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Spherical Base Isolation and Hybrid Spherical Base Isolation Systems: A Critical Review of Current Research, Seismic Performance, Design Methodologies and Future Research Directions.

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ABSTRACT

Spherical base isolation systems, especially friction pendulum systems (FPS), are extensively investigated as a means of reducing the transfer of earthquake induced forces from the ground to the superstructure. However, conventional fixed-base structural systems, which resist earthquake loading predominantly through strength and ductility, spherical sliding isolation systems acquaint a regulated sliding interface between the foundation and the superstructure. The sliding surface furnishes a gravity-based restoring mechanism, while friction at the sliding interface contributes to energy dissipation. These characteristics enable the isolation period and displacement response to be modified through bearing geometry, friction properties and axial loading.

This review scrutinizes the technology, fundamental mechanics, classifications, experimental investigations, numerical modelling approaches and practical applications of spherical base isolation systems. Specifically consider single-concave, double-concave, triple friction pendulum and other multistage configurations. Furthermore, the review contemplates Hybrid spherical isolation systems that link frictional pendulum bearings with supplementary energy-dissipation, as well as viscous dampers, inverter-based devices, shape-memory alloy components and uplift restraint mechanisms.

The Literature indicates multistage and hybrid systems can furnish greater flexibility in controlling displacement, stiffness and energy dissipation than conventional single- surface bearings. However, their result is persuaded by frictional variability, sliding velocity, contact pressure, temperature, vertical ground motion, near-fault pulse effects and long-term changes in bearing properties. Lately research published journals has outstretched the field towards variable-friction numerical elements, full-scale testing, torsional response, seismic resilience assessment, hybrid inverter system and uplift resistant configurations.

The review determines various fields entail further investigation, specifically long-term field performance, experimental validation of integrated hybrid systems, reliable modelling of frictional behaviors, performance under near-fault and vertical ground motion and cost-effective design optimization. Ultimately the spherical base isolation remains a promising seismic protection technology. However, more comprehensive application depends on upgrading the reliable design and establishing stronger links between analytical predictions, experimental evidence and actual structural performance.

Keywords: Spherical base isolation; Friction pendulum system; Double friction pendulum; Triple friction pendulum; Hybrid base isolation; Seismic response; Energy dissipation; Inverter damper; Variable friction; Structural control.

1.0 INTRODUCTION:

Earthquake are one of the major natural hazards the cause damage for all the structure on the ground. During earthquake the vibration produce forces within the structure, which may cause lateral displacement, inter storey-drift, acceleration and in severe cases the structure collapse. Conventional earthquake design primarily depends upon the strength, stiffness, and ductility of structure to with stand the vibrations. Although this approach reduces the severe damage (structural collapse) it cannot completely prevent damages to the structure and non-structure components. To conquer these limitations, seismic isolation technology has been developed as an alternative method of earthquake protection. In lieu of making the whole structure stronger to resist vibrations, this methodology reduces the transfer of seismic vibration from ground to superstructure by furnishing the isolation layer between foundation and superstructure. Antonyms the

different isolation techniques, Friction Pendulum Systems (FPS) have enhanced substantial attention due to simple arrangement, restoring mechanism and ability to adopt large horizontal movements. The essential concept was introduced by Zayas, Low and Mahin (1990), who developed a curved sliding surface that connect pendulum action with frictional energy dissipation. In due course experimental studies by Mokha et al. (1991) evince the effectiveness of these systems in diminishing the seismic response of structure.

A typical Friction Pendulum System consists of a sliding element; a concave spherical surface and low-friction contact interface. During earthquake movement, the sliding element drift along the curved surface, while the load acting vertically on the bearing create a restoring force that helps the structure return to its original position. Concurrently friction between the sliding surface dissipate the energy produced by the earthquake. The spherical shape also allows movement in different horizontal directions, creating the system suitable for structure subjected to multidirectional ground motion. Based on the basic FPS concept, researchers have developed double concave and multi-surface friction pendulum bearings to improve displacement capacity, stiffness and energy dissipation. Furthermore, hybrid isolation systems have been investigated by connecting spherical sliding bearings with other devices such as Viscous dampers, tuned mass dampers, inter devices and shape-memory alloy components. These combinations aim to conquer some of the limitations of conventional FPS, encompass excessive sliding displacement, residual displacement and changes in friction properties. Although numerous experimental and numerical studies have demonstrated the potential of these systems, certain aspects still require further investigation, specifically vertical ground motion, torsion response on the structure, long-term friction variation, different bearing to bearing distance and performance of hybrid system under severe earthquake condition. Consequently, a rigorous review of existing research on spherical base isolation and hybrid spherical isolation systems is essential to understand their development, performance, limitations and future scope in earthquake resistant structural design.

1.1 Research Objectives:

The main objectives are:

1. Describe the fundamental working principles of spherical base isolation systems.
2. Scrutinize the development of single, double and multi friction pendulum bearings.
3. Reviewing experimental and numerical investigations concerning their seismic performance.
4. Analyze the influence of friction, curvature, axial load, velocity and ground motion characteristics.
5. Investigating the hybrid isolation systems integrating auxiliary damping and control devices.
6. Comparing the advantages and limitations of conventional and hybrid spherical isolation configurations.
7. Identifying the research gaps and endorse directions for future investigation.

1.2 Scope and significance of the review:

This review considers published journal research related to friction pendulum systems, spherical sliding bearings, adaptive friction mechanisms and hybrid isolation arrangements. The review emphasizes on friction based spherical sliding isolation systems used for earthquake protection. It encompasses single, double, triple concave friction pendulum bearings and multistage configurations. Hybrid systems are considered where spherical sliding bearings are connected with additional damping and control mechanism.

The term hybrid spherical base isolation is used for arrangements in which a spherical sliding bearing is combined with an additional functional mechanism. Such mechanisms may include viscous dampers, inverters, springs, semi-active control devices or displacement-restraint systems. The purpose of adding these devices is generally to improve one or more aspects of the structural response, such as displacement control, energy dissipation or overall seismic performance. A clear virtue should be maintained between hybrid systems and multi-stage friction pendulum bearings. For example, a triple friction pendulum bearing contains several internal sliding surfaces and can provide different response characteristics at different displacement levels. However, the proximity of multiple sliding surfaces alone refrains from making the bearing a hybrid system. Its versatile behaviour is produced by the arrangement of the bearing's internal components in lieu of addition of a separate response-control device.

2.0 FUNDAMENTAL PRINCIPLES OF SPHERICAL BASE ISOLATION:

2.1 Concept of spherical sliding isolation:

A typical spherical sliding bearing consists of a concave spherical surface, a sliding element and a low-friction interface. It is generally installed between the foundation and the superstructure so that controlled relative movement can take place when the ground is subjected to earthquake excitation.

When horizontal ground movement occurs, the slider forges ahead the concave surface of the bearing. whereas the sliding surface is curved, this movement also generate a small vertical displacement of the supported structure. As the slider detaches from its original equilibrium position, the gravitational potential energy increases. The consequent gravitational action generates a restoring force that tendency to move the slider towards the centre of the concave surface.

Simultaneously, friction enhances between the sliding surfaces. This friction opposes the relative movement and dissipates part of the energy transferred to the structure during the earthquake. Thus, the behaviour of a spherical sliding isolation system is mainly controlled by two mechanisms:

- Gravity-induced restoring action
- Friction-induced energy dissipation

The combined operation of these mechanisms permits the bearing to accommodate horizontal movement while limiting the transfer of earthquake-induced forces to the superstructure.

In summary seismic response is consequently governed by gravity induced restoring action and friction induced energy dissipation. The original experiment work of Zayas et al. [1] established this principle, while Mokha et al. [2]-[6] investigated the mechanical behavior and frictional characteristics of sliding interfaces.

2.2 Mechanical behavior and governing parameters:

For a perfect spherical bearing with a steady effective radius of curvature, the horizontal restoring force can be stated as

$$F_r = \frac{W}{R}u$$

,

Were,

F_r = The gravity-induced restoring force

W = The vertical load supported by the bearing

R = The effective radius of curvature

u = The horizontal displacement of the slider.

The frictional force can be provided in simplified form as

$$F_f = \mu W \ \mathrm{sgn}(\dot{u})$$

were,

μ = The coefficient of friction

$\dot{u}$ = The relative sliding velocity.

$\mathrm{sgn}(\dot{u})$ = Direction of the sliding motion

The total horizontal resistance is approximately

$$F = F_r + F_f$$

Actual bearings exhibit more complex behaviour because friction may vary with velocity, contact pressure, temperature, wear and accumulated sliding distance.

For an ideal single-surface pendulum system, the approximate effective isolation period is

$$T = 2\pi\sqrt{\frac{R}{g}}$$

where, g represents gravitational acceleration.

Increasing the radius generally enhances the isolation period and reduces effective lateral stiffness. However, enhancing the isolation period also affects the required displacement capacity. Bearing curvature must. Thus, selected bearing curvature must consider both acceleration reduction and displacement demand.

2.3 Influence of friction characteristics:

Friction is included in most significant parameters governing spherical sliding isolation. A comparatively high friction coefficient increases energy dissipation may also increase the horizontal force transferred to the superstructure. Vice versa, low friction can reduce force transmission but outcome maybe in larger isolation displacement. Mokha et al. [3]–[6] investigated the frictional behavior of Teflon sliding bearings and developed mathematical models to represent the reliance of friction on sliding velocity and loading conditions. Dolce et al. [14] examined steel-PTFE interfaces. Full-scale dynamic testing by Pigouni et al. [15] further highlighted the importance of vertical load when distinguishing frictional properties.

3.0 DEVELOPMENT AND CLASSIFICATION OF SPHERICAL SLIDING BEARINGS:

3.1 Single-concave friction pendulum system:

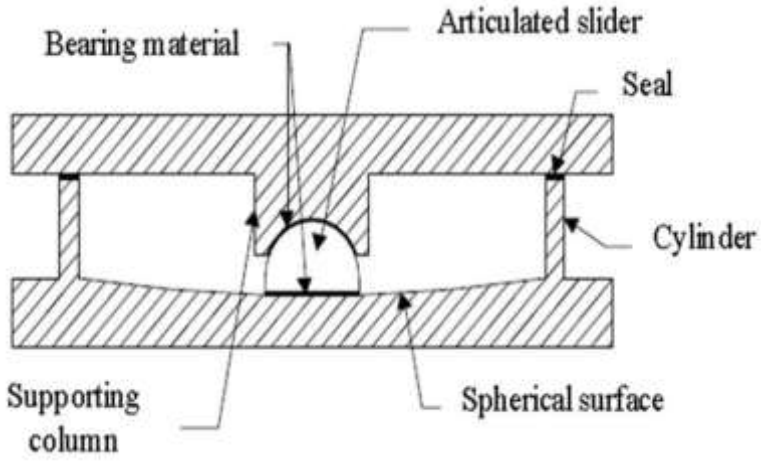


Fig - 01

The single-concave friction pendulum system epitomizes the conventional configuration of spherical sliding isolation. It dwell with one concave sliding surface and a slider that forges ahead the curved interface throughout the earthquake excitation. Its advantages include a comparatively simple mechanical configuration, gravity-based restoring mechanism, frictional energy dissipation and an isolation period controlled primarily by surface curvature.

Zayas et al. [1] established the fundamental concept, while Mokha et al. [2] demonstrated its effectiveness through shake-table experiments. Almazán and De la Llera [12] subsequently developed an analytical model for structures isolated using frictional pendulum systems. Despite its advantages, the standard single-concave system has limitations associated with displacement capacity and fixed mechanical properties.

3.2 Double-concave friction pendulum bearing:

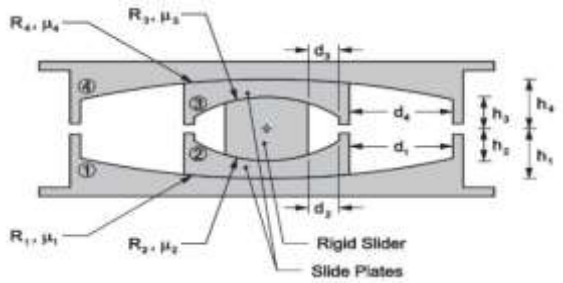


Fig - 02

The double-concave friction pendulum bearing integrates two contrary curved sliding surfaces. Fenz and Constantinou [7] presented a detailed investigation of its behavior in 2006. Research revealed that the structure could accommodate greater displacements than a conventional friction pendulum bearing with corresponding plan dimensions. The reaction relies on the geometrical properties and frictional features of both sliding surfaces. Variations between interfaces introduce additional intricacy into the mechanical behavior and numerical modelling.

Bao and Becker [28] investigated failure behavior of double friction pendulum bearings under pulse-type ground motions, emphasizing the importance of evaluating accuracy under extreme excitation.

3.3 Triple friction pendulum bearings:

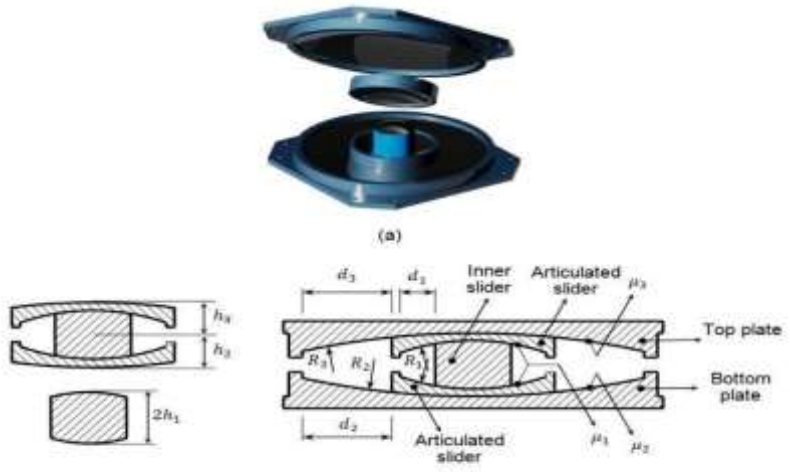


Figure 1: Triple friction pendulum bearing
(a) Three-dimensional view
(b) Section view and basic parameters

Fig - 03

Triple friction pendulum bearings contain multiple concave sliding interfaces, allowing different effective stiffness and damping characteristics at different displacement levels. Fenz and Constantinou [8], [9] developed theoretical and experimental investigations of spherical sliding isolation bearings with adaptive behavior. Becker and Mahin [10] investigated two-way behavior and prepared a nonlinear kinematic model integrating coupled plasticity and circular restraining surfaces. Their work presented that the model could replicate two-way bearing behavior and track internal component movement.

An important advantage is the capability to provide different response features under different displacement demands. However, the additional sliding interfaces increase model complexity and necessitate prudence representation of internal sliding transitions.

3.4 Quintuple and multi-stage friction pendulum systems:

Multi-stage spherical bearings extend the adaptive isolation concept. Lee and Constantinou [11] investigated the behaviour, modelling and validation of a quintuple friction pendulum isolator. Multiple sliding stages enable different effective stiffness and damping properties over a wider displacement range. Keikha and Ghodrati Amiri [35] reviewed simplified analytical methods for isolated structures with quintuple friction pendulum isolators under bidirectional near-field excitation. Multi-stage configurations offer opportunities for different response characteristics under moderate and severe earthquakes, but their performance depends on transition displacements, friction coefficients and effective radii of curvature.

4.0 EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON SPHERICAL BASE ISOLATION:

4.1 Experimental investigations:

Preliminary testing has performed a key role in advancing and validating spherical isolation systems. Zayas et al. [1] confirmed the feasibility of a spherical sliding interface. Mokha et al. [2] carried shake-table experiments on a six-storey quarter-scale model structure and furnished evidence that isolation can enhance the tested model's seismic performance.

Later work by Fenz and Constantinou [9] verified adaptive spherical sliding bearings by experimentation, whereas Becker and Mahin [10] investigated bidirectional triple friction pendulum response. Pigouni et al. [15] protracted the testimony through full-scale dynamic testing. Akazawa et al. [16] investigated a full-scale steel frame supported on low-friction spherical sliding bearings.

4.2 Numerical modelling of spherical bearings:

Numerical modelling is necessary due to bearings demonstrate nonlinear behavior because of friction, variations in sliding direction, geometric restoring action and transitions between sliding surfaces. Almazán and De la Llera [12] developed an analytical framework for friction pendulum systems. Whereas, Fenz and Constantinou [8] developed academic formulas for accommodative spherical bearings, while Becker and Mahin [10] extended modelling to bidirectional triple friction pendulum response. Simplified sliding-friction models may be suitable for preliminary investigations, but advanced models are required to measure friction dependency, internal slider movement, axial-load variation or bearing instability.

4.3 Influence of near-fault ground motions:

Near-fault ground motions may include strong velocity pulses and long-period features that substantially affect displacement response. Mazza and Mazza [27] investigated nonlinear seismic behavior of irregular reinforced-concrete buildings isolated using friction pendulum systems under near-fault excitations, considering torsional response, residual displacement and bearing uplift. Whereas, Bao and Becker [28] examined failure behavior of double friction pendulum bearings under pulse-type motions. Tajammolian and Khoshnoudian [29] studied reliability of symmetric and asymmetric structures supported on triple-concave friction pendulum bearings under near-field earthquakes.

4.4 Influence of vertical ground motion:

Vertical ground motion is significant because frictional resistance counts on the normal force acting on the sliding surface. Ryan [18] investigated the influence of vertical ground shaking on bridges isolated with spherical sliding bearings. Modification in bearing axial force can affect the horizontal friction force and seismic base shear. Research on subterranean stations with friction pendulum bearings has also indicated that vertical ground motion can minimize the isolation effectiveness under certain conditions [25]. Three-dimensional analysis is therefore important where vertical excitation is significant.

4.5 Applications in buildings and bridges:

Spherical sliding bearings have been investigated for buildings, bridges, liquid storage tanks and spatial structures. Abal and Uçkan [17] investigated isolated liquid storage tanks through curved surface sliding bearings, emphasizing variations in axial force throughout the earthquake excitation. Bridge research has examined the efficacy of friction pendulum bearings and transverse hammering at shear keys [26]. Research on spherical reticulated shell structures has also considered friction pendulum bearings [37]. Structural configuration, support conditions, axial-load distribution and displacement capacity must be considered when extending the technology to different infrastructure systems.

5.0 HYBRID SPHERICAL BASE ISOLATION SYSTEMS:

5.1 Concept and development:

Standard spherical sliding bearings provided by isolation through pendulum motion and frictional energy dissipation. Their operation may turn into less advantageous when severe earthquake excitation generates displacement requirements above the available bearing capacity. Hybrid spherical base isolation integrates a conventional spherical bearing with an additional energy-dissipation, restoring or response-control mechanism. Potential configurations include friction pendulum bearings with viscous dampers, inverter systems, supplementary restoring springs, semi-active control devices and displacement or uplift restraints.

It is essential to identify enhancements achieved through variations to the spherical bearing itself from enhancements obtained by connecting the bearing with an independent supplementary device.

5.2 Friction pendulum bearing combined with viscous damper:

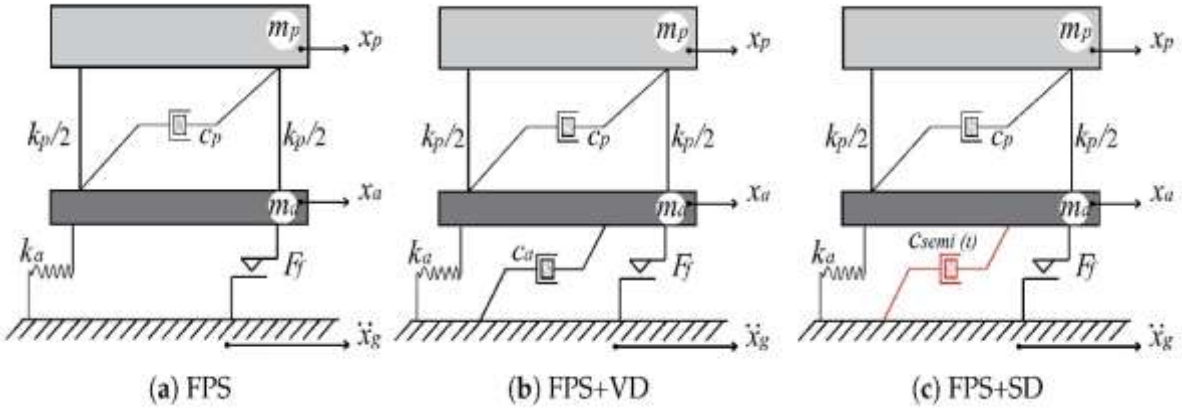


Fig - 04

A viscous damper enhances a resisting force subjected to relative velocity. Its simplified as

$$F_d = C|\dot{u}|^{\alpha}\,\mathrm{sgn}(\dot{u})$$

Were,
C = Damping coefficient
$\dot{u}$ = relative velocity.
F_d = Viscous damping force
α = Velocity exponent
The combined isolation system can be represented as

$$F_{\text{hybrid}} = F_r + F_f + F_d$$

where, F_r, F_f, and F_d represents the restoring, frictional and viscous damping forces
Chen and Xiong [32] investigated a friction pendulum bearing–viscous damper configuration. Their study stated that enhancement in structural response and control of extravagant isolation displacement under the scrutinized state.

Possible benefits incorporate extra energy dissipation, enhanced control of peak isolation displacement and minimizing the reliance on friction alone. However, damping coefficients must be selected cautiously due to excessive damping can maximize the force transmitted through the isolation layer. Damper stroke, arrangement, torsional effects and force distribution must also be considered.

5.3 Friction pendulum bearing combined with inverter systems:

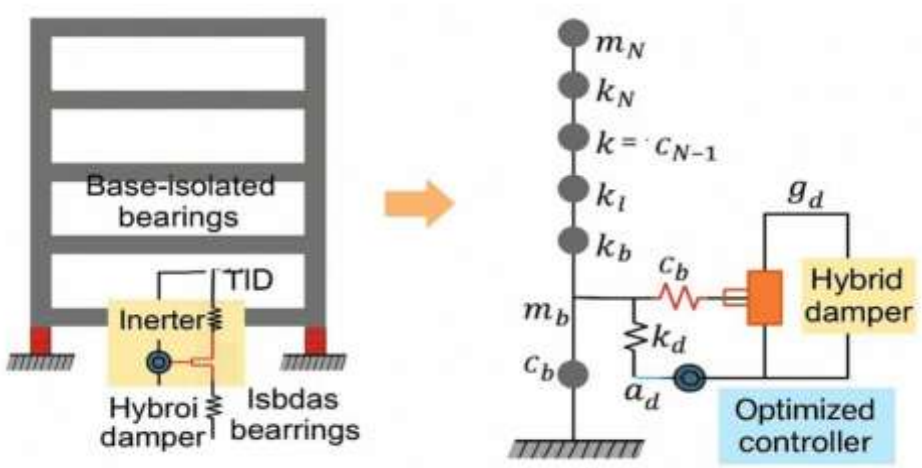


Fig - 05

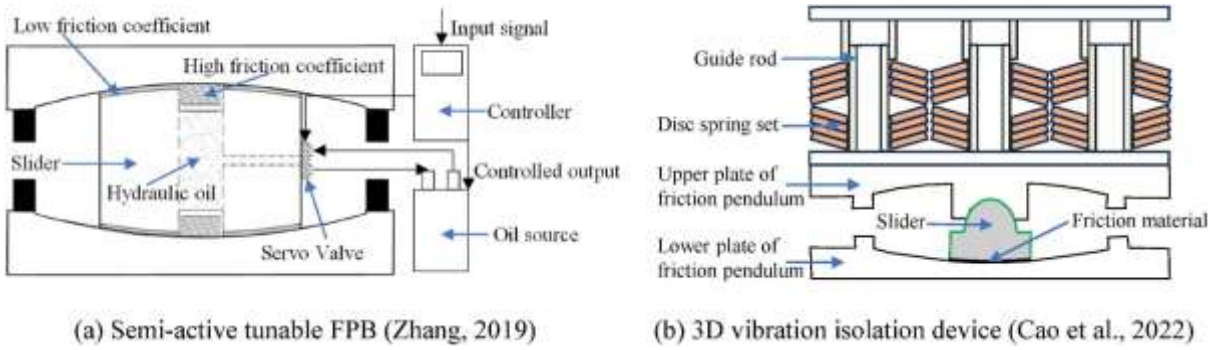
An inverter creates a resisting force proportionate to comparative acceleration between its terminals. Its theoretical relationship is

$$F_i = b(\ddot{u}_1 - \ddot{u}_2)$$

were,
F_i = Inverter force
b = Inertance
$\ddot{u}_1$ and $\ddot{u}_2$ = terminal accelerations.

De Domenico, Ricciardi and Zhang [33] investigated optimal design and seismic performance of a tuned fluid inverter applied to structures with friction pendulum isolators. Zhang, Men and Rong [34] examined friction pendulum inverter systems under near-fault earthquakes. These studies indicate additional possibilities for controlling isolation displacement and superstructure acceleration. Practical implementation must consider mechanical complexity, connection forces, maintenance and reliability.

5.4 Semi-active and tunable friction pendulum systems:



(a) Semi-active tunable FPB (Zhang, 2019) (b) 3D vibration isolation device (Cao et al., 2022)

Fig - 06

Standard friction pendulum systems function apathetically, with frictional and restoring features unyielding by bearing geometry and materials. Semi-active control initiates the opportunities of altering response features during operation. Study on adjustable friction pendulum systems [35] has examined adjustable friction mechanisms for semi-active control. Such systems may adapt to changing demands, but require reliable sensing, control algorithms, actuators and power arrangements. Performance beneath the sensor failure, power interruption and unanticipated earthquake features should be evaluated.

5.5 Hybrid configurations with supplementary restoring mechanisms:

Supplementary restoring mechanisms may be useful where improved recentering or residual displacement control is required. Potential configurations include mechanical springs, self-centering components, shape-memory-alloy elements and elastic restraint mechanisms. These elements may minimize the residual displacement, but additional stiffness variations the dynamic features of the isolation system. Extravagant restoring force may reduce the effective isolation period and increase force transfer. Such arrangements should be treated as research directions necessitating the component-level and system-level validation.

5.6 Uplift restraint and displacement-control mechanisms:

Elevate and extravagant sliding displacement can affect stability throughout the severe earthquakes. Reversal effects, non-uniform vertical loading and strong vertical excitation may cause minimized potential elevate at certain bearings. Roussis and Constantinou [30] investigated an elevate-restraining friction pendulum isolation system. Restraint mechanisms must evade sudden involvement and extravagant impact forces, and should not interrupt with intended isolation behavior.

5.7 Comparison of spherical and hybrid systems:

- **Single-concave FPS:** gravity restoring and friction; simple and established, but displacement capacity may be limited.
- **Double-concave FPS:** two spherical sliding surfaces; increased displacement capacity, but more complex sliding behaviour.
- **Triple FPS:** multiple sliding stages; adaptive stiffness and damping, but complex transition modelling.
- **Quintuple FPS:** multiple internal sliding interfaces; wider adaptive response, but detailed component modelling is required.
- **FPS with viscous damper:** friction and velocity-dependent damping; additional displacement control, but potentially increased transmitted force.
- **FPS with inverter:** friction and acceleration-dependent force; additional dynamic response control, but greater mechanical complexity.
- **Tunable FPS:** adjustable friction; adaptability to changing demands, but control-system dependency.
- **FPS with restoring device:** pendulum and supplementary restoring force; potential reduction in residual displacement, but possible increase in effective stiffness.

6.0 CRITICAL EVALUATION AND SYNTHESIS OF EXISTING RESEARCH:

6.1 Evolution from conventional to adaptive spherical bearings:

The advancement of spherical sliding isolation can be extensively viewed in three stages. The first established the conventional friction pendulum system and its experimental confirmation through the work of Zayas et al. [1] and Mokha et al. [2]. The second focused on maximizing displacement capacity and adaptive mechanical features through double-concave and multi-stage bearings, confirmation through work by Fenz and Constantinou [7] – [9], Becker and Mahin [10] and Lee and Constantinou [11]. The third stage involves additional control mechanisms, including viscous dampers, inverters and semi-active friction systems.

6.2 Limitations of existing experimental investigations:

An important ratio of innovative research is based on isolated bearing components. Scaling results to full-scale structures demands cautious attention to resemblance conditions. Contact pressure, sliding velocity, material behavior, temperature and cumulative sliding distance may not be duplicated accurately in small-scale models. Full-scale testing such as that reported by Pigouni et al. [15] is valuable, but identical evidence for complex hybrid spherical configurations remains limited.

6.3 Limitations of conventional friction models:

Many structural analyses assume a constant coefficient of friction. This may be giving satisfactory result for preliminary studies but might not portray actual behaviour under different earthquake conditions. Research paper work by Mokha et al. [3] – [6] and Dolce et al. [14] demonstrates that friction depends on several parameters. Li and Kishiki [24] examined friction dependencies in bidirectional double-concave bearing response, while wear-related investigations [19] highlight the importance of accumulated sliding distance. Advanced performance evaluation should consider velocity- and pressure-dependent friction were supported by test data.

6.4 Limitations in the evaluation of hybrid systems:

Hybrid systems introduce additional parameters. An FPB-VD system requires evaluation of bearing curvature, friction coefficient, viscous damping coefficient and velocity exponent. An FPB-inverter system requires consideration of inertance, damping and mechanical configuration. Comparisons are not always performed using identical structural models, ground-motion sets and performance indicators, limiting direct ranking of effectiveness.

A systematic equivalence should include maximum and residual isolation displacement, maximum floor acceleration, damper force and stroke, component energy dissipation, inter-storey drift, base shear, bearing axial force, and bearing stability.

6.5 Research implications:

The reviewed research paper indicates that the future development of spherical isolation should not only focus solely on expanding the number of sliding surfaces or adding extra damping devices. Instead, The principal research objective of a balanced response under different intensity of earthquake: an effective system should control displacement, maintained bearing stability, reduced acceleration transfer, and limited residual displacement without excessive force demands. This requires integrated consideration of the bearing, supplementary devices, structural system and seismic hazard.

7.0 RESEARCH GAPS AND FUTURE DIRECTIONS:

7.1 Limited experimental validation of hybrid spherical bearings:

An important experimental literature exists for standard and multi-stage spherical bearings, but minimum studies have examined complete hybrid isolation systems through full-scale testing. Future research should include component-level tests, subassembly testing and shake-table experiments, with attention to interaction between the bearing and supplementary damping devices.

7.2 Development of improved friction models:

Friction depends on velocity, vertical pressure, temperature, wear and sliding history. Subsequent investigations should develop advanced friction models integrating this limitation and validate them using representative experimental loading conditions.

7.3 Behaviour under near-fault and long-duration earthquakes:

Future research should examine near-fault pulse-like ground motions, long-duration subduction earthquakes, combined vertical and horizontal excitation, bidirectional and three-dimensional ground motions, and mainshock-aftershock sequences. Hybrid devices should be compared against conventional spherical bearings under equivalent ground-motion conditions.

7.4 Optimization of hybrid damping mechanisms:

The simultaneous optimization of bearing radius, sliding friction, damper coefficient, inverter parameter, supplementary restoring stiffness and displacement capacity is a multi-objective problem. Optimization should seek to reduce acceleration, displacement and force demands while satisfying stability and practical design constraints.

7.5 Residual displacement and self-centering behavior:

Residual displacement may affect post-earthquake functionality. Although spherical geometry provides a restoring tendency, friction can prevent complete recentering. Future researchers should explore additional springs, self-centering elements and shape-memory-alloy components without significantly expanding isolation forces.

7.6 Long-term durability and maintenance:

Material degradation, wear, corrosion and environmental exposure influence long-term bearing performance. Researcher should scrutinize the bearings after prolonged service and accumulated sliding, supported by long-term experiments and field monitoring.

7.7 Performance-based seismic design:

Future design approaches should incorporate repairability, residual displacement and post-earthquake functionality, in addition to base shear, displacement and acceleration. The objectives must be considered based on different earthquake intensity levels and structural performance.

7.8 Proposed framework for future experimental research:

- Selection of spherical bearing configuration
- Characterization of sliding materials
- Development of nonlinear bearing model
- Integration of supplementary damper
- Component-level experimental testing

- Validation of hybrid numerical model
- Nonlinear response-history analysis
- Parametric and multi-objective optimization
- Full-scale or shake-table validation
- Performance-based design recommendations

8.0 CONCLUSIONS:

- Spherical sliding bearings provide an effective seismic isolation through gravity-induced restoring action and frictional energy dissipation. The fundamental operating principle was established in early research and thereafter validated experimentally.
- The development of double-concave, triple friction pendulum and multi-stage spherical bearings has enhanced the displacement capacity and adaptability of isolation systems. These configurations allow variations in effective stiffness and damping as the bearing moves between different sliding stages.
- Seismic performance is strongly influenced by frictional characteristics. Variations in sliding velocity, vertical pressure, temperature and accumulated sliding distance can affect bearing response. Realistic friction models and experimental characterization are therefore essential.
- Near-fault excitation, vertical ground motion and structural irregularities can influence isolated-structure response. Far-field records solitary may not adequately evaluate the severe earthquake conditions.
- Hybrid spherical isolation is a promising direction. Viscous dampers and inverter systems provide additional possibilities to control isolation displacement and superstructure acceleration.
- The effectiveness of hybrid isolation depends on appropriate selection of supplementary-device parameters. Extravagant damping or restoring stiffness may increase force transfer and minimize the isolation effectiveness.
- The available literature indicates a need for more experimental validation of complete hybrid systems. Full-scale testing, durability assessment and advanced nonlinear modelling are important for establishing practical reliability.
- Future research should focus on multi-objective optimization, improved friction characterization, residual displacement control, multi-directional earthquake response and performance-based seismic design.

Overall, spherical sliding isolation has been developed from a standard passive friction pendulum mechanism into a extensive clan of adaptive and hybrid seismic protection technologies. Further research into the connection between spherical bearings and supplementary response-control devices could contribute to more credible and resilient earthquake-resistant structural systems.

9.0 COMPARATIVE LITERATURE SYNTHESIS:

The reviewed studies cover several connected research areas. Conventional FPS studies by Zayas et al. [1] and Mokha et al. [2] establish the technology and its experimental basis. Friction characterization studies [3] – [6], [14], [19], [24] explain the importance of sliding-interface properties. Double-, triple- and multi-stage bearing studies [7] – [11] develop flexible structure and modelling approaches. Structural application and earthquake-response studies [17], [18], [25] – [29], [37] consider tanks, bridges, spatial structures, near-fault motion and vertical excitation. Hybrid-control studies [32] – [35] explore viscous damping, inverters and tunable friction.

Three observations emerge. First and foremost, conventional and multi-stage spherical bearings have a relatively confirmed theoretical and experimental foundation. Second, response is not governed by curvature alone: displacement history friction, vertical loading, and earthquake characteristics have substantial affect. Third, hybrid spherical isolation remains an emerging area requiring further experimental and relative investigation. A major opportunity is to compare conventional FPS, adaptive multi-stage bearings and hybrid systems under the same structural and earthquake conditions.

10.0 RESEARCH CONTRIBUTION AND POTENTIAL NOVELTY FOR FUTURE PUBLICATION:

10.1 Development of an improved hybrid spherical isolation configuration:

An updated configuration could incorporate a multi-stage spherical bearing with a additional damping mechanism. The objective would be to balance reductions in isolation displacement, superstructure acceleration, inter-storey drift, base shear and residual displacement. The proposed configuration should be compared with conventional single-surface and multi-stage bearings.

10.2 Numerical investigation using realistic friction characteristics:

A nonlinear model could incorporate velocity-dependent friction, pressure-dependent friction, bidirectional sliding, multiple sliding stages, supplementary damper response and axial-load variation. To published experimental results before parametric analysis, the model should be validated against it.

10.3 multi-objective optimization:

Design parameters can be optimized from minimize to maximum isolation displacement and maximum superstructure acceleration while maintaining acceptable bearing forces and stability. A Pareto-based approach may be useful because competing performance objectives need not have a single common optimum.

10.4 Performance under different earthquake characteristics:

The proposed system should be evaluated under far-field, near-fault, pulse-like and long-duration ground motions. Where bidirectional or vertical excitation is important, then three-dimensional response-history analysis can be considered.

10.5 Experimental validation:

An experimental program should include cyclic bearing tests, damper characterization and, where facilities permit, shake-table testing of the complete hybrid system. Experimental findings should be compared with the nonlinear model to validate accuracy and identify modelling limitations.

These are potential research contributions, not established findings. A novelty claim should only be made after a systematic search of recent literature, relevant patent records and existing experimental configurations.

11.0 REFERENCES:

The following 40 journal publications form the proposed core bibliography. They cover the development of spherical bearings, experimental investigations, nonlinear modelling, multi-stage isolation and hybrid response-control systems.

A. Fundamental development and friction pendulum systems:

[1] Zayas, V. A., Low, S. S., and Mahin, S. A. (1990). A simple pendulum technique for achieving seismic isolation. Earthquake Spectra, 6(2), 317–333.

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