness (Purba & Bruneau, 2010).

The performance of the steel infill plate can also be optimized by varying parameters such as plate thickness, material properties, and connection details (Driver et al., 2008). Thicker plates typically offer greater strength and stiffness, but they may require special design considerations to avoid localized buckling (Behbahanifard et al., 2003).

Boundary Elements

Boundary elements, comprising beams and columns that form the surrounding frame of the SPSW, play a vital role in maintaining the stability and load-carrying capacity of the entire system (Driver et al., 1998). These elements act as critical supports that channel the forces resisted by the steel infill plate to the foundation and adjacent structural components. Research highlights the influence of boundary element design on SPSW effectiveness (Thorburn et al., 1983). The performance of these elements is particularly crucial during seismic events, where they must maintain their structural integrity while accommodating significant deformations (Berman & Bruneau, 2003).

The design of boundary elements requires careful consideration of multiple factors to ensure optimal system behavior. Studies have shown that the stiffness and strength of these elements significantly influence the overall behavior of SPSWs under seismic loading (Sabelli & Berman, 2001). The boundary elements must be designed to resist both the vertical gravity loads and the additional forces generated by the tension field action in the infill plates during lateral loading events (Kulak & Driver, 1999). This dual role necessitates careful attention to member sizing and detailing to prevent premature failure or excessive deformation.

Recent research has focused on optimizing the interaction between boundary elements and infill plates, particularly during cyclic loading conditions (Driver et al., 2008). The boundary frame must possess sufficient rigidity to anchor the tension field forces developed in the steel plate while maintaining its own structural integrity. Experimental studies have demonstrated that proper connection details between boundary elements and infill plates are crucial for achieving the desired energy dissipation capacity and overall system ductility (Lubell et al., 2000). Furthermore, the configuration and spacing of boundary elements significantly influence the development of tension field action in the infill plates, which is essential for the system's lateral force resistance (Behbahanifard et al., 2003).

Column Restrainers

Column restrainers are an essential component designed to enhance the performance of SPSWs by minimizing lateral column displacement and stabilizing the overall structure (Bruneau & Bhagwagar, 2002). These elements are strategically positioned to prevent excessive column sway and ensure efficient load transfer throughout the system. Research has demonstrated that properly designed restrainers significantly improve both the strength and stiffness of SPSWs, making them particularly valuable in tall buildings where lateral force distribution and variability are more pronounced (Takahashi & Sato, 1998).

The effectiveness of column restrainers depends heavily on their configuration and connection details. Studies by (Berman & Bruneau, 2005) have shown that restrainers must be carefully designed to balance the need for stability with the requirement for controlled deformation during seismic events. The placement and spacing of restrainers along the column height can significantly impact the system's overall performance. Research indicates that optimized restrainer arrangements can enhance the development of tension field action in the infill plates while preventing undesirable column buckling modes (Driver et al., 2008).

Recent investigations have focused on innovative restrainer designs that improve constructability while maintaining structural effectiveness. According to (Purba & Bruneau, 2010), advanced restrainer configurations can facilitate easier installation and reduce construction costs without compromising system performance. The interaction between restrainers and other SPSW components has been extensively studied, with findings indicating that properly designed restrainers contribute significantly to the system's energy dissipation capacity (Shishkin et al., 2009). Furthermore, experimental research has demonstrated that column restrainers play a crucial role in maintaining the stability of boundary elements during extreme loading events, thereby enhancing the overall seismic resilience of the structure (Behbahanifard et al., 2003).

4. Performance Evaluation of SPSWs

Seismic Response and Ductility

Ductility is a fundamental characteristic of Steel Plate Shear Walls (SPSWs) and plays a pivotal role in ensuring that structures can undergo significant deformations during seismic events without experiencing catastrophic failure (Berman & Bruneau, 2003). The study by (Vian & Bruneau, 2006) delves into how self-centering connections enhance the ductility of SPSWs. These connections allow the walls to "snap back" to their original position after seismic loading, minimizing residual displacements and reducing the potential for permanent structural deformation.

The ductility of an SPSW system is further influenced by the characteristics of the steel infill plates, boundary elements, and the interaction between the components (Driver et al., 1998). For instance, thin, low-yield-point (LYP) steel plates can provide higher ductility by yielding early and undergoing significant plastic deformation (Purba & Bruneau, 2010). The controlled buckling of the steel infill plates also contributes to ductility by ensuring that the deformation is distributed throughout the system rather than being concentrated in a single weak point (Lubell et al., 2000).

Energy Absorption

The ability of an SPSW system to absorb and dissipate energy during seismic events is a critical measure of its performance (Rezai, 1999). High energy absorption ensures that the system can reduce the forces transmitted to the rest of the building, thereby protecting other structural and non-structural elements. Research by (Purba & Bruneau, 2010) demonstrates that the use of corrugated steel plates can significantly improve energy absorption, especially during cyclic loading.

The energy absorption capacity of SPSWs can be tailored by varying the thickness, material composition, and geometric configuration of the infill plates (Behbahanifard et al., 2003). Research has shown that using double-corrugated low-yield-point (LYP) steel plates results in a system with superior energy dissipation properties compared to traditional flat or single-corrugated plates (Elgaaly, 1998).

Lateral Load Resistance

Lateral load resistance is one of the defining features of SPSWs, making them ideal for buildings subjected to high-wind or seismic forces (Astaneh-Asl, 2001). SPSWs resist lateral loads through a combination of axial tension in the steel infill plates and the interaction with the boundary elements (Thorburn et al., 1983). The study by (Driver et al., 2008) emphasizes the flexibility and adaptability of SPSWs in high-rise buildings, where lateral loads increase with height.

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5. Case Studies and Practical Applications

Real-world Implementations of SPSWs

Steel Plate Shear Walls (SPSWs) have been employed in numerous real-world projects across the globe, showcasing their effectiveness in enhancing the seismic resilience and lateral stability of buildings (Sabelli & Berman, 2001). The SPSW systems incorporated within various buildings have demonstrated outstanding performance during significant seismic events (Vian & Bruneau, 2005).

Beyond these high-profile cases, SPSWs have been successfully integrated into numerous smaller-scale projects, including retrofits of existing buildings and infrastructure upgrades (Bruneau & Bhagwagar, 2002). Retrofitting older buildings with SPSWs can significantly enhance their seismic performance without the need for extensive reconstruction (Kulak & Driver, 1999).

Such implementations underscore the ability of SPSWs to meet and often exceed modern performance-based design criteria for seismic safety.

Beyond these high-profile cases, SPSWs have been successfully integrated into numerous smaller-scale projects, including retrofits of existing buildings and infrastructure upgrades. Retrofitting older buildings with SPSWs can significantly enhance their seismic performance without the need for extensive reconstruction, offering a cost-effective solution to improving resilience. For example, in Vancouver, Canada, several aging structures have been retrofitted using SPSWs, leading to improved seismic safety and compliance with updated building codes. These case studies demonstrate the versatility of SPSWs across different scales of construction, reinforcing their role in modern seismic design strategies.

Challenges in Design and Construction

While SPSWs offer numerous benefits, they also pose several challenges that must be carefully addressed during the design and construction phases (Driver et al., 1998). Fabricating and installing steel infill plates with high precision is crucial, as any misalignment or improper connections can compromise the system's structural integrity (Shishkin et al., 2009).

The complexity of SPSW systems can lead to higher initial costs compared to more conventional lateral load-resisting systems (Roberts & Sabouri-Ghomi, 1992). Engineers must also consider issues such as out-of-plane buckling, potential corrosion of steel plates, and the effects of long-term fatigue due to repeated seismic events (Lee & Kim, 2002).

The complexity of SPSW systems can lead to higher initial costs compared to more conventional lateral load-resisting systems. This cost factor, coupled with the need for specialized labor, can pose challenges for widespread adoption, particularly in regions with limited technical expertise or budget constraints. To mitigate these challenges, ongoing training programs, investments in advanced construction equipment, and detailed design guidelines have been proposed. For example, pre-engineered SPSW panels with factory-installed connections can streamline on-site assembly and reduce potential errors.

Engineers must also consider issues such as out-of-plane buckling, potential corrosion of steel plates, and the effects of long-term fatigue due to repeated seismic events. Addressing these challenges requires comprehensive design and analysis during the planning phase, including finite element modeling and performance-based testing to ensure that the SPSW system behaves as intended under both static and dynamic loading conditions.

Overall, while the design and construction of SPSWs present unique challenges, their demonstrated effectiveness in real-world applications and ongoing advancements in technology make them a vital tool in the pursuit of resilient, seismic-resistant structures. By carefully managing construction complexities and investing in skilled labor and innovative fabrication techniques, the full potential of SPSWs can be realized, contributing to safer and more sustainable buildings in earthquake-prone areas.

6. Future Directions and Research Needs

Need for Further Experimental Studies

While Steel Plate Shear Walls (SPSWs) have demonstrated significant potential in enhancing the seismic resilience of buildings, there remains a pressing need for further experimental research to optimize and expand their applications (Berman & Bruneau, 2005). One promising avenue for exploration is the development of hybrid systems that combine steel with other advanced materials (Driver et al., 2008).

Moreover, there is a need for targeted research into the long-term performance of SPSWs under cyclic loading, environmental exposure, and repeated seismic events (Lubell et al., 2000). This research should include full-scale testing of SPSWs in different configurations (Behbahanifard et al., 2003).

The study "**Development of a Recentering Steel Plate Shear Wall and Addressing Critical Research Needs**" suggests that such hybrid systems could provide additional benefits in terms of resilience and adaptability, particularly in mixed-use and high-performance buildings where varying material properties are often required. For instance, composite-infused steel plates can be designed to offer lightweight properties, high strength, and improved damping capacity, making them suitable for complex structural applications. Experimental investigations into the mechanical behavior, failure modes, and fatigue resistance of these hybrid systems under different loading conditions would be instrumental in broadening their use in practical construction scenarios.

Moreover, there is a need for targeted research into the long-term performance of SPSWs under cyclic loading, environmental exposure, and repeated seismic events. This research should include full-scale testing of SPSWs in different configurations, including multi-story assemblies and retrofitted structures, to evaluate their real-world performance over extended lifecycles. Additionally, the effects of localized buckling, connection failures, and material degradation under extreme loading conditions need to be better understood to develop more robust design and construction guidelines.

Integration of Digital Technologies

The integration of digital technologies into the design, analysis, and optimization of SPSWs offers tremendous potential for improving the efficiency, accuracy, and performance of these systems (Shishkin et al., 2009). Finite Element Analysis (FEA) has already proven to be a powerful tool for simulating SPSW behavior under various load conditions (Driver et al., 2008).

In addition to FEA, AI-driven predictive modeling and machine learning algorithms offer a new frontier for optimizing SPSW design. By analyzing large datasets of past earthquake events, material properties, and structural performance outcomes, AI algorithms can identify patterns and optimize design parameters for maximum resilience and cost-effectiveness. For example, machine learning models could predict the most critical failure modes for specific building geometries or environmental conditions, enabling engineers to design more targeted mitigation strategies. AI-based optimization can also reduce design iterations and construction costs, leading to more efficient deployment of SPSWs in a wide range of building types and seismic regions.

Building Information Modeling (BIM) is another key technology that can be leveraged to streamline the design and construction of SPSWs. BIM allows for the creation of detailed 3D models of SPSWs and their integration with other structural components, improving coordination between architects, engineers, and contractors. By incorporating SPSW-specific parameters into BIM models, project teams can simulate construction sequences, identify potential conflicts, and optimize installation processes before construction begins. This level of digital integration not only improves the accuracy and quality of SPSW installations but also minimizes on-site errors and enhances overall project efficiency.

The Internet of Things (IoT) and smart sensor technology also hold significant promise for enhancing the monitoring and maintenance of SPSWs over their operational lifespan. By embedding sensors within SPSWs, building owners and engineers can continuously monitor key performance metrics, such as stress, strain, temperature, and vibrations. Real-time data collected from these sensors can be analyzed using AI algorithms to detect anomalies, predict potential failures, and schedule proactive maintenance interventions. This proactive approach to structural health monitoring ensures that SPSWs remain functional and resilient throughout their service life, even in high-risk seismic zones.

In conclusion, the integration of digital technologies, combined with continued experimental research into hybrid systems and material innovations, represents a transformative direction for the future development of SPSWs. By leveraging these advancements, engineers can design, construct, and maintain SPSW systems that are not only highly effective in resisting seismic forces but also adaptable, cost-efficient, and tailored to the evolving demands of modern construction. The continued exploration of these research needs will be critical in advancing the state of the art in SPSW technology and promoting safer, more resilient buildings for communities worldwide.

7. Conclusion

Steel Plate Shear Walls (SPSWs) present a cutting-edge approach to enhancing the seismic and lateral stability of modern buildings. By providing high ductility, superior energy absorption, and adaptability, SPSWs offer an effective means of dissipating seismic energy, minimizing structural damage, and maintaining the functionality of buildings during and after extreme events. This paper has reviewed key aspects of SPSW performance, with a particular focus on their primary components, including the steel infill plates, boundary elements, and column restrainers. Each of these elements plays a critical role in achieving the desired structural behavior under lateral loads, emphasizing the need for careful design and precise construction practices.

Real-world implementations, such as the Nippon Steel Building in Tokyo and the Casa Grande Building in San Francisco, underscore the practical effectiveness of SPSWs in protecting structures from seismic forces. These case studies highlight their proven ability to reduce damage, enhance safety, and ensure rapid post-event recovery, making them a preferred choice in earthquake-prone regions. Despite these successes, the adoption of SPSWs does come with challenges, such as fabrication complexities, connection precision, and the need for skilled labor. Addressing these challenges through continued research and advancements in construction technology will be critical to furthering the widespread application of SPSWs.

Looking ahead, SPSWs are poised to play an increasingly significant role in the construction industry's quest for safer, more resilient buildings. Emerging innovations, such as self-centering systems and hybrid material designs that integrate steel with composites or advanced polymers, promise to enhance their performance and broaden their applicability. The integration of digital technologies, including finite element analysis, AI-driven predictive modeling, and real-time monitoring systems, will further optimize the design, construction, and maintenance of SPSWs. As research and experimentation continue, SPSWs are expected to become even more effective and versatile, solidifying their position as a staple in the structural design of resilient, earthquake-resistant buildings. The future of SPSWs lies not only in their current capabilities but in the potential for continued evolution and adaptation to meet the demands of a changing world.

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